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How do sound rhythms affect heartbeat: Comparison of linear and non-linear analyses of R-R intervals

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A 2x3 within groups experiment with two levels of sound intensity and three levels of tempo of sound rhythm was conducted. Eleven psychology students participated in the study. SMI index, 1/f spectra slopes and some non-linear analyses parameters - correlation dimension and largest Lyapunov exponents - were used. Decrease in SMI indexes in low and medium spectral bands occurred with more intensive sound rhythms as a function of rhythm tempo increase which may point to increased stress and mental load. Spectral analysis showed no clear interference between sound and cardiac rhythm. Changes in 1/f spectra slopes were similar to those of SMI indexes. A decrease in correlation dimension for more intensive rhythms points to decrease of series dimensionality which is probably the result of domination of non-linear factors determining dynamic system. More evidence for such an interpretation was indicated by decrease in system predictability when exposed to sound rhythms, as shown by an increase in Lyapunov exponents.

Keywords: non-linear analyses, chaos, sound rhythms, heartbeat variability, Lyapunov exponent

Changes in different parameters of the cardiac activity such as heart rate and heart rate variability have been extensively investigated in the last two decades as quantitative indicators of the autonomous nervous system activity. R-R interval, which is time interval between successive R peeks of ECG is the most often used parameter, as well as variability parameters of R-R intervals.

Results of some investigations (Kalsbeek, 1971; Kalsbeek, 1973; Lee & Park, 1990) have shown that heart rate variability (HRV), i.e. *sinus arrhythmia*, is a more sensitive indicator of mental load than heart rate. It seems that heart rate reflects effects of stress, emotions and different internal and external factors. It was also shown that HRV decreases when mental load increases during laboratory tasks of different kinds (mental, psychomotor, repetitive) and complexities (Mulder, 1973; Zwaga, 1973; Mulder, 1988; Manenica, 1977; Manenica, 1981; Manenica & Krošnjar, 1990), while a number of other authors (Jorna, 1993; Backs, Lenneman, & Sicard, 1999; Gaude, Laursen, Jorgensen, & Jensen, 2002) obtained similar results in real-life situations such as office work or pilots during flight (Jorna, 1993; Backs et al., 1999; Gaude et al., 2002). Manenica (1981) found similar results with participants who performed easy repetitive industrial-type task. Increased number of components that reached the assembly line in unit of time and which were supposed to be put together by participants was followed by higher regularity of R-R intervals while heart rate remained unchanged. There was an attempt to detect the effects of imposed rhythms of work by using different parameters of HRV. Manenica (1977) found longer and more variable R-R intervals during work in conditions of imposed work rhythm which was identical to non-imposed work rhythm in other instances.

Apart from usual parameters of HRV spectral analysis was used in some studies for identification of the effects of various stressors on people, such as imposed rhythms of work, interference of biological rhythms with each other, exam stress, etc (Charnock & Manenica, 1978; Proroković, 1999; Manenica & Proroković, 2000; Šimić, 2003).

Mulder (1988) showed that different spectral bands of HRV time series were not equally sensitive to changes in mental load. Mulder, as well as some other authors (Aasman, Mulder, & Mulder, 1987; Keselbrener & Akselrod, 1998) divided frequency spectrum into three major bands: low frequency band (LF) ranging from 0.02 to 0.06 Hz; medium frequency band (MF) between 0.07 and 0.14 Hz and high frequency band (HF) from 0.15 to 0.50 Hz. LF band seems to reflect changes in metabolic processes which

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regulate body temperature, MF band appears to reflect changes in blood pressure and mental load, while HF band reflects respiration pattern and some task properties such as repetitiveness. Some of these results have been confirmed by laboratory experiments where mental arithmetic tasks, Stroop's task and reaction time tasks were used (Langewitz & Ruddel, 1989; Langewitz, Ruddel, Noack, & Wachtarz, 1989; Sloan, Korten, & Myers, 1991; Sloan, DeMeersman, Shapiro, Bagiella, Chernikhova, Kuhl, Zion, Paik, & Myers, 1997; Šiška, 2002). As the task complexity increased (Mulder, 1988; Aasman et al., 1987; Sammer, 1998; Sloan et al., 1991; Sloan et al., 1997; Langewitz & Ruddel, 1989) or when the task demands changed on pilots during flight (Veltman, 2002), suppression of power spectrum in medium frequency was observed. There are, however, numerous studies of effects of mental load on sinus arrhythmia parameters but very few concerning emotional component in stressful situations. Some authors point out that stress could be the cause of spectrum power suppression in HF band which they explained by reduced vagal activity on the cardiac atrial node (Sloan, Shapiro, Bagiella, Fishkin, Gorman, & Myers, 1995; Papousek, Schulter, & Premsberger, 2002). In other studies authors attributed the suppression of power spectrum in LF band to effects of stress as well (Sloan, Shapiro, Bagiella, Bigger, Lo, & Gorman, 1996; Šimić, 2003).

