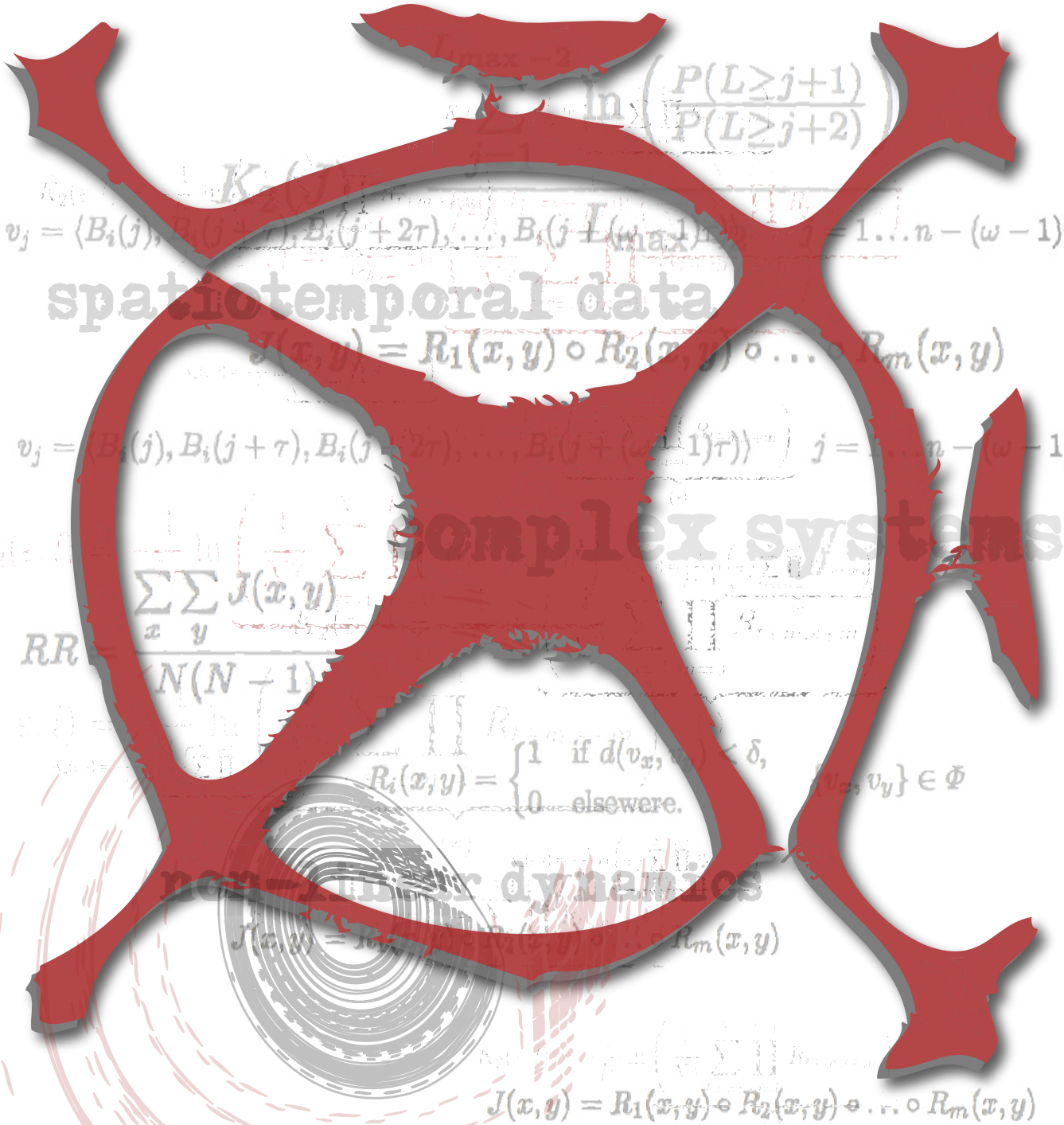
PROGRAM AND ABSTRACTS

3RD INTERNATIONAL SYMPOSIUM ON RECURRENCE PLOTS

Recurrence plots at the crossroad between theory and application:
A flexible approach for studying complex systems



AUGUST 26 - 28 2009

MONTRÉAL, QUÉBEC, CANADA

Scientific and Organisational Committee

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Aims

A human cell, a stock market, a city, a bridge, a forest, and a social community all have in common that they form complex systems made of nonlinearly interacting units, which are hierarchically organised in time and space. The objective of the symposium is the exchange of knowledge among scientists investigating different classes of complex phenomena by means of recurrence analysis.

Recurrence plots (RP) form an efficient strategy for both visualising and quantifying nonlinear spatiotemporal dynamics and have found applications in various fields. The flexibility of the RP approach resides notably in its robustness regarding nonstationarity and transient dynamics. While theoretical works on RP have now reached maturity, the approach is at the crossroads in terms of expanding its potential to the study of empirical systems.

For instance, various scientific disciplines are all tackling similar questions that require a complex systems approach:

- Can we develop indicators that serve as warning signals for impending regime shifts or critical thresholds in the system dynamics?
- What is the characteristic observation scale that allows for an optimal description of the system dynamics in space and time?
- How to quantify the resilience (return time to equilibrium) and stability (resistance to external forcing) of a system subjected to disturbance regimes?
- Can we derive generalities on how natural and man-made systems develop in time?
- Amongst interacting units in the system, which ones are the keystones for sustaining its global functioning?

The RP approach could help to tackle questions regarding the behavior of complex systems, but also to contribute novel hypotheses on the structure and functioning of these systems. Scientists from various research fields are invited to attend the symposium and investigate their favorite research questions through the use of recurrence plots.

Practical Workshop

The practical workshop is an opportunity for conference attendees to get hands on experience with recurrence analysis. Instructive presentations will introduce the RQA Software package and the CRP toolbox for Matlab. Participants will learn the basics of performing recurrence quantification analysis as well as more advanced

techniques to study multivariate interrelations or synchronisations. Participants are encouraged to bring their own data sets for analysis.

Internet Access

Conference attendees can access Wi-fi from their laptops in the cafeteria on the ground floor of the building. Usernames and passwords can be obtained from the registration desk.

Social Event

It is planned to have a dinner at the "Le Paris-Beurre" on Thursday, 19:30. The restaurant is located at 1226 ave. Van Horne and is a 10 to 15 minutes walk from the conference building. All are welcome to attend.

Location

Montréal is the third largest primarily French-speaking city in the world, after Paris and Kinshsa, and the Latin capital of North America. It is a city where the European charm and the North American spirit mix like nowhere else. It clearly is a city that deserves to be experienced and not just passed by.

Lectures, Practical Workshop and Poster Session

The symposium takes place in the Strathcona Building, University of Montreal, 520 Côte Ste.-Catherine. The presentation sessions will be held in room 430, on the 4^{th} floor. The practical workshop will be held in the LEMIG computer lab, in room 304. Lunches and poster session will be held in the cafeteria, on the ground floor of the building.

Excursion

On Friday, August 28th, we will visit a traditional maple sugar shack outside of the city at Mont Rigaud. We can walk around in a forest full of walking trails, visit the sugar shack buildings and have a traditional meal.

We will leave Montreal at 15:30 returning at 23:30 at the latest. The sugar shack (La sucrerie de la montagne) will be expecting us at about 17:00 and dinner is at about 18:00. The tour includes:

- a ride in horse drawn wagons to take us from the parking area up to the sugar shack;
- a tour of the maple sugar making cabin and of their facilities;
- an all you can eat meal;
- live traditional québécois music;
- maple sugar taffy on snow.

