conference program

Scientific and Organisational Committee

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Aims

Advances in recurrence quantification analysis (RQA) and its applications in many fields of science and technology are accumulating at a very rapid rate. The Fifth International Symposium on Recurrence Plots will provide the community of recurrence analysis users a focused venue for communication and collaboration that cuts across interdisciplinary boundaries. Recurrence plots and RQA have proven to be valuable data visualization and analysis tools in the study of complex, time-varying dynamical systems in biology, mathematics, neuroscience, kinesiology, psychology, physiology, engineering, physics, geosciences, linguistics, finance, economics, and other disciplines. Consistent with this, the meeting will have a highly interdisciplinary focus. Special areas of emphasis will include applications to biological systems and the analysis of coupled systems using cross-recurrence methods. The symposium will be held August 14-16, 2013 at the Water Tower Campus of Loyola University Chicago. We hope everybody will enjoy the meeting and find new inspirations and cooperations.

Location

The symposium will be held at the the Water Tower Campus, 2 blocks from Michigan Avenue's Magnificent Mile and a short walk or ride from major Chicago attractions.

Lectures

The meeting rooms are in the Corboy Law Center on the 25 E. Pearson St. (#3 in the map).

The lecture room is 206. Posters and discussion will be in room 207 (adjacent rooms).

Practical Workshop

In the symposium, several approaches of analysing recurrences can be practically applied to one's own data under supervision. Instructive presentations introduce in the *RQA software* and the *CRP toolbox*. A comprehensive RQA, study of interrelations, synchronisations or dynamical invariants can be provided.

The practical workshop will take place in the computer lab 710 of the Corboy Law School.

Lunch

Lunch will be served at Nina's café in the lower level of Corboy Law School.

Social Events

Thursday, August 15

For Thursday, 19:30, we have organised an optional *Millennium Park Event* with a Picnic Dinner and Jazz Concert with Dana Hall and Black Fire. Please complete your order for your picnic meal with Connie Webber at the registration desk.

Friday, August 16

For Friday evening we have arranged an optional Chicago Architecture River Cruise. The meeting point is at the dock at 17:00. The boat leaves 17:30. The costs for conference participants is US$20, for guests US$40. Please pay the tour at Connie Webber at the registration desk.

After the boat trip, consider trying a Chicago style deep dish pizza at Gino's at 162 E. Superior Street (about 12 blocks north of Millennium Park and close to Michigan Ave.). More information on Ginos Pizza will be provided in the conference packet.

Internet Access

Open a web browser and go to

`netreg1.luc.edu`

(at the Lake Shore Campus) or

`netreg2.luc.edu`

(at the Water Tower Campus) in order to register your device. Follow the "REGISTER NOW" link and select the "Loyola Guests" option. Enter the following Conference ID and Conference Password:

Conference ID: `FISymposium`
Conference Password: `lu449781`

Finish the registration by entering your personal information.

Presentations

The speakers have to upload their presentation to the computer in the lecture hall in advance of their talk (in the morning of the day of their talk). The time for the talk is 17 min, plus 3 min discussion (invited talks are 40 min, plus 5 min discussion).

Both MacOS and Windows machines will be available, installed with standard presentation software (PowerPoint, Acrobat, Preview, and Keynote). You may also bring your own computer or presentation device provided that it is fitted with the appropriate VGA output and that you are capable of installing and testing the machine prior to the scheduled session time.

Collection of Presentations

The symposium will adhere to the rules of good scientific and ethical practice. This means that it is not allowed to copy presentations from the presentation computer. It is also forbidden to take photographs of oral presentations and presented posters without explicitely given permission of the presenter.

We will provide a platform for sharing the presentations after the symposium in a secure way (password protected web site, secured pdf documents). We will ask the authors of the presentations to give a written permission for this purpose during the symposium. Without such a written permission, presentation files on the presentation computer will be deleted after the symposium.

Note

The symposium will adhere to the rules of good scientific and ethical practice. This means that it is not allowed to copy presentations from the presentation computer. It is also forbidden to take photographs of oral presentations and presented posters without explicitely given permission of the presenter.