In the last two decades, there has been an increasing interest in applying techniques from the domains of non-linear analysis and chaos theory in studying biological systems. Normal heartbeat behavior typically shows chaotic, fractal and non-linear qualities (Goldberger, Rigney, Mietus, Antman, & Greenwald, 1987). This chaos is explained in terms of dynamics of the complex of sino-atrial and atrio-ventricular nodes which has been modeled as a system of non-linear coupled oscillators responsible for the heart rhythms (Sakki, Kalda, Vainu, & Laan, 2003). These chaotic, fractal and non-linear qualities of heartbeat behavior have inspired investigations to develop new methods of heart rate behavior analyses. Non-linear measures such as correlation dimension and Lyapunov exponents are often applied to time series with the intention of identifying the presence of non-linear, possibly chaotic behavior. The calculation of Lyapunov exponents which are quantitative measures of evolution of neighboring phase trajectories is a useful technique for distinguishing chaotic and non-chaotic behavior (Baker & Gollub, 1990). There are many methods of Lypunov exponent calculation, and Wolf's algorithm (Wolf, Swift, Swinney, & Vastano, 1985) is one of the most popular. This parameter of non-linearity may be used to obtain measure of sensitive dependence upon the initial conditions that is characteristic of chaotic behavior. Lyapunov exponents are defined as the long time average exponential rates of divergence of nearby states. If a system has at least one positive Lyapunov exponents, it is chaotic. Larger the positive exponent, more chaotic the system becomes. If Lyapunov exponent is negative, system is not chaotic: it is predictable (Owis, Abou-Zied, Abou-Bakr, & Kadah, 2002).

Fractal dimensions are indicators of system complexity. Correlation dimension, as a sort of fractal dimension, is most efficient for experimental data or higher-dimensional dynamical systems (Grassberger & Procaccia, 1983). This method of estimating the dimension of a set has the advantage of using less computer memory and computational time. Correlation dimension is defined as slope of the linear region of plot of $log(C(r))$ versus $log\ (r)$ (Owis et al., 2002) where r is the radius and $c(r)$ is a headwise function which counts the number of points within radius. High complexity of HRV is common. Some authors (e.g. Sakki et al., 2003) concluded that high values of the HRV correlation dimension indicate the healthiness of the heart.

Some investigations (Sammer, 1998) showed different sensitivity correlation dimension and Lyapunov exponents have on changes of mental load. Correlation dimension was more sensitive to task type (mental, physical) while Lyapunov exponents were sensitive to mental workload and not to task type. In Proroković, Gregov, and Valerjev (2003) dual psychomotor task study the clear evidence of non-linear determinism was found in tapping activity during simultaneous performance and in the complex response time dynamics during more difficult task performance which were indicated by increase of Lyapunov exponents.

Music, as rhythmic stimulus, can motivate, move or excite people. Accordingly to that, sound rhythms could act as stressors to organism. Main assumption of the previous study (Valerjev & Šimić, 2002) was that sound, regardless of its form: music, sound beats or noise; could produce changes in listeners' cardiac rhythm. Effect of sound rhythms on cardiac rhythms was apparent and more prominent for louder rhythms (80 dB) while the effect for less loud rhythms is not clear. It seems that sufficiently loud sound rhythms affect heart rate making it lower in situation where listener is listening to them quietly. Interestingly, this effect is contrary to excitement that music could produce and looks more like relaxation effect. It is also interesting that the described effect is strongest when listening to slow rhythm (60 BPM) which is close to heartbeat frequency. Authors speculated that the interference of two rhythms occurred. If this explanation holds, it would be similar to Charnock and Manenica's (1978) results where externally imposed rhythm of work interfered with participants' cardiac rhythm. In this investigation, all listening situations also resulted with decrease in variability of cardiac rhythm. This effect is probably connected with mental load effects. Possible explanations could include listeners' analysis of sound rhythms. However, this effect isn't simple but lowest for slow sound rhythms. The interference that was mentioned earlier could also contribute to the variability of cardiac rhythm which would support that hypothesis.

Previous study (Valerjev & Šimić, 2002) was focused on basic linear aspects of heart rate changes during sound rhythm exposure. The aim of this study was further and more detailed analysis of cardiac rhythm data gathered during the sound rhythm listening process by means of more complex linear as well as non-linear analyses by which their comparison and complementary insight into involving changes were provided.

METHOD

Participants and experimental design

Study was carried out on 11 female psychology students aged between 18 and 20. Experimental design was 3 x 2 within-subjects design with factors of Tempo and Intensity of sound rhythm. Tempo factor included three levels while Intensity factor included two levels. The experiment consisted of six experimental situations and each was preceded by silence-control situation. Each participant passed through all six experimental situations, sequence of which was rotated according to the Latin square principle.