There are also extensive trails in the forest for those who want to take a walk.

The meal is a traditional sugar shack meal, including, minimally: pea soup, tourtière, homemade sausages, fried pork fat, beans, eggs, pancakes, sugar pie, coffee, tea, condiments, and, of course, maple syrup on everything. It is all you can eat and very filling! People who are vegetarian or who don't eat pork can have a vegetarian tourtière or pea soup and many other items without pork – please tell us whether you need a vegetarian dinner. Alcohol is available on site at extra charge.

The total charge for the excursion is $60 per person. The event is also appropriate for accompanying persons and children, if people are travelling with their family.

If you want more information about the sucrerie, the web site is: `http://www.sucreriedelamontagne.com`.

Special Issue

All contributors are invited to submit their work for a special issue entitled: "Recurrence plots at the crossroad between theory and application: A flexible approach for studying complex systems" that will be published in a selected scientific journal. The standards for publication are as high as for a regular scientific paper (and thus are in general substantially higher than the standards for acceptance in the workshop). All of the papers are expected to describe original research.

Authors are encouraged to write short articles (page limit of 12 pages, incl. figures). If someone feels that his/her material cannot be presented on 12 pages, the author might ask us before writing the article whether it is justified to have a longer article on a specific topic (review-like article).

The manuscripts should be submitted by December 31, 2009.

Further information (templates, submission procedure) is available at:
`http://symposium.recurrence-plot.tk/index.php?a=proceedings`.

Programme

Wednesday, August 26th

8:30 Registration

Introduction

9:00 **L. Parrott**:
Welcome Note

9:15 **Ch. L. Webber**:
Remembrance Talk Recurrent Memories of Joe Zbilut and His Remarkable Scientific Career

10:00 **N. Marwan**:
Introduction Lecture Hot Topics in the Recurrence Plot Field

10:45 *Coffee break*

Methodological Aspects

11:15 **M. Small**:
Keynote Lecture Complex Networks from Recurrence Plots and Time Delay Embeddings

12:00 J. Donges, Y. Zou, **R. Donner**, N. Marwan, J. Kurths:
The Complex Network Approach and Recurrence Quantification Analysis

12:20 F. Strozzi, **J.-M. Zaldivar**, K. Poljansek, F. Bono and E. Gutierrez:
From complex networks to time series analysis and viceversa: Application to metabolic networks

12:40 **Y. Zou**, M. C. Romano, M. Thiel, N. Marwan and J. Kurths:
Extracting indirect coupling by means of probabilities of recurrence: revisited

13:00 *Lunch*

14:40 **Y. Hirata**, K. Aihara:
Testing serial dependence on recurrence plots

15:00 **S. Schinkel**, N. Marwan, J. Kurths:
Confidence bounds of recurrence-based complexity measures

15:20 **Y. Saiki**, M. Yamada:
Time averaged properties along unstable periodic orbits in some systems of differential equations

15:40 *Coffee break*

Applications in Economics

16:10 **P. M. Crowley**:
Comparing cycles in the US stockmarket and macroeconomic growth using recurrence plots

16:30 **A. Piskun**, Vladimir Soloviev, Sergio Piskun:
Recurrence Quantification Analysis of Stock Market Crashes

Applications in Engineering

16:50 **G.Litak**:
Dynamics of a regenerative cutting process

Thursday, August 27th

8:50 Welcome & miscellanous announcements

Applications in Biological Systems I: Psychology

9:00 **S. E. J. Wallot**, G. Hollis, G. C. Van Orden:
Temporal patterns in text reading

9:20 **R. F. A. Cox**, F. Hasselman:
Insight in Problem Solving: Recurrence Analysis of Structural Changes in Cognition

9:40 **G. Varni**, A. Camurri, P. Coletta, G. Volpe:
Real-time Computation of Recurrence and Phase Synchronisation in Social Applciations

10:00 **F. Hasselman**, R. F. A. Cox:
Probing the temporal structure of human interaction: Recurrence analysis of behaviour observation data

10:20 *Coffee break & Poster Session*

10:50 **R. Dale**, D. C. Richardson:
Psycholinguistic synchrony: Cross-recurrence shows coordination in the many dimensions of human conversation

11:10 **S. Hermann**:
Using Synchronization Analysis by Means of Recurrences for Quantification of the Degree of Automobile Driver's Discomfort

12:30 *Lunch*

Workshop

14:00 **Practical Tutorials & Concurrent Poster Session**
CRP Toolbox for Matlab, RQA Software
Poster session in the Cafeteria

19:30 *Social Event: Supper at "Le Paris-Beurre"*

Friday, August 28th

8:50 Welcome & miscellanous announcements

Applications in Earth Sciences

9:00 **H. Lange**:
Keynote Lecture Recurrence Quantification Analysis in ecosystem research: examples and possibilities

9:45 **S. Li**, Z. Zhao, Y. Gao, Y. Wang:
Determining the predictability and the spatial pattern of urban vegetation using recurrence quantification analysis: A case study in Shenzhen City

10:05 **R. Proulx**, L. Fahrig, L. Parrott, D. Currie:
Predicting mammal species richness at the global scale: Resource

10:25 *Coffee break*

Applications in Biological Systems II: Cardiology and Medical Problems

11:00 **Ch. L. Webber**, Jr., Zh. Hu, J. Akar:
The importance of recurrent singularities in cardiac dynamics

11:20 **E. E. N. Macau**, L. Y. Ling, J. J. Barroso de Castro, M. F. de Godoy:
Combined use of methods of nonlinear dynamics and neural networks in the evaluation of heart rate variability in different clinical situations

11:40 **D. Chuckravanen**, M. Angelova, A. St. Clair Gibson, K. Thomas, M. Stone, L. Ansley, K. G. Thompson:
Recurrence quantification analysis of the system control Mechanisms

12:00 **S. Carrubba**:

Effects of magnetic fields on human brain activity detected by recurrence analysis

12:20 **A. Schumacher**, B. Waghorn, N. Yanasak, T. Hu:
Nonlinear Assessment of Manganese-enhanced Magnetic Resonance Images with Recurrence Quantification Analysis

12:40 *Lunch*

15:30 *Excursion to a traditional maple sugar shack*

Poster

Methodological Aspects

Poster 1 **E. J. Ngamga**, J. Kurths:
Characteristic Distributions of the Mean Recurrence Time

Applications in Economics

Poster 2 **P. M. Crowley**, A. P. Schultz:
Measuring the Intermittent Synchronicity of Macroeconomic Growth in Europe

Applications in Engineering

Poster 3 **R. Donner**, U. Hinrichs:
Symbolic recurrence plots – Theory and application to traffic and production systems

Applications in Earth Sciences

Poster 4 F. Angermüller, **H. Lange**, G. Lasslop, M. Reichstein:
Recurrence Quantification Analysis of carbon fluxes

Poster 5 **R. Donner**, H. von Suchodoletz:
Similarity structures and dynamical transitions in uni- and multivariate palaeoclimatic time series: A recurrence plot approach

Applications in Biological Systems

Poster 6 **H. Castellini** CANCELLED:
Using RQA to study the nonlinear viscoelastic behavior of red blood cells

Poster 7 **A. Novellino, J.-M. Zaldivar Comenges**:
Characterization of neuronal activity of Multielectrode Arrays using Recurrence Quantification Analysis

