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Time-frequency heart rate variability characteristics of young adults during physical, mental and combined stress in laboratory environment

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Abstract— **The goal of this study was to evaluate the changes in heart rate variability (HRV) parameters due to a specific physical, mental or combined load. More specifically, the difference in effect between mental load and physical activity is studied. In addition, the effect of the combined physical and mental demand on the HRV parameters was examined and compared with the changes during the single task. In a laboratory environment, 28 subjects went through a protocol with different types of load (physical and/or mental), each followed by a period of rest. Continuous wavelet transformation was applied to create time series of instantaneous power and frequency in specified frequency bands (LF and HF). HF could distinguish the active conditions from the rest condition, meaning that HRV is sensitive to any change in mental or physical state. Differences in HRV parameters were observed between physical, mental and the combined load. In conclusion, we were able to distinguish between rest, physical and mental condition by combining different HRV characteristics. The addition of a mental load to a physical task had an extra effect on the HRV characteristics.**

I. Introduction

SINCE the nineties, markers of stress and other psychosocial factors are associated with diseases [1,2]. Forty to fifty percent of all work-related absences are related to stress. The European commission states that this problem leads to losses of 0.5 to 2% of Gross National Product (GNP) per year [3].

Stress, here defined as a mismatch between perceived demands and perceived capacities to meet those demands [4], is a psychophysiological phenomenon that changes the physiological balance of amongst others the autonomic nervous system (ANS) [5]. The ANS is divided into a sympathetic and parasympathetic or vagal branch. Both components operate simultaneously and balance each other dynamically in normal conditions. When a person is exposed to a stressor, the sympathetic system becomes more activated. In addition, the parasympathetic system is shut down. This brings the body in an arousal state, called the fight or flight reaction [6], resulting in changes in several physiological systems (a.o. increased heart rate). When the stressor disappears, the vagal system takes over and the sympathetic activation disappears.

Heart rate variability (HRV) refers to alternations in heart beat time-intervals and provides quantitative markers of autonomic regulation [7]. Moreover, it is a simple and powerful noninvasive methodology having enormous advantages with a minimum of technical constraints, which makes it useful in many applications. Therefore, HRV has been used to examine the responses to mental and physical demands on the ANS. Many studies only focus on either physical or mental load, but only a few consider both [8].

The goal of this study was to evaluate the changes in HRV parameters due to a specific physical, mental or combined load to study the effect of each individual load on the HRV parameters. More specifically, the difference in effect between mental load and physical activity, in literature known to be methodologically difficult [9], is studied. In addition, the effect of the combined physical and mental demand on the HRV parameters was examined and compared with the changes during the single task. However the relative contribution of mental and physical stress on HRV parameters is still not completely clear. A bigger change of the HRV parameters is hypothesized, in the combined task compared to a single task.

In a previous study, the traditional linear HRV parameters were described [10]. This study focuses on the time evolution using time-frequency analysis (TFA). TFA, as applied here, was rarely used in literature, although it enables to study trends within the same condition or transitions between several conditions. Moreover it enables the comparison of these trends within one condition as well as between the several conditions.

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II. Methods

A. Data

28 participants were monitored, 15 men and 13 women with mean age of 22 ± 1.96 (19-26) years and an average body

mass index of 22.2 ± 0.43(18-29) kg/m^2. The experiment was approved by the Ethics Committees of the Department of Psychology. Each subject provided a written informed consent before participating. The study complies with the Declaration of Helsinki.

Upon arrival, the test subjects were prepared for the measurements. Electrodes (Ag-AgCl, Nikomed, Denmark) were placed on the body to measure simultaneously the electrocardiogram (ECG). The ECG was obtained by two electrodes placed around the heart. The data were registered with EMG preamplifiers (Mega Electronics Ltd, Finland). The Daqbook 2005 (IoTech, Ohio, USA) was used to digitize the signals at a frequency of 1000 Hz with 16-bit.

In a laboratory environment, the subjects were instructed to perform four tasks. A first task, the rest phase (R) implied sitting at ease. A second task was a postural load (PT) where a shoulder abduction of 45° during 6 minutes was performed. A third task consisted of a mental stressor (MT) where the subjects were performing a mental task (part 1 of the home version of the MENSA test) within 10 minutes. Subjects were not informed about the expired time, causing an extra stressor. The subjects answered orally to the experimenter. The combination of a mental and postural load was the fourth condition (MPT), were the subjects solved part 2 of the MENSA test within 10 minutes.