Equipment and materials

Equipment included two computers with appropriate software for sound rhythms of various tempo and intensity. Stereo earphones were used to apply six different sounds. Sound rhythms consisted of low frequency beats similar to bass drum beats. *PowerLab* system and chest electrodes were used for continuous measurements of cardiac R-R intervals.

Procedure

Each listener was individually seated in a quiet room with earphones plugged into sound rhythm generating computer. Cardiac R-R intervals were recorded via electrodes on listeners' chests. R-R intervals recording started during the first five-minute period of silence. Five-minute silence pauses were interpolated between experimental situations and last of them was followed by one as well. Each listener was instructed to relax and listen to rhythms *actively* and *carefully* and was told about the order of appearance of experimental situations and silence. Listeners' ECGs were recorded continuously for 65 minutes during all experimental situations and also during all silence pauses.

RESULTS AND DISCUSSION

Interference of cardiac and sound rhythms

In the previous study (Valerjev & Šimić, 2002), an assumption about the possibility of the occurrence of cardiac and sound rhythms' interference in participants' heartbeats was set. A comparison of participants' spectrograms in silence situation and in situations of sound rhythm exposure has been made accordingly. Figure 1 demonstrates a typical example of R-R intervals power spectrum in silence and rhythm exposure situations. Unfortunately, peaks at the expected points of interference of the two rhythms were not clearly visible in spectrogram. Points of possible interference were calculated as common multiples of sound rhythm and average cardiac rhythm frequency. Reason for such a result could be twofold:

a) the amount of noise in the results was too large for such an interference to be visible; or
b) interference of sound and cardiac rhythms resulted in increased non-linear changes that were not displayed as apparent peaks in spectrogram.

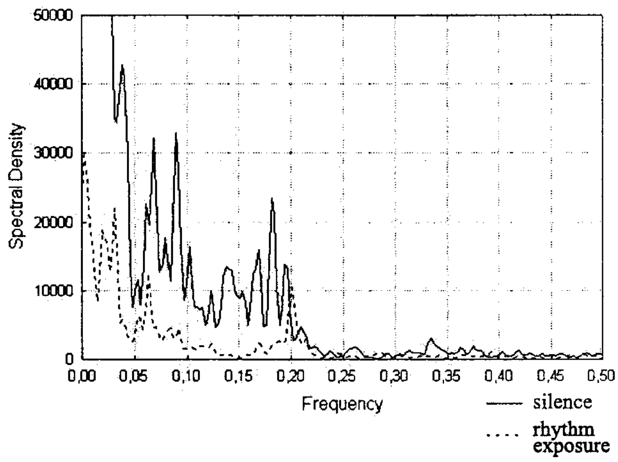

Figure 1. Example of comparison of power spectra of R-R time series in silence and rhythm exposure situation for participant I.B.

SMI indexes analysis

Data analysis included application of spectral analysis procedures. Based on individual spectrum frequency for five-minute rhythm exposure of different tempo and intensity and for silence situations, parameters of power - the so-called SMI indexes were calculated for three spectrum frequency bands. SMI index is the sum of squared spectral densities divided by average squared R-R interval magnitude. In this study, SMI index values were transformed to logarithm scale (log10) to reduce the skewness of the distributions. ANOVA was used to test the significance of their changes.

First, changes of SMIs as a function of time were analyzed. Analysis showed significant SMI index changes for LF band as a function of time (see Figure 2). Lowest SMI index values were established in the first silence situation, while increase in SMI index value occurred as a function of time (i.e. rhythm listening and silence situations). Changes in this part of the spectrum in which homeostatic processes involved in body temperature regulation are reflected can be attributed to stress (Sayers, 1973; Mulder, 1988). Other evidence showed the decrease of power in LF spectrum area and the phenomenon was also attributed to stress (Sloan et al., 1991; Sloan et al., 1997). Accordingly, the lowest SMI index values in the first silence situation point to the stressfulness of this situation, while the increase of power in this part of the spectrum as a function of time, however, can be attributed to habituation to experimental situations. On the contrary, no significant changes of power in medium and high frequency spectrum areas as a function of time were found ($F_{LF}(5,50)=5.73$, $p<.01$; $F_{MF}(5,50)=0.8$, $p>.05$; $F_{HF}(5,50)=1.85$, $p>.05$; see Figure 2).