Poster 8 **K. Andrade**:
Recurrence quantification analysis of single auditory evoked potential acquired in the MR environment

Poster 9 **N. Kuznetsov**, M. A. Riley, J. Gottschall, V. Lippens:
Detecting Deterministic Structure in Time Series of Human Balance Performance: A Comparison of RQA and the Langevin Method

Poster 10 **Chr. K. Rhea**, A. W. Kiefer, J. A. Weast, S. Cumins-Sebree, K. Shockley, M. A. Riley:
Global vs. individual input parameter selection: Impacts on analyzing human postural time series

Poster 11 **A. W. Kiefer**, J. A. Weast, S. Teredesai, S. Cumins-Sebree, K. Shockley, M. A. Riley, J. Haas:
Young ballet dancers exhibit different postural sway dynamics than untrained controls

Abstracts

Recurrence Quantification Analysis of Single Auditory Evoked Potential Acquired in the MR Environment *Poster*

Kátia Andrade

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The electrophysiological changes in response to external stimuli are low in amplitude if compared with the background electroencephalographic (EEG) signal. In evoked-related potential (ERP) analysis, time-locked stimulus induced responses are usually averaged to remove the background EEG activity and to increase the signal to noise ratio. On the other hand, signal averaging assumes that the electrophysiological response will be similar for stimuli with the same characteristics (stationary signal). Thus, the averaging method is not optimal if temporal changes in subject performance, attention, arousal level or habituation occur which may alter the ERP amplitude. In addition, the high temporal resolution of the raw EEG is being collapsed by the averaging process, as a consequence, the recent technique of acquiring simultaneously EEG/fMRI cannot properly correlate this high EEG temporal resolution with the fMRI unmatched spatial resolution. In the present work, we propose to apply the Recurrence Quantification Analysis (RQA) to improve ERP characterization. RQA is a nonlinear method that was proposed by Zbilut and Webber (1992) and has the advantage of makes no assumption about the statistic properties of the data. In contrast to other non-linear methods, RQA can also be applied to short non-stationary time series (Marwan 2003). In 2004, Marwan and Meinke showed in a first approach that, in an oddball paradigm, RQA can basically be used to analyze individual ERPs. Our goal was test the RQA stability when applied on single trials and to extend report of results from individual levels to group statistics. We were further interested to apply the method inside the magnetic environment of an MR system, known to affect ERP signal quality. We used a classic active auditory oddball protocol to compare the efficiency of RQA parameters versus amplitude analysis of ERP graphoelements, as P300, in distinguishing between frequently and infrequently stimuli. In addition, we also aimed to access the effects of the magnetic environment artefacts on the ERP results by comparing experiments inside and outside the MR. We found that RQA better distinguished between frequently and infrequently stimuli in both cases, outside and inside the MR, if compared with P300, P200 and N100 amplitude analyses. Furthermore, RQA was the only one able to differentiate between frequently tones, discriminated by the temporal position relative to the infrequently tones. We showed that RQA can be consistently useful to improve the trial by trial ERP analysis; nevertheless, more studies should be done to better understand it behaviour when applied in ERP data.

Recurrence Quantification Analysis of Carbon Fluxes

Friedrich Angermüller, Holger Lange, Gitta Lasslop, Markus Reichstein

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Carbon fluxes obtained from flux towers using the EC method are one of the backbones of terrestrial ecosystem monitoring. They comprise a set of temporally highly-resolved time series, measured since a number of years. Two variables deduced from EC data is the Net Ecosystem Exchange (NEE) and the Gross Primary Productivity (GPP). It is largely driven by available radiation on short time scales, while the influence of the phenological status strengthens for middle and long time scales. A simple approach to relate NEE or GPP and global radiation (Rg) exploits light use efficiency models with parameters describing initial slope, maximum productivity, and plant respiration. Here, we want to assess the impact of the different driving factors, meteorological and phenological, on GPP in more detail. We investigate the dynamical properties of and relations between GPP, Rg and modelled GPP for 1000 $Wm^{-}2$, which is related to the phenological status of the vegetation, using Cross Recurrence Plots and RQA for 16 tower sites in temperate climate. Cross correlation sums as well as the determinism are explored for different lags. The time scale covered by the embedding vectors reaches from 20 days to one year, with a typical embedding dimension of m=5.

Effects of Magnetic Fields on Human Brain Activity Detected by Recurrence Analysis

Simona Carrubba

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Introduction. Man-made environmental electromagnetic fields (EMF) such as those produced by power lines and mobile phones are pervasive in the environment, thereby

raising questions about potential health adverse effects. Despite many studies, the nature and significance of EMF-induced bioeffects remains a central problem in modern biology. We hypothesized that the solution to the problem depended on the recognition that: (1) the overall interaction between EMF and biological systems is nonlinear; (2) conventional nonlinear quantifiers were of little use in the analysis of nonstationary time series derived from biological systems. We tested our ideas using recurrence analysis (RA) to study electroencephalographic (EEG) time series. Our aim was to determine whether EMF effects on with brain electrical activity in human subjects could be detected using RA.

Methods. EEG voltages were recorded from human subjects during three experimental conditions in a single session, exposure to a 2-G 60-Hz magnetic field, an auditory stimulus (positive control), and a null stimulus (sham exposure). Stimuli were applied for 2 seconds with a 5-second interstimulus period (trial) while EEG voltages were recorded continuously from scalp electrodes. Exposure and control epochs from independent trials were embedded in phase space and recurrence plots for each epoch were generated and quantified by means of percent recurrence (%R) and percent determinism (%D). For each experimental condition, the exposure and control epochs were compared by means of the paired t test.

Results. Using %R and %D, we consistently detected evoked potentials in human subjects 100-500 ms after application of EMF stimuli: the potentials were not observed using linear analysis (time averaging), (1-3). The parameters needed for the recurrence analysis were determined using a model system that contained known nonlinear determinism.

Discussion. Recurrence analysis permitted us to establish the existence of magnetosensory evoked potentials in human subjects, a phenomenon that was previously unrecognized and which might deeply impact our current understanding of EMF bioeffects. Although RA was effective, the meaning of the recurrence variables is problematic; it is possible, for example, that the variables are redundant. Additionally, their relation to each other cannot currently be related to any known physiological variables.

References

1. Carrubba, S., Frilot, C., Chesson, A., & Marino, A. (2006). Detection of nonlinear event related potentials. J. Neurosci. Meth., 157, 39-47.

2. Carrubba, S., Frilot, C., Chesson Jr., A. L., & Marino, A. A. (2007). Evidence of a nonlinear human magnetic sense. Neuroscience, 144, 356-367.

3. Carrubba, S., Frilot, C., Chesson Jr., A. L., Webber Jr., C. L., Zbilut, J. P., & Marino, A. A. (2008). Magnetosensory evoked potentials: consistent nonlinear phenomena. Neurosci. Res., 60, 95-105.

Using RQA to Study the Nonlinear Viscoelastic Behavior of Red Blood Cells. *Poster*

Horacio Castellini

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Today it is well known that red blood cell membrane of mammals possesses both elastic and viscous properties to infer a complex viscoelastic behavior. Representation by a set of linear equations (or linear behavior) and subsequent study oscillatory regime, is well known and studied both empirically and theoretically. But has recently gained notoriety the study of nonlinear behavior of the red blood cell membrane to an oscillatory regime. This poster applies the recurrence quantification analysis (RQA) to study nonlinear behavior with the data obtained from an oscillating eritrodeformeter. This not only allows to characterize the nonlinear behavior of the attractor, also allows to characterize the alterations of human red blood cells.