Program

Tuesday, August 13th

18:00 Registration reception (until 21:00)
Baumhart Residence Hall, Foyer

Wednesday, August 14th

8:00 Registration & pay for registrations
Corboy Law School, Classroom #207

Introduction

9:00 **Charles L. Webber, Jr.**:
Opening Greetings
9:15 **Norbert Marwan**:
Introduction Lecture Potential Pitfalls in Recurrence Plot Analysis

Methodological Aspects

9:30 **Hui Yang**:
Keynote Lecture Multiscale analysis of recurrence patterns
10:15 Oleg Granichin, Olga Granichina, **Vladimir Kiyaev**:
Recurrence plots and randomization possibilities

10:35 *Coffee/tea break*

11:10 **Elbert E. N. Macau**, Laurita dos Santos, Jose Roberto C. Piqueira:
Quantifying the complexity in a recurrence plot
11:30 **Leonardo Lancia**:
Application of recurrence and cross recurrence analysis to the study of nonstationary signals from speech production
11:50 **Ioana Cornel**, Alexandru Serbanescu, Angela Digulescu, Florin-Marian Birleanu, Ion Candel:
Recent advances in non-stationary signal processing using recurrence plots
12:10 J.H. Feldhoff, **R.V. Donner**, J.F. Donges, N. Marwan, J. Kurths:
Geometric signatures of complex synchronization scenarios – A recurrence network perspective

12:30 *Catered Lunch: Nina's café in the lower level of Corboy Law School*

14:00 **Stephan Spiegel**, Johannes-Brijnesh Jain, Sahin Albayrak:
A Recurrence Plot-based Distance Measure for Time Series Clustering

14:20 **Paul E. Rapp**, David M. Darmon, Christopher J. Cellucci:
Quadrant Scanning Recurrence Diagrams: Identifocation of Transitions in Central Nervous System Behavior

14:40 **Dan Mønster**, Jacob Kjær Eskildsen, Dorthe Døjbak Håkonsson:
Robustness of cross-recurrence results in a social interaction experiment

15:00 **Paxton, A.**, Dale, R.:
B(eo)W(u)LF: Facilitating multi-level recurrence analysis in language

15:20 *Coffee break*

Applications in Physiology I

16:00 **Yu Yao**, Michael Schiek:
Improving reliability of recurrence plot analysis through nonlinear separation of signal components

16:20 **D. C. Soriano**, L. F. S. Uribe, F. I. Fazanaro, R. Suyama, G. Castellano, R. Attux, E. Cardozo:
A Recurrence-Based Feature Extraction Approach for Brain-Computer Interface Systems

16:40 Alejandro Aguado, Oscar Infante, **Claudia Lerma**:
Recurrence plot analysis of heart rate and systolic blood pressure: a strategy for embedding parameters estimation

Thursday, August 15th

8:50 **Charles L. Webber, Jr.**:
Welcome & miscellaneous announcements

Applications in Physiology II

9:00 **Andrew Marino**:
Keynote Lecture Recurrence Quantification Applied to the Analysis of Brain Electrical Activity

9:45 **S. Carrubba**, A. A. Marino:
RQA detects nonlinear determinism in the EEG

10:05 **Charles L. Webber, Jr.**, Zhihong Hu, Xiuzhen Duan:
Recurrence Categorization of Immunohistochemical Stainings of Her-2/neu in Breast Cancer

10:25 *Coffee/tea break*

Applications in Earth Science

11:00 **Holger Lange**, Sven Boese:
Recurrence quantification and recurrence network analysis of remote sensing data
11:20 Group photo shoot
11:30 Poster Session

12:30 *Catered Lunch: Nina's café in the lower level of Corboy Law School*

Workshop

14:00 **Practical Tutorials**
CRP Toolbox for Matlab, RQA Software
Computer lab 710 of Corboy Law School

19:30 *Social Event: Millenium Park, Picnic Dinner & Jazz Concert*

Friday, August 16th

8:50 Welcome & miscellanous announcements

Applications in Psychology

9:00 **Rick Dale**:
Keynote lecture Recurrence in language: from sounds to meanings
9:45 **Daniel Angus**, Andrew Smith and Janet Wiles:
Current Progress in Conceptual Recurrence Plotting
10:05 **William J. Bosl**, Adam Bates, Iván Sánchez Fernández, Tobias Loddenkemper:
Biomarkers for Neuropsychiatric Disorders from Recurrence Plot Analysis

10:25 **Riccardo Fusaroli**, Kristian Tylén:
Linguistic Dialog: individual processing, interactive alignment or interpersonal synergy?