Further analyses used the average SMI index values derived from all six silence situations for different spectrum areas as a comparison situation. Furthermore, as for the effects of rhythm intensity and tempo, this research used two rhythm intensities (40 and 80 dB) and three tempos (60, 200 and 400 BPM). ANOVA showed no significant changes in logSMI indexes for 40 dB rhythm intensity for different spectrum areas ($F_{LF}(3,30)=0.75, p>.05$; $F_{MF}(3,30)=0.61, p>.05$; $F_{HF}(3,30)=2.33, p>.05$). On the contrary, significant changes were found in logSMI indexes for LF band with greater intensity rhythm (80 dB) ($F_{LF}(3,30)=2.73$, $p<.05$; see Figure 3). Decrease of power in this part of frequency spectrum as a function of tempo increase can point to stress increase. Changes of SMI indexes for medium area of frequency spectrum (MF) also proved to be significant ($F_{MF}(3,30)=2.82$, $p>.05$; see Figure 3). Based on results of a number of studies (Mulder, 1988; Aasman et al., 1987; Sammer, 1998; Langewitz & Ruddel, 1989) in which changes in this part of spectrum were associated with mental load, decrease of power as a function of increase of rhythm tempo can be attributed to increased mental load. Results of this analysis were not completely in accordance with the previous study results (Valerjev & Šimić, 2002), where the suppression of variability (i.e. sinus arrhythmia, which also indicated mental load) was present in all sound rhythm exposure situations and here it was present only in more intensive situations. It seems that although both methods (variability analysis and MF-SMI index analysis) point to the same phenomenon, they don't share the same amount of sensitivity to it. Changes in high frequency spectrum area in which changes in breathing are being reflected did not prove to be significant during the exposure to different rhythm tempo ($F_{HF}(3,30)=0.48, p>.05$; see Figure 3).

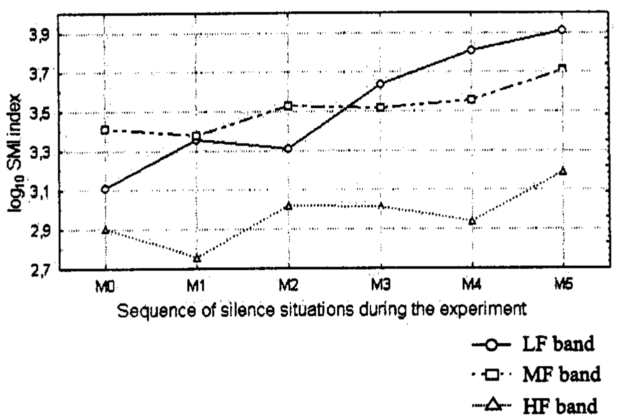

Figure 2. Changes of SMI indexes for low frequency (LF), medium frequency (MF) and high frequency (HF) bands in sequence of silence situations

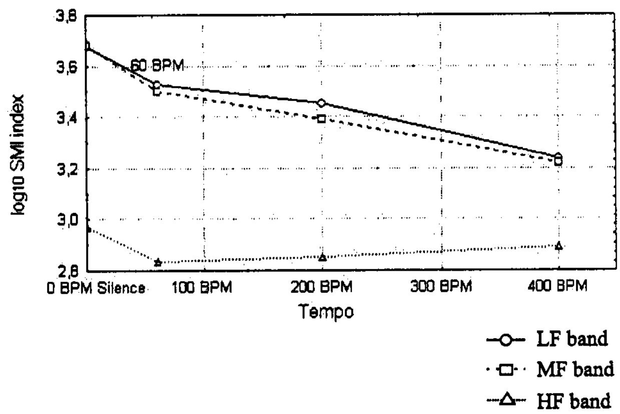

Figure 3. SMI indexes low frequency (LF), medium frequency (MF) and high frequency (HF) spectrum in more intensive sound rhythm exposure situations (80 dB)

1/f spectra slopes analyses

Spectral analysis alone cannot distinguish a chaotic process, but some authors (Goldberger & West, 1987) have suggested that a particular spectral pattern in which power density is inversely related to frequency and which makes 1/f spectra slope negative is highly suggestive of a non-linear or chaotic process. However, diagnostic value of this 1/f pattern has also been questioned by other authors (Pool, 1989).

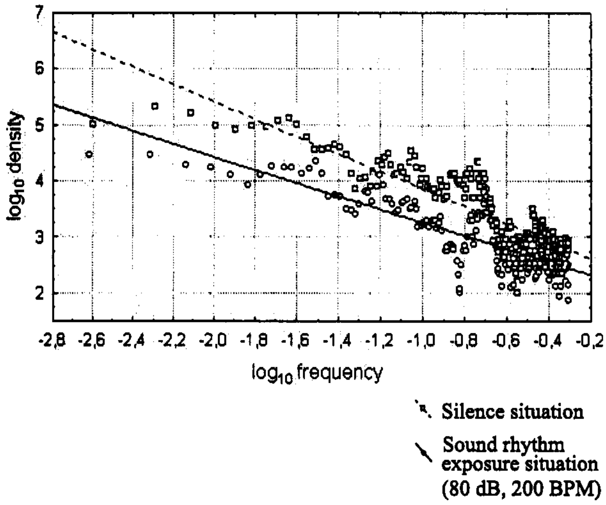

Figure 4. Example of comparison of 1/f spectra of R-R time series in silence situation and sound rhythm exposure situation for participant I.B.