Recurrence Quantification Analysis of the System Control Mechanisms

Dineshen Chuckravanen, M. Angelova, A. St. Clair Gibson, K. Thomas, M. Stone, L. Ansley, K. G. Thompson

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In exercise physiology, the study of the complex rhythms arising from the peripheral and central systems of the human body is crucial to optimise athletic performance. According to a novel theoretical model called the Central Governor Model (CGM) of fatigue1, 2, there is a central governor in the brain that regulates the physical activity to ensure that this exercise activity is completed without homeostasis failure through interactive communication between the physiological and central systems in a deterministic way. Therefore, there is an increasing need to investigate on the char-

acteristics of these system control mechanisms that regulate our homeostasis and control our behaviour and activity. In order to determine the characteristics of these complex system control mechanisms, recurrence analysis is used to locate any rhythms or patterns in these physiological data3, 4. In this study, various pacing strategies that are self paced, even paced and variable paced were used for a 20-km cycling time trial to observe how these pacing strategies influence the heart rate (HR) activities (BPM) and the volume of oxygen consumption (VO2 / L.min-1) of these cyclists.

It was observed that for VO2, there is no significant difference between the RQA measures that are recurrence rate (RR), determinism (DET) and trapping time (TT) for all ten cyclists performing the different pacing strategies. The mean RR is 9%, DET is 29.6% and TT is 2.5 s and there is no significant difference between the aforesaid RQA measures for heart rate activities for all pacing strategies and the mean value RR is 10%, DET is 89% and TT is 8.2 s. The difference in the trapping times and the determinism values between VO2 and HR suggests that each physical system has different characteristic behaviour. It is observed that the heart rate activities of these cyclists stay three times longer in a particular physiological state than that of the respiratory system. Interestingly, for the heart rate with mean DET of 89% implicates that these activities can be predicted much easier than the random process of the events observed from the respiratory system even though the probability of recurrence in both cases are low. Moreover, the trapping times for the heart rate activities are significantly different for each pacing strategy and there is the tendency of the imposed pacing strategy to force that physical system to imitate its behaviour as shown by the duration of the mean trapping time to remain in a state is highest in even paced strategy (10.9s) and least in variable paced strategy (6.7s).

References

1. St Clair et al., (2004) 'Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans', B J Sports Med, 38, pp. 797-806.

2. St Clair et al., (2005) 'Metabolic setpoint control mechanisms in different physiological systems at rest and during exercise', J of Theo Bio, 235, pp. 60-72.

3. Trulla, LL, Giuliani A., Zbilut JP., and Webber Jr. CL (1996), 'Recurrence quantification analysis of the logistic equation with transients'. Physics Letters, A (223), pp. 225-260.

4. Zbilut JP, Zak M, Webber Jr. CL (1995), 'Nondeterministic chaos in physiological systems', Chaos, Solutions, and Fractals 5, pp. 1509-1516.

Insight in Problem Solving: Recurrence Analysis of Structural Changes in Cognition

Ralf F. A. Cox, Fred Hasselman

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It has been recognized that eye-movement data provide an essential window on the mechanism underling the emergence of insight and representational change during problem solving (Knoblich, Ohlsson & Raney, 2001). Eye-movements and fixations are used to derive theories and test inferences about problem-solving strategies. Mean fixation times and spatial patterns of fixations, for instance, expose attention allocation and attentional shifts, which are considered as important indicators of different types of mental processing. The present talk demonstrates how the dynamics of the eye movements reveal a fundamental bidirectional link between perceptuomotor processes and structural changes in cognition. Recurrence analysis offers a sound framework for the quantification and interpretation of the temporal structure in the eye movements. Measures derived from this analysis, in particular entropy, predict the occurrence of the insight.

Measuring the Intermittent Synchronicity of Macroeconomic Growth in Europe *Poster*

Patrick M. Crowley and Aaron P. Schultz

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It has been recognized that an emergent European business cycle now exists within the European Union, likely due to the single market initiatives as well as the introduction of the single currency (the euro) in 1999. As a result, it is not surprising that an increasing degree of synchronicity in growth cycles exists between European member states, although research using recurrence plots (by Crowley (2008)) suggests that real output growth in European economies is only "intermittently" synchronized. In this paper we use recurrence metrics of synchronicity to show how tightly coupled euro area member states are with each other and the EU as a whole. The synchronicity metrics are then aggregated to look at the euro wide patterns of coupling between member states.

Comparing Cycles in the US Stockmarket and Macroeconomic Growth Using Recurrence Plots

Patrick M. Crowley

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It has long been recognized in economics and finance that the stockmarket is a leading indicator of economic activity. In this paper Empirical Mode Decomposition (EMD) is first used to extract embedded frequencies in stockmarket data, macroeconomic growth data (including both investment and consumption) for the United States. These cycles are then compared in terms of their frequency composition and then recurrence plots are used to extract various metrics to measure the extent of the lagged effects in stockmarket movements and also which frequency movements in stock prices are associated with movements in real GDP. These metrics are used to evaluate the contemporaneous versus leading indicator content of stockmarket data, and the extent to which stockmarket movements reflect changes in consumption and/or investment.

Psycholinguistic Synchrony: Cross-Recurrence Shows Coordination in the Many Dimensions of Human Conversation

Rick Dale, Daniel C. Richardson

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Recent accounts of human interaction have emphasized processes of coordination and coupling (e.g., Pickering & Garrod, 2004; Shockley, Richardson, & Dale, 2009). From perceptual processes (e.g., vision) into high-level linguistic dimensions (e.g., meaning), two humans reveal a capacity to couple cognitive processes while they engage in conversation. In this talk, we showcase a series of studies employing cross-recurrence quantification analysis to investigate conversational interaction along these numerous dimensions. We present a measure drawn from cross-recurrence plots, which we call the diagonal-recurrence profile, that serves as a quantifiable signature of this coupling. In studies of visual attention, gesture, syntax, and semantics, cross-recurrence may permit a detailed analysis of this coupling beyond what other correlational or lag-sequential methods have yet revealed.

Symbolic Recurrence Plots – Theory and Application to Traffic and Production Systems *Poster*

Reik Donner, Uwe Hinrichs

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Methods of symbolic time series analysis such as mutual information or entropies are often applied if observables are characterised by only a discrete set of possible values or when a high noise level requires a coarse-graining to capture the essential deterministic part of the dynamics. Recently, we have shown that the consideration and quantitative assessment of recurrence plots obtained from symbolic sequences allows a deeper understanding of the dynamics of such observables. As some specific examples, we present applications of symbolic recurrence quantification analysis to different time series from traffic and production systems, and discuss the potential benefits and problems of the symbolic with respect to the traditional RQA.

Similarity Structures and Dynamical Transitions in Uni- and Multivariate Palaeoclimatic Time Series: A Recurrence Plot Approach *Poster*

Reik Donner, Hans von Suchodoletz

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The concept of recurrence can be used as a basis for investigating the mutual similarity of environmental conditions that are captured in palaeoclimatic time series. This presen-

tation gives some examples of the power of the corresponding approach to detecting sudden as well as gradual changes of geological properties that encode climate variability in the past. A main focus lies on the consideration of compositional data and their treatment within the framework of recurrence plots. Specifically, different approaches are discussed to obtain distance and recurrence matrices from grain-size distributions in sedimentary sequences, including proximity measures such as the simplex (Aitchison) distance as well as two-sided chi-squared, Kolmogorov-Smirnov, and other related statistics. The performance of the different approaches and their use for obtaining complementary quantitative information about past climate variability is exemplified for records of aeolian dust input obtained from different sediment traps (so-called vegas) on the Canary islands.

