Analysis of Cardio-respiratory Dynamics during Mental Stress using (Partial) Time-Frequency Spectra

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Abstract

Mental stress is a major problem in today's society. It is therefore important to determine the mechanisms underlying stress. In this paper, we aim at studying the cardio-respiratory response to mental stress using a nonparametric multivariate time-frequency approach. In addition, partial spectra are considered to separate RR interval variations (RRV) that can be related to respiration from RRV that are unrelated to respiration. The results confirm vagal withdrawal during mental stress and also reveal that the autonomic response to stress is driven by mechanisms both related and unrelated to respiration that are characterized by different response times.

1. Introduction

Mental stress is a growing problem that has been investigated widely as it seems to be one of the risk factors for cardiovascular diseases [1]. In order to gain insights and deal with this problem, we need to identify the underlying stress mechanisms responsible for this increased cardiovascular risk. Most studies focus on the impact of stress on the cardiovascular system by means of RR interval variability (RRV) [2], as this is a measure of the well-functioning of the autonomic nervous system (ANS). Yet, there is a strong interaction between RRV and respiration, termed respiratory sinus arrhythmia (RSA) [3], which is mostly ignored, thereby leading to possible false interpretations of ANS functioning [4]. It is therefore important to conduct a combined analysis of the cardio-respiratory system.

In this study, we will perform cross time-frequency (TF) analyses of RRV and respiration during mental stress and sustained attention. TF analyses are chosen because they can deal with nonstationary signals and can be used to assess the dynamic spectral response on cardio-respiratory coupling. In addition, partial TF spectra are introduced to disentangle the effects of respiratory influences on RRV separately from other processes, unrelated to respiration, that also contribute to RRV. We hypothesize that this approach might reveal RR interval variations that are influenced by mental stress that are otherwise masked by the dominant effect of respiration on RRV.

2. Material and methods

2.1. Data aquisition and preprocessing

The data for this study were measured at the Department of Psychology and Educational Sciences of the KU Leuven (Leuven, Belgium) [5, 6]. The electrocardiogram (ECG, sampling frequency $f_s = 200$ Hz) and respiration ($f_s = 50$ Hz) of 40 healthy students (age: 18-22 years) were recorded using the LifeShirt System (Vivometrics Inc., Ventura, CA). The participants were instructed to perform 2 types of tasks. The first task was a nonstressful attention task (AT) where the subjects had to indicate the largest number on a computer. During the second task, stress was induced using a mental arithmetic task. The whole protocol consists of one AT and two stress tasks (MT1 and MT2), in randomized order, each followed by a recovery period. Prior to any task, there was a resting period during which the subjects watched a relaxing documentary (RD). Each task had a duration of 6 minutes.

The RR interval series are obtained by detecting the R peaks in the ECG using the Pan-Tompkins algorithm. The respiratory signal and RRV are resampled at 4 Hz using cubic spline interpolation, and both signals are highpass filtered with a cutoff frequency of 0.003 Hz to remove very slow oscillations. All processing steps of the data are performed in MATLAB R2012a (MathWorks, Natick, MA).

2.2. Time-frequency analysis

The cross time-frequency spectrum $S_{xy}(t,f)$ of signals $x(t)$ and $y(t)$ is estimated using a time-frequency distribution (TFD) [7]:

$$S_{xy}(t,f) = \int\int_{-\infty}^{+\infty} \Phi(\tau,\nu) A_{xy}(\tau,\nu) e^{j2\pi(t\nu - \tau f)} d\nu d\tau \quad (1)$$

$$A_{xy}(\tau,\nu) = \int_{-\infty}^{+\infty} x\left(t+\frac{\tau}{2}\right) y^*\left(t-\frac{\tau}{2}\right) e^{-j2\pi\nu t} dt \quad (2)$$

with $A_{xy}(\tau,\nu)$ the cross-ambiguity function. Smoothing is performed by an exponential kernel:

$$\Phi(\tau,\nu) = \exp\left\{-\pi\left[\left(\frac{\nu}{\nu_0}\right)^2 + \left(\frac{\tau}{\tau_0}\right)^2\right]^{2\lambda}\right\}. \quad (3)$$

The values of τ_0, ν_0 and λ are set to 0.050, 0.046 and 0.3 respectively, resulting in a kernel function with a TF resolution of $\{\Delta_t, \Delta_f\} = \{10.9\text{ s}, 0.039\text{ Hz}\}$, where Δ_t and Δ_f quantify the spreading by the kernel [7, 8].