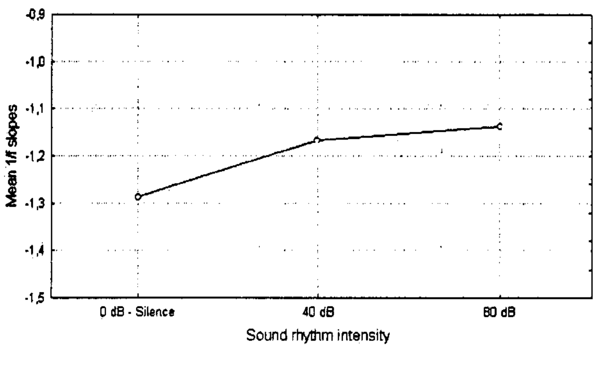

Figure 5. Mean 1/f slope changes as a function of sound rhythm intensity

1/f slopes were calculated for all situations and all participants (see Figure 4). Three participants showed inconsistence and were not taken into analysis. All slopes were negative which means that they showed typical pattern and that time series could involve non-linear or chaotic processes.

Analysis also showed typical changes of slopes as a function of sound rhythm intensity ($F(2,14)=3.76$, $p<.05$; see Figure 5) and as a function of sound rhythm tempo ($F(3,21)=3.17$, $p<.05$; see Figure 6). The latter effect was more apparent for more intensive rhythms as expected ($F(3,21)=3.17$, $p<.05$; see Figure 7).

Although the changes in 1/f slopes are clear and connected to chaotic processes by some authors (which is most probably the case here), this can not be asserted with certainty. There is a possibility that they are caused by processes that also lie in the base of SMI index changes and which are usually not connected with chaotic processes in literature. All changes made 1/f slopes flatter, that is, less negative or less steep, respectively, which is consistent with shown SMI indexes changes.

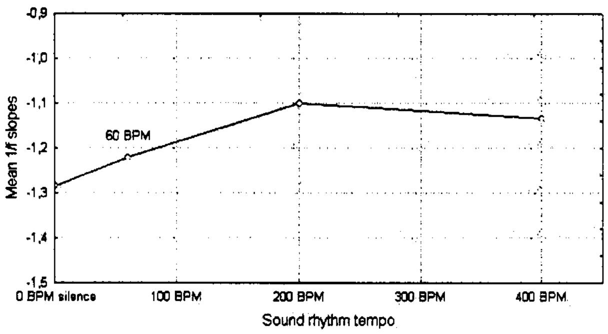

Figure 6. Mean 1/f slope changes as a function of sound rhythm tempo

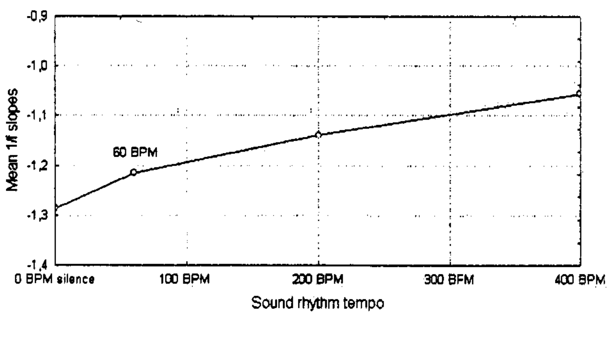

Figure 7. Mean 1/f slope changes as a function of sound rhythm tempo for intensive rhythm situations (80 dB)

Non-linear analyses

Correlation dimensions (CD) and largest Lyapunov exponents (LLE) were calculated for all experimental as well as for all silence situations. Both parameters showed invariant values for all successive silence situations interpolated between sound listening situations. No significant difference between them was found. Individual values of CD varied between 4.4 and 5.6; while values of LLE varied between 0.58-3.6. Parameters gathered in the first silence situation were considered to be the point of reference for all further analyses and comparisons with sound rhythm exposure situations. Average correlation dimensions calculated for sound rhythm exposure situations showed significant fall for more intensive rhythms situations when compared to initial silence situation ($F(6,60)=4.18, p<.001$). Difference was not significant between less intensive sound rhythms exposure situations and silence situation (see Figure 8).