The Complex Network Approach And Recurrence Quantification Analysis

Jonathan Donges, Yong Zou, Reik Donner, Norbert Marwan, Jürgen Kurths

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The possibility of characterising time series by means of complex networks has been proposed recently in different works. The recurrence matrix as derived from a time series is an ideal candidate for being interpreted as an adjacency matrix of a complex network. We discuss similarities and differences between recurrence quantification analysis and complex network theory. Measures of complex network theory applied on a recurrence matrix provide a new quantitative approach to recurrence analysis by quantification of different local and global topological features in the recurrence structure. We show how we can interpret these measures in terms of state space properties and why they bear new and complementary insights, not yet covered by the standard recurrence quantification analysis. Future directions related to specific practical questions of time series analysis are outlined.

Probing the Temporal Structure of Human Interaction: Recurrence Analysis of Behaviour Observation Data.

Fred Hasselman, Ralf F. A. Cox

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In contemporary psychology temporal information is usually discarded in studies of behaviour observation and measures of central tendency or simple frequency of occurrence are used in analyses (f. i. Behaviour A occurred x times and lasted y minutes on average). In this talk several examples will be presented which show RQA outcomes can capture information in categorical behavioural data (such as sleep-wake cycles of infants and mother-child interaction) not detectable by traditional measures. However, some issues arise with the (psychological) interpretation of RQA outcomes when data are on a nominal scale because information about which category is recurring is lost. Some suggestions for a solution will be discussed such as per-category recurrence measures and recurrence of specific behavioural patterns.

Using Synchronization Analysis by Means of Recurrences for Quantification of the Degree of Automobile Drivers Discomfort

Sonja Hermann

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Early detection of the onset of discomfort and associated physical fatigue of a driver while driving for extended periods of time is useful in designing countermeasures with the aim to extend the drivers comfort. In a previous study we have used recurrence plots to identify patterns of increasing sitting postural discomfort of an automobile driver over a few hours of driving in a real traffic situation. The center of pressure (COP) was validated against the seat interface pressure under the ischial tuberosities (IP) and pressure under the upper thighs (TH) with the aim of the COP to serve as a

single measure to validly describe discomfort levels. It was concluded that the COP measure holds the potential to serve as a measure to reveal discomfort over time.

In the current study we use the seat interface pressure in the 4 areas of the seat (left, right IT and left, right upper TH) to construct a 4 dimensional vector and compare it to the COP vector to attempt to identify how the 4 areas of the seat-sitter interface contribute altogether to the evolvement of discomfort. A joint recurrence plot between this vector and the COP vector are computed. The JRP shows cluster of recurrence points for zones of (higher) discomfort as compared less recurrence points in zones of temporary comfort. Next the joint recurrence rate was calculated to identify the degree of synchronization between the COP vector and the % pressure summary vector. We have found a high degree of synchronization between the two systems in areas of discomfort ($> 0.8 - 0.9$) as compared to a low degree of synchronization in areas of temporary comfort ($< 0.2 - 0.4$) over 12 subjects. These findings suggests that the synchronization between the COP and % seat interface pressure vector increases with increased discomfort and might be interpreted as the postural control system kicking in to initiate a different posture in order to improve the seated interface pressure, and hence drivers comfort, During those adjustment actions both systems (COP and %Pressure) seem to be coordinated and act less independently to improve the discomfort situation. These results may be of value when predicting discomfort states from a present state of the drivers COP and % pressure.

Testing Serial Dependence on Recurrence Plots

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It is a trend to quantify recurrence plots. One of the main quantities is DET, which is the ratio of plotted points forming diagonal lines. But, to show the significance of DET, the current common practice is to use it with surrogate data. By changing the definition slightly and considering statistical independence, we can derive error bars for the quantity upon the null-hypothesis that there is no serial dependence. By using the error bars, we can show the significance of the quantity. We apply this idea for characterizing the multiscale aspects of wind. The same idea can be used to test excessive joint recurrences.

Young Ballet Dancers Exhibit Different Postural Sway Dynamics than Untrained Controls *Poster*

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Postural sway – spontaneous, continuous, low-amplitude fluctuations of the bodys center of mass that occur when standing – is assumed to reflect the output of neuromuscular processes exercised to maintain postural stability. Postural sway is noisy and non-stationary, making quantification of sway challenging. Recurrence quantification analysis (RQA) is ideally suited for such data, however, and has previously demonstrated sensitivity to subtle variations in balance performance. In the present research we used RQA to determine whether differences in the quality of postural performance are reflected in the dynamics of postural sway. As part of a larger cross-sectional study on postural control in ballet dancers, we compared two groups of female elementary school students – those in their first years of ballet training and controls who were not taking ballet ($N = 10$ per group). Our aim was to determine if brief amounts of training are sufficient to produce changes in the quality of postural performance. We manipulated the availability of vision (eyes open, eyes closed) and the bio-mechanical stability of stance (i.e. stance; feet together, feet shoulder-width apart) as ways of varying postural demand, with the eyes-closed, feet-together condition being most demanding and the eyes-open, feet-apart condition the least challenging. We used a force platform to record the postural center of pressure (COP) in the medial-lateral (ML) and anterior-posterior (AP) directions during each 30 sec trial. We quantified the amount of COP variability as the standard deviation (SD) and local standard deviation (LSD; this is the average of SDs computed over non-overlapping 1 sec windows of data and thus is a measure of fine-grained variability) of each time series. We also quantified the COP dynamics using RQA. For the variability measures, results indicated a Vision $\times$ Stance $\times$ Group interaction was present ($p < 0.05$) for COP SD in the AP direction. Follow-up comparisons revealed greater variability in the controls between the most difficult balance condition and the easiest balance condition ($M = 0.331$ and $M = 0.252$, respectively; $p < 0.001$) while ballet dancers exhibited no differences between those two conditions ($p >$

0.05). RQA revealed a number of effects on COP dynamics. A significant main effect for group was present in the ML direction for %Recurrence (%REC; $p < 0.001$; dancers $= 2.319$ vs. controls $= 1.505$), Entropy ($p = 0.023$; dancers $= 4.357$ vs. controls $= 3.875$), Trend ($p = 0.005$; dancers $= -1.827$ vs. controls $= -1.223$), and in the AP direction for %REC ($p = 0.044$; dancers $= 2.107$ vs. controls $= 1.709$). A Stance $\times$ Group interaction was also present in the ML direction for %REC ($p = 0.006$) with the dancers exhibiting more recurrent sway in the feet-apart condition compared to both their own feet-together condition and the controls – feet-apart condition (all $p < 0.05$). In contrast, the controls exhibited greater %REC in the feet-together condition compared to their own feet-apart condition ($p < .05$). Our results suggest that postural control differences are present in ballet dancers as early as two years into ballet training. Additionally, the RQA results suggest the young dancers exhibit different postural sway dynamics compared to controls, even after only a small amount of ballet training. In general, the dancers – sway was more recurrent, more complex, and more non-stationary than the controls – sway. Group differences were more apparent in the dynamics of sway than in sway variability.