10:45 *Coffee/tea break*

11:20 **James Dixon**:
Keynote lecture RQA applications to the micro-development of cognitive structure

12:05 **Carlos A. Torre**:
Hearts & Minds: Physiology, Emotions, & the Readiness-to-Learn

12:25 **David W. Vinson**, Rick Dale:
How CRQA can shed light on two-person anticipatory systems

12:45 *Catered Lunch: Nina's café in the lower level of Corboy Law School*

13:30 Poster Session

Applications in Economics and Financial Markets

14:30 Catherine Kyrtsou, Anastasios Malliaris, **Christina Mikropoulou**:
Informational content of Monday returns and the role of dynamic invariants

14:50 **Patrick M. Crowley**, Chris I. Trombley:
Is US State Macro Data Synchronous?

15:10 **Catherine Kyrtsou**, Angeliki Papana, Costas Vorlow:
Further insights on the connectivity between money supply and interest rates

15:30 **Charles L. Webber, Jr.**:
Closing

17:00 *Chicago Architectural Boat Tour Excursion*

Poster

Poster 1 **Jose-Ruben Luevano**:
Spectra of recurrence times in the chaotic region of the logistic map

Poster 2 **Aloys Sipers**, Paul Borm, Ralf Peeters:
Unthresholded recurrence plots for complex-valued representations of narrow band signals

Poster 3 **Aloys Sipers**, Paul Borm, Ralf Peeters:
Redundancy and the information content of lines in unthresholded recurrence plots

Poster 4 **Ashley E. Walton**, Brian A. Eiler, Rachel W. Kallen, Steven J. Harrison, Michael J. Richardson:
Quantifying degree and directionality of coupling using cross recurrence analysis

Poster 5 Joshua Gordon, Vijaya Patil, Andrew Keller, Charles L. Webber, Jr., **Morris Fisher**:
Classification of F-Waves by Coupling Principle Component Analysis with Recurrence Quantifications

Poster 6 **Hortensia Gonzalez**, Oscar Infante, Claudia Lerma:
Recurrence plot analysis of the response to active standing of heart rate, systolic blood pressure and systolic blood volume

Poster 7 **Singh G.**, Lu H., Avitall B.:
Recurrence Quantification Analysis of Clinical Data

Poster 8 **Ali Keshavarz Panahi**, Ikechukwu Ohu, Sohyung Cho, Ahmed M. Zihni, Michael M. Awad:
Can Fatigue Levels in Laparoscopic Surgery be deduced through Recurrence Plots and Disorder Index Analysis?

Abstracts

Current Progress in Conceptual Recurrence Plotting

Daniel Angus, Andrew Smith and Janet Wiles
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At the 2011 Recurrence Plotting Symposium we introduced delegates to the Conceptual Recurrence Plotting technique (Angus, Smith, & Wiles, 2011). Unlike previous recurrence plotting approaches for language and conversation (Dale & Spivey, 2006; Richardson, Dale, & Kirkham, 2007), conceptual RPs model speech utterances at a semantic level such that recurrence can occur between conceptually related, yet symbolically different terms, for example "cat" will match "dog" if they are both used in a similar context.

Since the last symposium we have developed this approach further (Angus, Smith, & Wiles, 2012a), through broadening the technology to include RQA style metrics (Angus, Smith, & Wiles, 2012b) and also through application and validation across different data domains (Angus, Rintel, & Wiles, 2013). Now called "Discursis", a neologism of the Latin Discursus, this software platform is allowing social scientists to analyse conversation and other temporally organized text data in ways that were not previously possible. Discursis enables analysts to quickly overview an entire text and see-at-a-glance the turn-taking dynamics (who speaks when and for how long), the conceptual content of the text over time, and regions of conceptual coherence over short (turn-turn), medium (10-20 turn) and long (whole conversation) time scales. While Discursis can be used to provide an at-a-glance overview of a whole interaction, it can also be used for locating and representing sections of interaction where participants engage in shared concepts, repeat their own content, or lack conceptual coherence.

Previous research has applied Discursis in the analysis of a range of communication behaviors including doctor-patient interactions (Angus, Watson, Smith, Gallois, & Wiles, 2012), phone conversations, and aircraft transcripts (Angus, Smith, et al., 2012b). Discursis has also been used to analyze and interpret the recurrence of conceptual content of interviews conducted on the Australian TV talk show Enough Rope (Angus, Smith, et al., 2012a, 2012b). These analyses demonstrate the utility of the tool for determining the global and local structure of interviews.

In this talk we will present examples of findings from these studies and also discuss future directions for the Discursis software including new domains for analysis, information visualization approaches, and the incorporation of video and audio data.