Also, significant effect was found for intensity factor, that is, correlation dimension for intensive rhythms situations is significantly lower than the one for less intensive rhythms situations ($F(1,10)=34.73, p<.001$; Figure 9). On the other hand, no significant effect was found for tempo factor, nor for the two factors interaction. As it is already known, correlation dimension is a way of determining of the set fractal dimension whose calculating procedure was developed by Grassberger and Procaccia (1983) and which proved to be suitable for experimental and high-dimensional dynamic systems (Baker & Gollub, 1990). Dimensionality of the dynamic system shows its complexity or the quantity of non-linear factors determining it. The fall of correlation dimensions when exposed to more intensive rhythms shows decrease of complexity of R-R interval set. Since the study of Valerjev and Šimić (2002) showed the fall of variability of R-R intervals (SD and DM indexes) and here the fall of complexity, this means that heart rate rhythm is more regular when exposed to more intensive sound rhythm and also under the influence of lesser number of factors or under the stronger influence of some of the factors. In preceding explanation it was assumed that certain mental load connected to more intensive activity of simpaticus appears in those situations and, in return, possibly results with decrease of R-R intervals complexity. Decrease of complexity was also found in some other studies involving some form of mental load. For example, De Waard (1996) reported such phenomenon in car driving situations.

The second parameter often used in non-linear analysis is largest Lyapunov exponent (LLE). All LLEs found in this research were positive as expected which means that heart beats showed certain chaotic behavior level (i.e. sensitivity to initial conditions) in all situations. Individual values in different situations vary between 0.58 and 3.6. Increase of average LLE for all sound rhythm exposure situations if compared to silence situation was present ($F(6,60)=2.58, p<.03$; see Figure 10). This increase was significant for most situations (four out of six). For unknown reasons, it was most apparent for slow tempo – less intensive situation (60 BPM, 40 dB) and for medium tempo – more intensive situation (200 BPM, 80 dB). Increase of LLE means lesser predictability and greater chaoticity of the dynamic system.

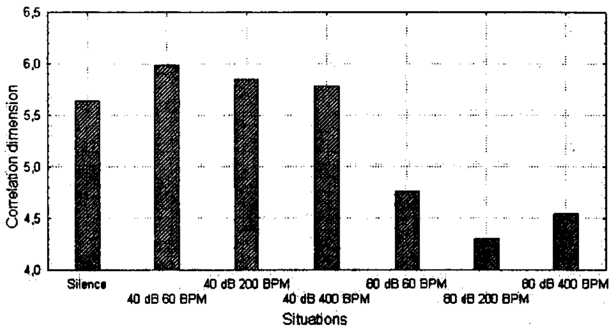

Figure 8. Correlation dimensions for silence situation and sound rhythm exposure situations

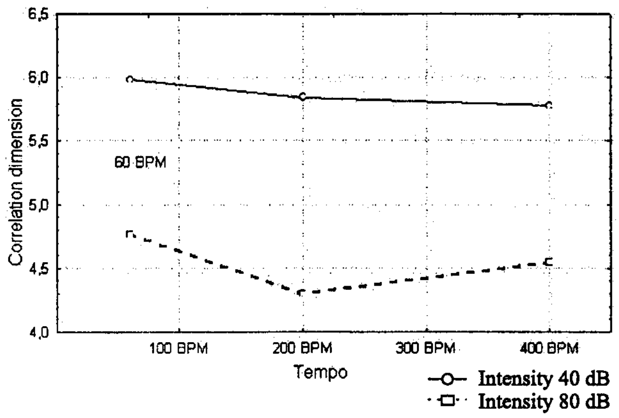

Figure 9. Correlation dimensions during situations of sound rhythm exposure

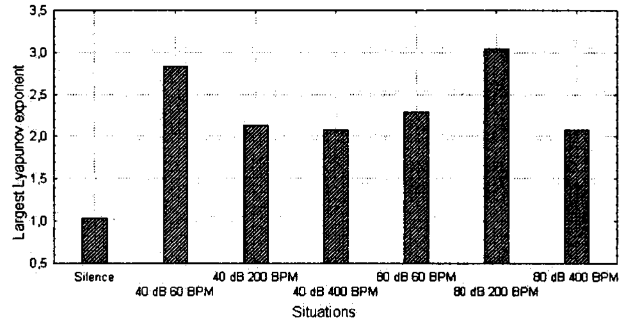

Figure 10. Largest Lyapunov exponents for silence situation and sound rhythm exposure situations

Some other evidence (Sammer, 1998) showed such LLE increase typical for performance in tasks that require increased mental load. Other effects, like Intensity or Tempo of sound rhythms were not significant for LLE change $F_I(1,10)=0.13, p>.05$; $F_T(2,20)=2.17, p>.05$).

GENERAL COMPARISON OF LINEAR AND NON-LINEAR ANALYSES: IMPLICATIONS AND CONCLUSION

Different analyses revealed common aspects of changes in heartbeat behavior during participants' exposure to sound rhythms only partially. What was immediately obvious is that all investigated effects became prominent in this way or another during the sound rhythm exposure. Furthermore, most of parameters changes were more prominent for more intensive rhythm exposure (lowering R-R intervals down, lowering SMI indexes down for LF and MF bands, leveling of the 1/f slopes and decrease of correlation dimension). Effect of sound rhythm Tempo is not as frequent as Intensity effect. However, it manifests in form of SMI index decrease for LF and MF bands and for leveling of 1/f spectra slopes.