Detecting Deterministic Structure in Time Series of Human Balance Performance: A Comparison of RQA and the Langevin Method *Poster*

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We examined two methods of assessing the level of signal determinism in human balancing data: the Langevin equation (Gottschall et al., 2009) and recurrence quantification analysis (RQA). The Langevin method dissociates contributions from random noise and deterministic sources, which might be advantageous in some research contexts, but is more restrictive than RQA and, moreover, presupposes that random and deterministic influences are distinct and combine additively. The purpose of this research was to compare the two methods by applying them to the same data set.

We reanalyzed data from Gottschall et al. (in press). Twelve adult participants stood on an unstable, instrumented platform (Wagner et al., 2003). The platform's mediolateral angular velocity was analyzed. Participants performed three experimental conditions – balancing alone, balancing with a motor constraint, or balancing while performing a perceptual search task. Preliminary analyses showed that the standard deviation of the angular velocity time series decreased in the perceptual task but did not change in the motor task.

After determination of the appropriate embedding dimension ($d = 6$) and delay ($= 4$) using false nearest neighbors and average displacement, we examined the RQA measure %DET across the experimental conditions. %DET increased in the presence of the motor constraint compared to the balancing only condition. The perceptual search task led to a slight but non-significant decrease of %DET compared to the balancing only condition.

Analysis of the same data with Langevin equation revealed that there was an increase in deterministic dynamics and no change in the stochastic component while balancing with a motor constraint. Conversely, in the presence of a perceptual task, there was a trend toward a decrease in the deterministic dynamics that approached significance as well as a decrease in the stochastic component.

The results of both analyses confirmed that the level of determinism increased in the motor constraint condition. However, %DET did not significantly change with a decrease of dynamic noise indexed from the Langevin equation in the perceptual condition. %DET seems to map more closely to changes in the deterministic than the random component of the Langevin equation. We further discuss possibilities and potential issues for cross-validation of the level of system determinism using the two methods.

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Geographical Patterns of Photosynthetic Activity in Terrestrial Ecosystems Revealed by Recurrence Quantification Analysis

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Current efforts to monitor the terrestrial biosphere rely on remote sensing of vegetation states. In particular, the fraction of absorbed photosynthetically active radiation, or FAPAR, can be used as a proxy variable for the dynamics of Gross Primary Productivity, i.e. the terrestrial CO_2 uptake.

This study aims at describing the spatiotemporal characteristics of FAPAR on a global scale. We used FAPAR data obtained from the SeaWiFS sensor available since 1998 at a $0.5^\circ \times 0.5^\circ$ spatial and 10 days temporal resolution. Conventional linear trend and spectral analysis reveals a complex pattern, reflecting both the large-scale climatic zones of the Earth as well as local peculiarities. Here, we investigate nonlinear properties of this large set of time series using Recurrence Quantification Analysis (RQA). In particular, the RQA variables determinism, entropy, and Renyí entropy K_2 are determined and their spatial patterns are compared. We comment on differences and similarities to the linear properties of FAPAR, and thus to the additional information obtained using RQA.

Recurrence Quantification Analysis in Ecosystem Research: Examples and Possibilities

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Ecosystems are often considered as prototypical complex systems. Whatever precise notion of complexity is implied here, nonstationary and nonlinear temporal dynamics and complicated spatial patterns are typical indicators. The timescale-dependent dynamics, often expressed as scaling laws, is hardly ever reproduced by process-based models. Thus, measured time series from monitoring networks are a precious non-substitutable source of information.

In this presentation, we try to elaborate on the potential of RQA in analysing time series from ecosystems. Starting with an overview and then using examples from catchment hydrochemistry, meteorology, stream hydrology and other areas, it is demonstrated that RQA captures intriguing nonstationarities in these series, related to known driving forces, ageing of measurement devices, or to unknown reasons potentially reflecting the intrinsic dynamics of the ecosystem. Using RQA measures to evaluate the performance of process-based models are also providing a challenge for the latter, which is complimentary and more rigorous than usual overall goodness-of-fit indicators.

Determining the Predictability and the Spatial Pattern of Urban Vegetation Using Recurrence Quantification Analysis: A Case Study in Shenzhen City

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The property of underlaying surface in urban area is being significantly changed due to rapid increase of population and accumulation of large amount economic elements. It is important issue of analyzing the variation of urban vegetation and its predictability for the scientific planning of the ecological landuse. In this paper recurrence quantification analysis (RQA), an extension of recurrence plots (RPs), was used to measure the predictability of Normalized Difference Vegetation Index (NDVI) series and the spatial patterns by using the SPOT-VEGETATION NDVI data with 10-day temporal resolution and 1 km spatial resolution from 1999 to 2006. The results indicate that all indices of RQA of NDVI series in study area lie between the stochastic series and deterministic series, suggesting the property of NDVI series in Shenzhen City belongs to deterministic chaotic time series. The nonlinear properties of NDVI series differ in different landuse and landcover types, and generally characterized

by the highest regularity in woodland, higher regularity in cropland, and lower regularity in built-up area, inferring impacts of human activities being as a gauss white noise on the NDVI series. Moreover, second order Rényi entropy, K_2, was proposed to indicate the long-term predictability of NDVI time series. The statistical values of K_2 in whole study area are: maximum value 0.76, minimum value 0.32, mean value 0.60, and standard deviation 0.06. The analysis of spatial autocorrelation in ArcGIS 9.2 suggests that K_2 shows a better performance for the discerning the spatial differentiation of K_2, resulting from different landuse and landcover. On the whole, spatial distribution of K_2 exhibits significant regional differentiation, characterizing by lower k_2 values, i.e., higher predictability in the northwest and southeast region with higher elevation and dense vegetation cover, and higher k_2 values, i.e., lower predictability in the middle and south resident area, suggesting human disturbance may be major driving factor for causing non-stationary dynamic characters of NDVI series. The combination of RPs and Geographical Information System is a useful approach not only in displaying the spatial patterns of RPs computing results but also in analyzing relationships among the influencing factors.

Dynamics of a Regenerative Cutting Process

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We examine the regenerative cutting process by using a single degree of freedom non–smooth model with a friction component and a time delay term.In a cutting process chaotic vibrations and chatter appearance are known to develop harmful operating conditions leading to poor final surface quality. To detect a chaotic behaviour with changing time delay we study recurrence rate as a function of embedding dimension. The resulting surface quality of the cutting has been also characterized by other parameters which are provided by recurrence quantification analysis as the determinism, laminarity and entropy.

Combined Use of Methods of Nonlinear Dynamics and Neural Networks in the Evaluation of Heart Rate Variability in Different Clinical Situations

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Cardiovascular diseases are the major cause of death in our country. Currently, a main ally to the realization of the pathophysiology studies of biological systems in the field of heart diseases is the technique known as the heart rate variability (HRV). However, the HRV has a complex behavior, making it difficult to identify patterns of specific diseases. Thus, in this work, recurrence plots of data HRV, based on measures of complexity, and the values of the indicators under review for quantification of recurrence (RQA) are being used. The classification of data in groups of diseases is performed with the use of artificial neural networks of type of multi-layered perceptron (MLP); and to compare the quality of classification of groups of patients, using the Self-Organized Maps (SOM). Present here a discussion about the forms and structures (topology) of neural networks required to classify these data.