Time-frequency coherence, $\gamma_{xy}(t,f)$, and phase difference, $\Theta_{xy}(t,f)$, are computed as [7]:

$$\gamma_{xy}(t,f) = \frac{|S_{xy}(t,f)|}{\sqrt{S_{xx}(t,f)S_{yy}(t,f)}}\ ; \gamma_{xy}(t,f) \in [0,1] \quad (4)$$

$$\Theta_{xy}(t,f) = \arctan\left[\frac{\Im[S_{xy}(t,f)]}{\Re[S_{xy}(t,f)]}\right]\ ; \Theta_{xy}(t,f) \in [-\pi,\pi]. \quad (5)$$

The separation of respiratory influences from RRV is performed using partial TF spectra, obtained by:

$$\begin{aligned} S_{xx/y}(t,f) &= S_{xx}(t,f) - \frac{S_{xy}(t,f)S_{yx}(t,f)}{S_{yy}(t,f)} \\ &= (1-\gamma_{xy}^2(t,f))S_{xx}(t,f). \end{aligned} \quad (6)$$

We focus on the partial spectrum of the RRV ($x = R$) from which the respiratory influences ($y = r$) are removed ($S_{RR/r}(t,f)$). This is estimated as the difference between the RRV spectrum, $S_{RR}(t,f)$, and the distribution which represents the RRV linearly related to respiration, $S_{RR,r}(t,f)$. The latter is defined as:

$$S_{xx,y}(t,f) = \gamma_{xy}^2(t,f)S_{xx}(t,f). \quad (7)$$

2.3. Time-varying parameters

The time courses of several indices that quantify the interactions between RRV and respiration are determined. The instantaneous power of TF spectrum $S_\alpha(t,f) \in [S_{RR}(t,f),\ S_{RR/r}(t,f),\ S_{RR,r}(t,f)]$ in specific frequency bands β, with f_β the frequencies in β, is computed as:

$$P_\alpha^\beta(t) = \sum_\beta S_\alpha(t,f_\beta)\delta_f \quad (8)$$

with δ_f the frequency step in the spectrum, which is equal to 2/2048 Hz/sample. The considered bands β are based on the traditional RRV frequency bands: $LF = [0.04\text{ Hz}, 0.15\text{ Hz}]$; $HF = [0.15\text{ Hz}, 0.40\text{ Hz}]$; and $TOT = [0.04\text{ Hz}, 0.40\text{ Hz}]$.

The local coupling between RRV and respiration is computed in a time-varying frequency band $\beta_r(t) = F_r(t) \pm \frac{\Delta_f}{2}$ which is centered around respiratory frequency $F_r(t)$:

- Coherence $\gamma_{Rr}^{\beta_r}(t) = \text{mean}_{f\in\beta_r}[\gamma_{Rr}(t,f)]$;
- Phase difference $\Theta_{Rr}^{\beta_r}(t) = \text{mean}_{f\in\beta_r}[\Theta_{Rr}(t,f)]$.

In addition, the instantaneous respiratory frequency, $F_r(t)$, and heart rate, $HR(t)$, expressed in beats per minute [bpm], are considered.

2.4. Statistical analysis

In order to study only relative changes, regardless of the subject's general condition or prior influences, we apply a correction at the onset of each task for all instantaneous powers. The reference used for the correction is determined by the mean instantaneous power in a window Δ_t around the onset of each task. No correction is applied for the coherence and phase difference.

The Wilcoxon signed rank test is used to assess statistical differences between AT, MT1, MT2 and RD. In order to study the dynamic response to each task, statistical analysis was conducted sample by sample to track the p-values in time. A $p < 0.05$ is considered statistically significant.

3. Results

Figure 1 displays the RRV, respiratory signal and their TF coherence, $\gamma_{Rr}(t,f)$, during the first mental stress task of one subject. A strong coherence can be noticed around respiratory frequency, indicating the respiratory influence in RRV. In addition, the RRV TF spectrum and the partial spectra, $S_{RR,r}(t,f)$ and $S_{RR/r}(t,f)$, are shown. We can observe that $S_{RR,r}(t,f)$ not only contains power in the HF band but also in the LF band. $S_{RR/r}(t,f)$ comprises most power in the LF band. However, some power can still be noticed in the HF band, though strongly reduced.