Two parameters were used in the previous study (Valerjev & Šimić, 2002): (1) R-R changes; (2) HRV variability; and following five analyses and/or parameters were used in current investigation: (3) power spectra; (4) SMI indexes; (5) 1/f spectra slopes; (6) correlation dimension and (7) largest Lypunov exponent. Rhythm exposure vs. Silence factor showed apparent effect on all parameters (1) – (7), at least for more intensive rhythms. On the other hand, Intensity factor showed effects on variables (1), (2), (4), (5) and (6); and Tempo factor only on variables (4) and (5). These effects point to stress that appears with more intensive rhythms and increases as a function of Tempo; mental load, present in all sound rhythm exposure situations and interference of sound rhythm with cardiac behavior which does not seem to be just a simple appearance of appropriate sound rhythm frequencies in cardiac rhythm, but results with more complex non-linear changes and increased chaoticity of heartbeat behavior.

Linear analyses show that the sound-rhythm exposure affects listener stressfully and represents a certain mental load. These effects are more prominent with more intensive rhythms. Non-linear analyses show an interesting phenomenon: mental load increase produces increased chaoticity and decrease of heartbeat complexity. This points to the fact that cardiac dynamic system is under more prominent influence of a lesser number of non-linear factors (more intensive activity of simpaticus) and/or under weaker influence of linear factors in mental load situations.

When discussing linear and non-linear methods comparison, different methods of analysis point to similar phenomena of R-R intervals nature. However, they are so complex that each of the applied analysis methods reveals only some aspects of the underlying mechanism so that the final accordance and consistency between analyses results is only partial. Accordingly, different dynamic analyses methods derived from linear and non-linear dynamics of heart rate behavior provide substantial complementary information so their application and their results interpretation in heartbeat behavior research should be complementary, too.

REFERENCES

Aasman, J., Mulder, G., & Mulder, L. J. M. (1987). Operator effort and the measurement of heart-rate variability. *Human Factors, 29*, 161-170.

Backs, R. W., Lenneman, J. K., & Sicard, J.L. (1999). The use of autonomic components to improve cardiovascular assessment of mental workload in flight simulation. *International Journal of Aviation Psychology*, 9, 1, 33-47.

Baker, G. L., & Gollub, J. P. (1990). *Chaotic dynamics: An introduction*. Cambridge: University Press.

Charnock, D. M., & Manenica, I. (1978). Spectral analysis of R-R intervals under different work conditions. *Ergonomics, 21*, 103-108.

De Waard, D. (1996). *The measurement of drivers' mental workload*. PhD. thesis, University of Groningen. Haren: University of Groningen, Traffic Research Centre.

Gaude, A. H., Laursen, B., Jorgensen, A. H., & Jensen, B. R. (2002). Effects of mental and physical demands on heart rate variability during computer work. *European Journal of Applied Physiology, 87*, 456-461.

Goldberger, A. L., & West, B. J. (1987). Applications of nonlinear dynamics to clinical cardiology. *Annals of the New York Academy of Sciences, 504*, 155-212.

Goldberger, A. L., Rigney, D. R., Mietus, J., Antman, E. M., & Greenwald, S. (1987). Nonlinear dynamics in sudden cardiac death syndrome: heart rate oscillations and bifurcations. *Experientia, 44*, 983-987.

Grassberger, P., & Procaccia, I. (1983). Measuring the strangeness of strange attractors, *Physica, 9D*, 449-470.

Jorna, P. G. A. M. (1993). Heart rate and workload variations in actual and simulated flight. *Ergonomics, 36*, 1043-1054.

Kalsbeek, J. W. H. (1971). Sinus arrhythmia and the dual task method in measuring mental load. In W. T. Singleton, J. G. Fox, & D. Whitfield (Eds.), *Measurement of man at work. An appraisal of physiological and psychological criteria in man-machine systems* (pp. 101-115). London: Taylor and Francis Ltd.

Kalsbeek, J. W. H. (1973). Do you believe in sinus arrhythmia? *Ergonomics, 16*, 99-104.

Keselbrener, L., & Akselrod, S. (1998). Time-frequency analysis of transient signals – Application to cardiovascular control. *Physica A, 249*, 482-490.

Langewitz, W., Ruddel, H., Noack, H., & Wachtarz, K. (1989). The reliability of psychophysiological examinations under field conditions: Results of repetitive mental stress testing in middle-aged men. *European Heart Journal, 10*, 657-665.

Langewitz, W., & Ruddel, H. (1989). Spectral analysis of heart rate variability under mental stress. *Journal of Hypertension, 7*, 32-33.

Lee, D. H., & Park, K. S. (1990). Multivariate analysis of mental and physical load components in sinus arrhythmia scores. *Ergonomics, 33*, 35-47.