Hot Topics in the Recurrence Plot Field

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In the last years, recurrence plot based techniques have been intensely studied and received a steep progress. For example, a recurrence based approach was proposed for the study of coupling directions or delayed synchronisation, for the effective dynamical construction of a long time-series, or as a surrogate test for couplings – just to mention some of these new developments. Meanwhile, it was mathemati-

cally proven that a recurrence plot contains the dynamics of the underlying system, and that it is possible to reconstruct a phase space trajectory from the recurrence plot. Moreover, using a recurrence plot of a measured time-series from driven system, even the driving force can be reconstructed.

Meanwhile, another method for the analysis of complex systems, the complex network theory, has received increasing attention and popularity. Both techniques, recurrence plots and complex networks exhibit astonishing similarities, as both approaches are based on a binary square matrix, either representing recurrences or links. Therefore, it is not a surprise that both techniques come together and that approaches from complex network theory have found their way into the recurrence analysis.

Introduction in the CRP Toolbox

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The practical and interactive introduction in the MATLAB CRP Toolbox enlightens the potentials and applicability of the toolbox for the analysis of various problems in different scientific fields, in particular in cardiology, cognitive science, image analysis and palaeo-climatology. The participants of the workshop will be tutored and supervised in order to be able to solve own problems with the toolbox.

Characterization of Neuronal Activity of Multielectrode Arrays using Recurrence Quantification Analysis *Poster*

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The variation of interspike spontaneous activity in a multielectrode array (MEA) has been studied using recurrence quantification analysis with the aim of characterizing and assessing the daily changes during more than one month. The results show the similarities/differences between several channels and time periods. Furthermore, cross correlation function and cross recurrence plots have been applied to analyse linear correlations between channels.

Recurrence Quantification Analysis of Stock Market Crashes

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In this paper we present results of crash time series analysis by means of Recurrence Quantification Analysis (RQA). The crash of NASDAQ 2000 was analyzed in [1]. For the present research the classical stock market crashes of 1929, 1987, 1994, 1997, 2000 and the current global financial crisis were taken. The application of RQA [2] allowed us to obtain next results. Measures of RQA are sensible to crash occurrence on financial markets. They quantitatively estimate different regimes of financial market functioning: market normal functioning; market instability that is promoted by volatility increasing; critical regime, after which the crash occurs. Thus measures of RQA allow to develop the precursor of stock market crashes. Also, measures detect the time of full market relaxation that's why it is possible to make forecast of current financial crisis ending.

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Predicting Mammal Species Richness at the Global Scale

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Coarse-scale empirical models for predicting the observed distribution of species richness based on just a few climatic variables, such as temperature and precipitation, can typically attain R2 determination coefficients around 0.8-0.9. Since the majority of these models are fitted using the regional average obtained from climatic variables, the

mechanisms underlying the distribution of species richness at the global scale are skewed towards the mean state hypothesis, that is: Increasing the available resources (sun and water) lead to more individuals (by increasing the carrying capacity) which allow greater inter-individual variations and functional specialisation into species. However, the mean state hypothesis is challenged by the disturbance hypothesis which stipulates that the temporal behaviour of climatic variables is explaining species richness better than mean estimates. Using recurrence plots metrics derived from temperature and precipitation time series for both North- and South-America, we show that climatic stochasticity and predictability are better predictors of mammal species richness than climatic means. Our results emphasise the counterintuitive idea that species rich regions are characterized by a higher climatic stochasticity and a lower temporal predictability.

Global vs. Individual Input Parameter Selection: Impacts on Analyzing Human Postural Time Series *Poster*

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RQA has many advantages for characterizing physiological and behavioral time series, which are often noisy, nonstationary, and brief. Parameter selection, for example, choosing phase space reconstruction parameters and the radius threshold for identifying recurrence of trajectories, remains challenging. The challenge is especially apparent when comparing groups with naturally different dynamics (e.g., adults vs. children), which might require, for instance, different time delay and embedding dimension choices. Changes in the parameters directly influence the magnitude of the output measures, however if the parameters are different across different groups, it may be impossible to attribute those differences to the group or to different parameters across groups. One must decide whether to employ a global set of RQA parameters for all of the time series, a more economical choice (especially for large data sets), or to identify input parameters separately for each time series. This study identified the effects of global versus individualized (trial-by-trial) parameter selection on RQA measures. A commonly employed strategy for selecting global parameters is to calculate the mean or maximum time delay, embedding dimension, and radius for a sub-set of the data and use those parameters for the entire data set. This has the potential advantage of ensuring that identified differences in the dynamics are not an artifact of differences in the parameters, but the potential disadvantage of decreasing sensitivity by using parameter values that are not optimized for any particular time series in the data set.

We used RQA to compare postural center of pressure (COP) time series of children and adults (5-8 and 18-30 years, respectively; N = 8 for each group). Subjects stood still with their eyes open and feet shoulder-width apart for 30 second trials. COP trajectories in the anterior-posterior and medial-lateral direction were recorded at 100 Hz using a force platform. RQA input parameters were selected six ways: (1) for each individual trial, (2) one set of mean values for children and one set of mean values for adults, (3) maximum values for children and maximum values for adults, (4) mean values of the combined child and adult data, (5) maximum values for the combined child and adult data, and (6) mean values obtained from three randomly selected trials of the child and adult data. For each input parameter selection, embedding dimension, delay, and radius were calculated using false nearest neighbors (Kennel et al., 1992), average displacement (Rosenstein et al., 1994), and radius selection (Riley et al., 1999) methods, respectively. Percent recurrence for all input parameter selection methods ranged from 1.1-4.2%, values within the suggested range of 1-5% for human postural data (Pellecchia & Shockley, 2005). A main effect of group was observed in percent determinism, linemax, entropy, laminarity, and trapping time in the medial-lateral direction and in all output variables in the anterior posterior-direction ($p < 0.05$), showing that children and adults have different postural dynamics. Parameter selection methods showed no main effects ($p > 0.05$), with the exception of trapping time in the medial-lateral direction and percent determinism and laminarity in the anterior-posterior direction ($p < 0.05$). No group by input parameter method interactions were observed in either direction ($p > 0.05$), showing that group differences did not depend on the input parameter selection method. The parameter selection methods yielded largely equivalent results, even though the groups we compared exhibited distinct postural dynamics. Although the generality of these results must be more fully explored, they suggest using global parameters may be an efficient method without sacrificing sensitivity or accuracy.

Time Averaged Properties Along Unstable Periodic Orbits in some Systems of Differential Equations

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By employing three chaotic systems described by ordinary differential equations, we compare time-averaged properties of a set of UPOs and those of a set of segments of chaotic orbits. For every chaotic system we study, the distributions of a time average of a dynamical variable along UPOs with lower and higher periods are similar to each other and the variance of the distribution is small, in contrast with that along chaotic segments. The distribution seems to converge to some limiting distribution with nonzero variance as the period of the UPO increases, although that along chaotic orbits inclines to converge to a delta-like distribution. These properties seem to lie in the background of recent results in fluid mechanics which show that a few UPOs with low periods can give good mean statistical properties in dynamical systems.

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Confidence Bounds of Recurrence-Based Complexity Measures

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Recurrence quantification analysis (RQA) has become an established tool for data analysis in various research areas. The complexity measures the RQA provides have been useful in describing and analysing a broad range of data. The RQA is known to be rather robust to noise and nonstationarities. Yet, one key question in empirical research concerns the confidence bounds of measured data or any derived quantities. In this talk we suggest a method for estimating the confidence bounds of recurrence-based complexity measures. We will show that this method allows us to investigate EEG measurements obtained during cognitive tasks (ERPs) on the scale of single measurements.