Each active condition (PT, MT and MPT) was followed by a rest condition (R), lasting for 3 minutes, and the sequence of the active conditions was fully randomized. All tasks were performed with the subject in a sitting position facing the screen to ensure similar effects across tasks on HRV.

To overcome possible effects of previous tasks in the test, the order of the active conditions was fully randomized, minimizing this effect in group analysis.

B. *HRV analysis*

Detection of the R peaks in the ECG signal was done by the Pan-Tompkins algorithm [11], resulting in a RR interval time series, often called tachogram. After checking the data for missing and ectopic beats, extra ventricular beats were replaced by a 20%-filter [12]. After resampling the tachogram at 2 Hz, a time-frequency representation (TFR) is used to monitor the possible non-stationarities in the data and to describe the quick changes in HRV spectra during transients. This study applies the wavelet decomposition technique [13] resulting in a good frequency resolution at the lowest frequencies and a good time resolution at the highest frequencies.

A decomposition of a time signal x(s) with wavelets starts from one mother wavelet, $\Psi_{t,a}(s)$, that can be shifted (time *t*) and dilated (scale *a*). The decomposition is given by next formula, where $TFR(t,a;\Psi)$ is the wavelet decomposition:

$$TFR(t,a;\Psi) = \int_{-\infty}^{+\infty} x(s) \cdot \Psi_{t,a}(s) \cdot ds \tag{1}$$

with $\Psi_{t,a}(s)$ defined as

$$\Psi_{t,a}(s) = |a|^{-1/2} \cdot \Psi\left(\frac{s-t}{a}\right) \tag{2}$$

where $\Psi_{t,a}(s)$ is the mother wavelet and a the scales related to the frequencies 0 – 0.4 Hz. The Morlet wavelet was selected as mother wavelet based on the literature [14].

From this TFR, a time course of spectral parameters can be extracted. The spectral bands are chosen in agreement with the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology [15], where the general regulations of HRV analysis are described, enabling the physiological interpretation of the results: LF band (0.04 – 0.15 Hz) and HF band (0.15 – 0.40 Hz). The instantaneous frequency of a signal is obtained using the definition of Claria et al [16], which is the most reliable definition in HRV applications:

$$f_s(t) = \frac{\sum_{n=n_b}^{n_e} f_n \cdot TFR(t, f_n)}{\sum_{n=n_b}^{n_e} TFR(t, f_n)} \tag{3}$$

with n_b, n_e respectively the beginning and end frequency of a selected frequency band and f_n the frequency equivalent of the scales *a*. The instantaneous frequency is calculated in the high frequency band (f_{HF}), while the analysis in the low frequency band is neglected because no agreement exists on physiological meaning of this frequency. Analogously, in the two frequency bands the power can be calculated by integrating the spectrogram, expressed in absolute values or normalized units.

$$P_s(t) = \sum_{n=n_e}^{n_b} TFR^2(t, f_n) \tag{4}$$

The duration of the different conditions is not consistent, which complicates the TFA. 16 out of 28 subjects finished the task with the mental load within 5 minutes. Therefore, the analyses are limited either to the 4 first minutes or to the length per condition. From the wavelet based time series of the different HRV parameters, minute-by-minute parameters can be extracted, removing the variation caused by the wavelet transforms, but enabling a tighter time window to visualize the trends in the data.

To have a fair representation on group level, the standard error around the mean will be used to correct for number of test subjects per minute.

The algorithms were implemented in-house using Matlab R2008a (The MathWorks Inc., Natick, MA, USA).

C. *Statistical analysis*

The effect of the executed task within one condition is studied by comparing pairwise the first and the fourth minute per condition with the Wilcoxon Signed Rank test. In addition, the effect of the executed task within one condition is analyzed using the differences between the conditions in the first and also in the fourth minute.

$P < 0.05$ was considered statistically significant.

III. RESULTS

Figure 1a shows a typical time series of one subject for HF power and LF/HF. This figure visualizes changes in these parameters within and between the conditions. The time series giving the instantaneous frequency in the high frequency band of the same subject is presented in Figure 1b reflecting fluctuations between 0.22 and 0.26 Hz.