The median instantaneous respiratory frequency, $F_r(t)$, heart rate, $HR(t)$, and coherence, $\gamma_{Rr}^{\beta_r}(t)$, are given in Figure 2. $F_r(t)$ and $HR(t)$ both increase during AT, MT1 and MT2, and slightly decrease during RD. When comparing RD with the other conditions, significant p-values are found within 10 s after onset of each task, throughout the whole task for $F_r(t)$. AT, MT1 and MT2 did not differ mutually in a significant way. $HR(t)$ displays significant

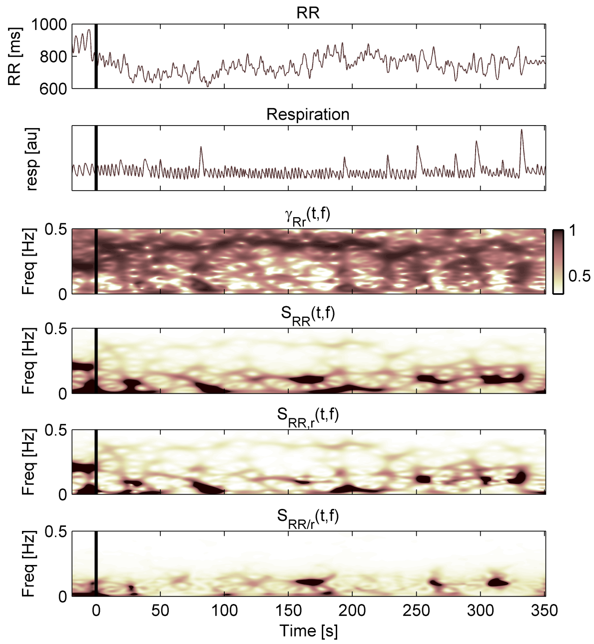

Figure 1. Example of RR interval series (RR) and respiratory signal, their TF coherence ($\gamma_{Rr}(t,f)$), the RRV TF spectrum ($S_{RR}(t,f)$) and the partial spectra ($S_{RR,r}(t,f)$ and $S_{RR/r}(t,f)$) during the first mental stress task of one subject. The vertical line indicates the onset of MT1.

differences between all conditions a few seconds after onset of each task, except between AT and MT2. A maximum difference in heart rates is found 30 s after the onset of the tasks. After 100 s, no differences between the 4 conditions can be noticed. The coherence, $\gamma_{Rr}^{\beta_r}(t)$, is slightly lower during MT1, though this is not persistently statistically significant. The phase difference did not change as a result of mental stress or attention (not shown).

LF and HF powers decreased during AT and MT1 compared with RD (not shown). During MT2, LF power was significantly lower compared to RD. The partialization of RRV reveals that, in the HF band and during stress, respiratory-related changes were faster and larger, than changes unrelated to respiration.

Figure 3 shows the median instantaneous powers in the total frequency band. $P_{RR}^{TOT}(t)$ decreased during mental stress compared to RD, which is already significant 10 s after onset of both mental tasks. Also a significant, but minor reduction is found during AT after 20 s. A similar pattern is observed for $P_{RR,r}^{TOT}(t)$ and shows that the responses to stress related to respiration are faster (3 s and 7 s for MT1 and MT2) than changes unrelated to respiration. $P_{RR/r}^{TOT}(t)$ displays still significant differences between RD, and MT1 and MT2, but only respectively 40 s and 30 s after onset of the tasks. Differences between RD and AT are observed, only for the period of 45 s to 80 s after onset.

4. Discussion and conclusion

The goal of this study was to characterize the dynamic interactions in the cardiorespiratory regulation in response to mental stress and sustained attention using cross time-frequency analyses. In order to separately evaluate the response of RR interval variations linearly related to respiration, and variations that are not linearly related to respiration, partial spectra were used.

During sustained attention, we observed an increased heart and respiratory rate. We also found that mental stress causes an increase in heart and respiratory rate. Stress also resulted in a reduction in cardio-respiratory coherence, HF power and LF power, indicating vagal withdrawal. The partial TF analyses revealed that the response to stress and attention of RR interval variations related to respiration is fast, while the variations unrelated to respiration appear with a slower temporal scale.