Nonlinear Assessment of Manganese-enhanced Magnetic Resonance Images with Recurrence Quantification Analysis

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Calcium ion (Ca^{2+}) transport dysfunction is a major component in the development of cardiac arrhythmias and/or heart failure. Direct, noninvasive, in vivo monitoring of intracellular Ca^{2+} activity is not currently possible. However, recent studies have shown that manganese ion (Mn^{2+}) serves as an analog/surrogate biomarker for Ca^{2+} since both ions use the same channels to move in and out of the myocardial cell. Therefore, manganese-enhanced magnetic resonance imaging (MEMRI) may be an appropriate method for indirectly assessing alterations in relative Ca^{2+} content via altered Mn^{2+} content in heart tissue. Recurrence quantification analysis (RQA) has been shown to assess the dynamic physiological characteristics contained in 2-D and 3-D images. Analyzing MEMRI with RQA may better quantify Mn^{2+} content by measuring the variation in signal intensity for each pixel in the nonlinear domain. To test this notion, pixel data taken from pre-existing T1 maps of MEMRI in healthy adult mice are currently undergoing RQA. The aim is to demonstrate that the nonlinear RQA indices better detect differences among nine experimental treatment groups compared to the standard linear indices typically used to measure Mn^{2+} content in T1 maps of cardiac MEMRI. The long term goal of this project is to develop at least one of the MEMRI-RQA indices into a sensitive imaging biomarker for understanding, diagnosing, and treating detrimental cellular activities that promote heart disease in people.

Complex Networks from Recurrence Plots and Time Delay Embeddings

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We describe a transformation from the time delay embedding to a complex network. We show that the structure of the complex network (and in particular the motif frequency distribution) depends on the nature of the underlying dynamics. For example, the networks generated from low dimensional (one positive Lyapunov Exponent) chaos are structurally similar, and yet distinct from those generated from hyper-chaos or a noisy periodic orbit.

An obvious adjunct to this method is to generate a complex network directly from the recurrence plot. Nonetheless, we show that the two methods are distinct. Using the recurrence plot to generate a complex network offers a new way to understand the structural properties of the recurrence plot, and yet the complex networks generated from the time delay embedding provide insight not available from recurrence methods alone.

From Complex Networks to Time Series Analysis and Viceversa: Application to Metabolic Networks

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The main idea of this work is to develop a general framework to move between complex network and nonlinear time series analysis and to explore the new research avenues that this change of prospective, in observing the system, could provide for its understanding. In addition to standard case studies such as random, periodic and chaotic time series; and random, cyclic, scale free networks, an application to metabolic networks will also be presented.

Real-time Computation of Recurrence and Phase Synchronisation in Social Applciations

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Social interaction is one of the fundamental components of human life. Social intelligence, understood as the ability of dealing effectively with social interaction, is a typical human ability, widely studied in psychology, which is receiving a growing interest from the HCI scientific community. The possibility of endowing machines with social skills, such as the ability of analysing the social behaviour of the users and showing empathy, would allow the development of innovative human-machine interfaces with a significant impact for both research and industry. A recent research direction at our Lab consists of developing computational models and algorithms for the analysis of social behaviour of subjects in non-verbal social interaction. Music has been chosen as an ideal test-bed for research in an ecological framework, since it is an intrinsically social activity and the mechanisms music exploits for conveying emotion are mostly non verbal. This talk will discuss the results obtained in a pilot experiment, where Phase Synchronization of two violin players performing a J.S. Bachs canon in different conditions has been analyzed by means of Recurrence, Recurrence Plots, and Recurrence Quantification Analysis. Phase Synchronization is considered as a low-level social signal and it is used as baseline to indirectly measure empathy and dominance in small groups of users. Results from the experiment are used to develop applications in user-centric media and active music listening, e.g., in the framework of the EU-ICT Project SAME (Sound And Music For Everyone, Everyday, Everywhere, Every way, www.sameproject.eu). Real-time implementation of the Recurrence Quantification Analysis is achieved in the EyesWeb XMI Social Signal Processing Library (www.eyesweb.org).

Temporal Patterns in Text Reading

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The research presented investigates the temporal dynamics involved in reading an ongoing flow of text. Reading times are obtained from a self-paced reading procedure. Participants with varying degrees of reading ability were tested in three different modes of text presentation: word-by-word, phrase-by-phrase, or sentence-by-sentence. Individual performances are analyzed with power spectrum analysis obtained from Fast Fourier Transformation and Recurrence Quantification Analysis (as proposed by Zilbut & Marwan, 2008). Cross Recurrence Quantification Analysis is used to

quantify differences and commonalities across tasks and readers.

Recurrent Memories of Joe Zbilut and His Remarkable Scientific Career

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Joseph Zbilut passed from this life on a snowy Saturday afternoon in Skokie, Illinois this past January 10th. Family, friends and colleagues in his department as well as those from around the world were shocked at the untimely death of this 60-year-old husband, father, clinician and scientist. Ever curious and highly intelligent, Joe was as conversant in Slavic languages, psychology, theology and ethics as he was in physiology, chemistry, mathematics and physics. An affable fellow, tolerant of contrary viewpoints, Joe was a patient mentor to many students, peers and a growing list of investigators from numerous disciplines. In this presentation Joes remarkable life will be recounted in both words and pictures with particular emphasis on his fathering of recurrence quantifications back in 1992. Joe continues to be sorely missed, but his scientific contributions resound through the literature as well as in the personal and professional lives he touched for the better.

The Importance of Recurrent Singularities in Cardiac Dynamics

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Normal physiological systems are characterized by nonlinearities, nonstationarities and noise in time. Such living systems are also discontinuous in time in the sense that dynamical fluctuations of system variables (trajectories) are repeatedly interrupted by static pauses (singularities). The punctuation of moving deterministic processes by intermittent and recurring stochastic stops helps maintain system stability in noisy, real-world environments. That is, piecewise determinism conveys dynamical flexibility to systems navigating familiar (healthy) or unfamiliar (diseased) territories, the so-called principle of homeodynamics. In this presentation, examples will be taken from human cardiac electrical activities including the electrocardiogram (ECG), derived RR intervals, and atrial electrograms. Cardiac singularities, defined as isopotential lines (flat lines) in bipolar recordings, register as rectangular blocks in recurrence plot representations. Three such singularities characterize the PQRST waveforms of the normal ECG including the PR interval, the ST segment, and the TP interval. During abnormal atrial fibrillation, however, singularities become abbreviated or even obliterated. Besides the classical regular versus irregular fibrillations found in atrial electrograms, evidence is accumulating that there is a full spectrum of fibrillation patterns depending upon the number and duration singularities in disease. Quantification of singularities at specific atrial sites may have important clinical relevancy in blocking atrial dysrhthmias by reinserting normal singularities into the system.

Extracting Indirect Coupling by Means of Probabilities of Recurrence: Revisited

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The identification of the coupling direction from time series taking place in a group of interacting components is an important challenge for many experimental studies. We propose a method to uncover the coupling configuration by means of conditional probabilities of recurrence, which was originally introduced to detect and quantify the weak coupling direction between two interacting systems. Here, we extend this approach to the case of multivariate time series, where the indirect interaction is present. We test our method for three Lorenz systems coupled via delays. Furthermore, some important issues about the implementation of this approach will be also discussed.