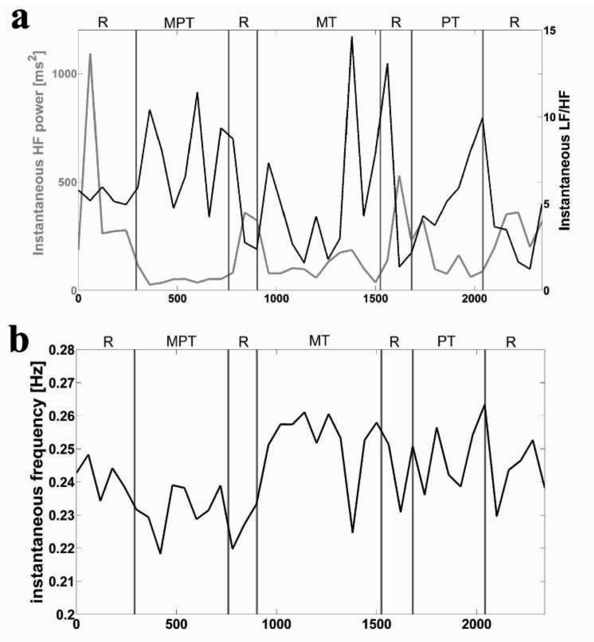

Fig. 1. Time frequency analysis: typical evolution in s. (a) instantaneous HF power (grey line) and LF/HF ratio (black line) over time and (b) instantaneous frequency in the HF band.

Figure 2 shows the time series of all the subjects for HF, LF, LF/HF and f_{HF}. The mean (± standard error) is given for each minute per condition. In addition, Table 1 shows the mean value of the different time-frequency parameters for the 4 conditions at the first and the fourth minute. An underlined value indicates a statistically significant difference with the first minute of the condition. In addition to this analysis, the first and the fourth minute per condition are mutually compared and indicated with letters.

TABLE I
TIME FREQUENCY MEASURES FOR MINUTE 1 AND 4

	PT		MT		MPT		R	
min	1	4	1	4	1	4	1	4
HF [ms²]	86.5	<u>56.9</u>	89.6	78.3 *	85.9	70.7	120 * ° “	96.6 * ° “
LF [ms²]	604	603	423 *	416	387 *	548	936 * ° “	<u>530</u>
LF/ HF	29.4	43.7	20.2	20.3	21.4	19.4	28.0 ° “	20.4 *
f_{HF} [Hz]	0.20	<u>0.22</u>	0.22 *	<u>0.21</u> *	0.22 *	0.22 °	0.21	0.20 * ° “

* significant difference with PT (p<0.05); ° Significant difference with MT (p<0.05); “ Significant difference with MPT (p<0.05); underlined: significant difference with the first minute during the condition.

The HF time series shows that HF power is statistically significantly higher during the rest period compared to the three active conditions for the complete 4 minutes. In the beginning, there are no differences between the three active conditions, but from minute 3 on, the two conditions with physical load have a lower HF power. The LF power during rest shows in the first minute a significantly higher value compared to the three active conditions. LF power during PT is statistically significantly higher compared to the two conditions with the mental load. Within the condition, these differences disappear. The decrease of LF power during R was statistically significant.

The sympathovagal balance, LF/HF, shows no difference in the beginning of each condition. After two minutes, the conditions with the physical load show a strong increase. In minute 3, the LF/HF balance during these two conditions are statistically significantly higher compared to the beginning of the condition and compared to the two other conditions.