Manenica, I. (1977). Comparison of some physiological indices during paced and unpaced work. *International Journal of Production Research, 15*, 261-275.

Manenica, I. (1981). Učinak uvježbavanja laganog repetitivnog zadatka na neke proizvodne i fiziološke parametre [Efficiency of training in light repetitive task on some performance and physiological parameters]. *Dani psihologije u Zadru 1980/1981*, Zbornik radova, Filozofski fakultet u Zadru, 135-147.

Manenica, I., & Krošnjar, N. (1990). Efekti mentalnog opterećenja i nametnutog ritma na parametre nekih psihofizioloških varijabli [Effect of mental load and paced work on parameters of some physiological variables]. *Radovi Filozofskog fakulteta u Zadru 1989/1990*, 29,6, 95-107.

Manenica, I., & Proroković, A. (2000). Effects of interference of some psychobiological rhythms on efficiency. *Proceedings of the IEA 2000/HFES 2000 Congress*, 3, 228.

Mulder, G. (1973). Mental load and the measurement of heart rate variability. *Ergonomics, 16*, 69-85.

Mulder, L. J. M. (1988). *Assessment of cardiovascular reactivity by means of spectral analysis*. Groningen: Rijksuniversiteit Press.

Owis, M. I., Abou-Zied, A. H., Abou-Bakr, M. Y., & Kadah, Y. M. (2002). Study of features on nonlinear dynamical modeling in ECG arrhythmia detection and classification. *IEEE Transactions on Biomedical Engineering, 49*, 733-736.

Papousek, I., Schulter, G., & Premsberger, E. (2002). Dissociated autonomic regulation during stress and physical complaints. *Journal of Psychosomatic Research, 52*, 257-266.

Pool, R. (1989). Is it healthy to be chaotic? *Science, 243*, 604-607.

Proroković, A. (1999). *Interakcija menstrualnog i cirkadijurnog ciklusa nekih psihofizioloških varijabli. [Interaction between menstrual and circadian cycles of some psychophysiological variables]. PhD thesis.* Zagreb: University of Zagreb.

Proroković, A., Gregov, Lj., & Valerjev, P. (2003). Mental load assessment by means of non-linear analysis of heart rate variability. *International Nonlinear Sciences Conference: Research and Applications in Life Sciences*. February 7, 8 and 9, 2003. Vienna, Austria.

Sakki, M., Kalda, J., Vainu, M., & Laan, M. (2003). What does measure the scaling exponent of the correlation sum in the case of human heart rate? *Physics, 11*, 2, 1-5.

Sammer, G. (1998). Heart period variability and respiratory changes associated with physical and mental load: non-linear analysis. *Ergonomics, 41*, 746-755.

Sayers, B. (1973). Analysis of heart rate variability. *Ergonomics, 16*, 17-32.

Sloan, R. P., Korten, J. B., & Myers, M. M. (1991). Components of heart rate reactivity during mental arithmetic with and without speaking. *Physiology and Behavior, 55*, 1039-1045.

Sloan, R. P., Shapiro, P. A., Bagiella, E., Fishkin, P. E., Gorman, J. M., & Myers, M. M. (1995). Consistency of heart rate and sympathovagal reactivity across different autonomic contexts. *Psychophysiology, 32*, 452-459.

Sloan, R. P., Shapiro, P. A., Bagiella, E., Bigger, J. T., Lo, E. S., & Gorman, J. M. (1996). Relationships between circulating catecholamines and low frequency heart period variability as indices of cardiac sympathetic activity during mental stress. *Psychosomatic Medicine, 58*, 25-31.

Sloan, R. P., DeMeersman, R. E., Shapiro, P. A., Bagiella, E., Chernikhova, D., Kuhl, J. P., Zion, A. S., Paik, M., & Myers, M. M. (1997). Cardiac autonomic control is inversely related to blood pressure variability responses to psychological challenge. *American Journal of Physiology, 272*, 2227-2232.

Šimić, N. (2003). *Neke psihofiziološke reakcije na ispitni stres [Some psychophysiological reactions on exam stress]. PhD thesis.* Zagreb: University of Zagreb.

Šiška E. (2002). New method for assessing the functions of the autonomic nervous system and their possible usage in psychophysiological research. *Studia Psychologica, 44*, 3.

Valerjev, P., & Šimić, N. (2002). Sound rhythm effects on cardiac parameters. *Review of Psychology, 9*, 41-48.

Veltman, J. A. (2002). A comparative study of psychophysiological reactions during simulator and real flight. *International Journal of Aviation Psychology, 12*, 33-48.

Wolf, A., Swift, J. B., Swinney, H. L., & Vastano, J. A., (1985). Determining Lyapunov exponents from time series. *Physica, 16D*, 285-317.

Zwaga, H. J. G. (1973). Psychophysiological reactions to mental tasks: effort or stress? *Ergonomics, 16*, 61-69.