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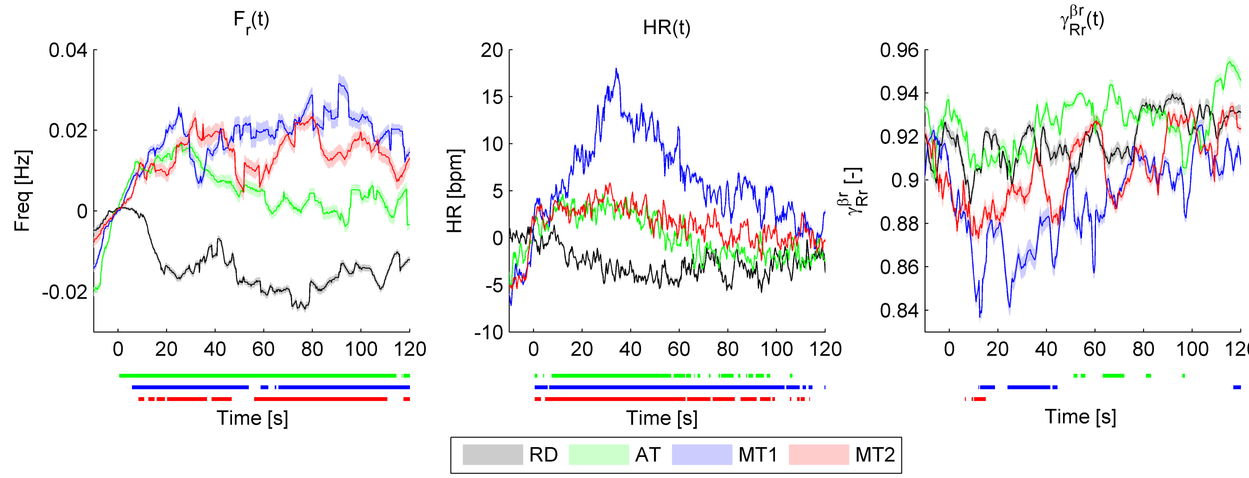

Figure 2. Median instantaneous respiratory frequency ($F_r(t)$), heart rate ($HR(t)$), and coherence ($\gamma_{Rr}^{\beta_r}(t)$) in the time-varying band $\beta_r(t)$. The standard error is shaded. The bars below each subplot indicate the time instances of significant differences between RD and the tasks.

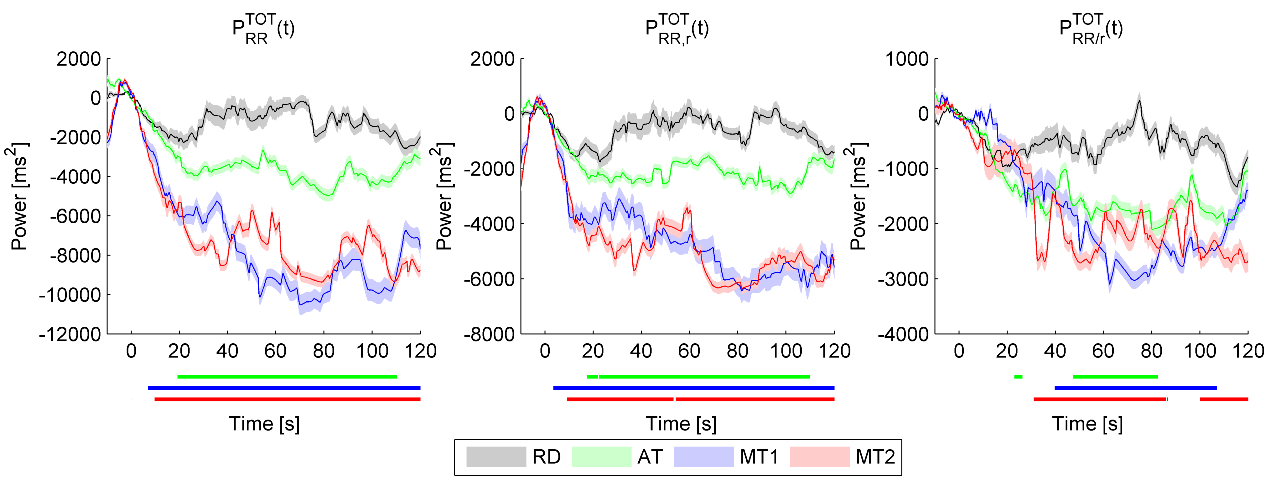

Figure 3. Median instantaneous power for TF spectra $S_{RR}(t,f)$, $S_{RR,r}(t,f)$ and $S_{RR/r}(t,f)$ in the total frequency band. The standard error is shaded. The bars below each subplot indicate the time instances of significant differences between RD and the tasks.

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