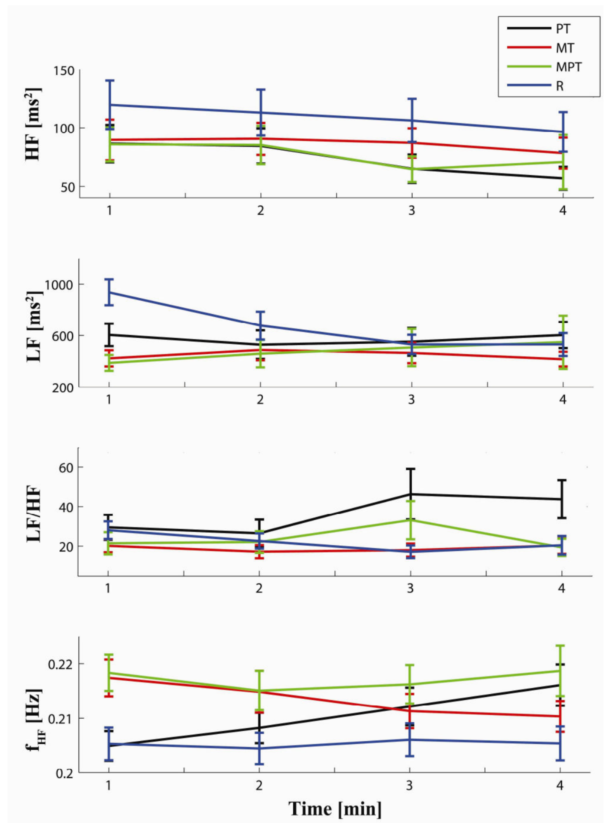

Fig. 2. Time frequency analysis: group analysis. Mean + standard error of the first minutes of (a) power in HF, (b) power in LF, (c) LF/HF ratio and (d) frequency in the HF band.

The instantaneous frequency in the high frequency band shows a constant frequency during the rest period. During MT, the instantaneous frequency shows a linear decrease, while it shows a linear increase during PT. Both changes are statistically significant from the first till the last minute of the condition. During MPT both effects are combined: a decrease because of the mental load and an increase because of the physical load, resulting in a constant frequency. In the first minute, the instantaneous frequencies of both mental conditions are statistically significantly higher compared to those of the two conditions without the mental load. Within the conditions, the instantaneous frequency shifts towards a higher frequency during the physical conditions compared to that of MT and R in the fourth minute.

IV. DISCUSSION

HRV parameters were calculated in several conditions: rest (R), physical task (PT), mental task (MT) and a combination of both tasks (MPT). The active conditions could be distinguished from the rest condition, meaning that HRV is sensitive to any change in mental or physical state. The combination of a physical and a mental task was expected to result in a higher load compared to one of both tasks separately. This hypothesis was confirmed in a previous study [10] with a significantly higher heart rate. The time series, using the wavelet transform reveals that the combined task has the same trend of the physical load in the HF parameter, while it follows the LF-values of solely the mental task. The effect of the physical task (increased HR, decreased vagal modulation) is superposed to the cardiovascular effect of the single mental load. Contrarily, Garde et al. [8] reported that the addition of mental demands to a physical computer task does not elicit any further effect on HRV parameters related to autonomic modulation meaning that the physical demands have a major influence on the ANS changes whereas the influence of the mental load is insignificant. Our study, having a heavier physical task, rejects their hypothesis.

Mental stress decreased HF power of heartbeat interval time series as already mentioned in previous studies [17].

The changes in instantaneous HF frequency can be related to changes in respiration frequency as the main peak in the HF band is normally linked with respiration [18]. Assuming this, the tasks with mental load have a significantly higher respiration rate compared to PT and rest. A possible explanation is the effect of speaking as the subjects answered orally on the MENSA test. However, during MT when the subjects underwent the mental load and answered orally, this frequency had a linear decrease within the condition. This decrease is not expected when the change at the beginning of the condition is only related to the influence of speaking, where a constant frequency during the complete task is expected. The increase in the beginning is related to the effect of the mental task and the decrease within one condition to habituation to the stressor. An increased respiration frequency during a mental stress task in healthy subjects was already shown in Vlemincx et al. [19], although Bernardi et al. [20] observed oppositely a lower respiration frequency. The linear increase in instantaneous frequency during PT can be related to incoming fatigue, which is an ongoing physiological process that initiates already from the beginning of the physical load. During MPT, the effect is the combination of both the physical and the mental effect on the frequency: a linear increase due to fatigue during the physical load and a decrease due to habituation of the mental load, resulting in a constant frequency. The respiration frequency during MPT is at each time instant the highest of the four conditions.

This indication of the fatiguing process of the body during the physical performance can also be seen in other parameters. In particular, the LF/HF ratio is increasing monotonously during PT and MPT (Figure 2), indicating the fast increase in sympathetic dominance caused by the heavy physical task. Evolutions in time were also observed within other conditions. The decrease in LF during rest condition can indicate recuperation after a physical load. With respect to the sympathovagal balance, there is a decrease during rest (not significant), but an increase during both conditions with mental load showing that the vagal pathways of ANS became relatively a bit more active in rest while the sympathetic modulation gained importance in case of mental stress.

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