Biomarkers for Neuropsychiatric Disorders from Recurrence Plot Analysis

William J. Bosl, Adam Bates, Iván Sánchez Fernández, Tobias Loddenkemper

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Background. The brain is a complex dynamical system. This is not an analogy or just a model: the brain is a complex dynamical system by definition. Bridging the gap between biological and psychological descriptions of cognitive function and mental disorders is the continual dance of electrical patterns supported by the neural network in the brain. The observable psychological characteristics that define normal and abnormal behavior are necessarily related to recurrent patterns of neural activity in the brain, but in perhaps complicated ways that are not easy to discern by traditional methods of cognitive neuroscience. Predictive analytics may be a powerful way to discover relationships between brain electrical activity and behavioral activity. We illustrate this approach to search for biomarkers of epilepsy, one of the most common neurological disorders in children. Epilepsy is the predisposition of a given brain to have seizures during normal activities that do not evoke seizures in most people. As there are not direct biomarkers of this predisposition, the diagnosis of epilepsy relies on the clinical detection of repeated seizures.

Hypothesis. Our hypothesis is that multiresolution recurrence plot analysis, which in principle characterizes all the relevant dynamics of a complex system, extracts dynamical variables that contain information to enable a predisposition to have seizures to be detected using relatively short inter-ictal EEG segments.

Methods. Multiresolution decomposition of EEG signals was performed. Recurrence quantitative analysis was applied to each channel of scalp EEG data to compute multiscale curves for each RQA variable. Machine learning algorithms were applied to these in a cross validation study to determine the classification accuracy of multiresolution recurrence plot values for distinguishing absence and Rolandic epilepsy patients from controls.

Results. Significant classification accuracies over 90% were obtained using this approach. Multiple resolution analysis was essential for classification, as values on a single resolution, including the original EEG data, were not sufficient for accurate classification.

Conclusions. Multiresolution recurrence plot analysis of the electroencephalographic signal extracts feature sets that are po-

tentially useful biomarkers for the detection of epilepsy even when overt epileptiform activity is not apparent in the EEG trace. We conclude that multiresolution recurrence plot analysis extracts information from EEG signals that may be useful for detecting the presence of absence epilepsy in inter-ictal EEG samples.

RQA detects nonlinear determinism in the EEG

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Introduction. A main limitation regarding essentially all methods for time-series analysis of biological signals, both linear and nonlinear, is the requirement of data stationarity. We employed RQA-based methods to overcome this difficulty. The validity of the methods was demonstrated in model systems. Then the methods were applied to the analysis of electroencephalographic time series (EEG) to help solve on of the central problems in biology whether environmental electromagnetic fields (EMFs) (power lines, mobile phones) can alter brain electrical activity in human subjects. Model. To mimic determinism occurring in the EEG in response to a sensory stimulus, linear and nonlinear signals were added to baseline EEG, and the ability of RQA (percent recurrence, %R, and percent determinism, %D) and conventional linear analysis to detect the added determinism was systematically evaluated.

Laboratory Studies. EEGs were recorded from human subjects during three experimental sessions: during exposure to an EMF (1 G, 60 Hz): during exposure to an audible sound (positive control); during exposure to a null stimulus (sham exposure). Stimuli were applied for 2 seconds, with a 5-second inter-stimulus period (trial) while EEG were recorded continuously from scalp electrodes. Exposure and control epochs were embedded in a five-dimensional phase space, using a time delay of 5, and recurrence plots for each of the epochs were generated and quantified using %R and %D. Statistical comparisons between exposure and control epochs were performed by means of the paired t test.

Results. RQA but not linear analysis permitted detection of the added nonlinear deterministic activity. RQA consistently detected EMF-induced brain potentials which could not be observed using linear methods. Detection of the effects occurred either by an increase or a decrease in %R or %D, depending on the particular subject, the electrodes location and the applied stimulus.

Conclusion. RQA can reliably be used to characterize nonlinear determinism in the EEG, and to assess whether EEGs obtained from a subject under different conditions differed from each other.

Recent advances in non-stationary signal processing using recurrence plots

Cornel Ioana, Alexandru Serbanescu, Angela Digulescu, Florin-Marian Birleanu, Ion Candel

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Our paper highlights the main results of our research in the field of recurrence plot analysis in non-stationary signal processing in the last five years obtained in real applications sustained by some theoretical contributions. Firstly, we studied the changes that take place in phase space reconstruction for the main reconstruction parameters (the delay, the embedding dimension) when the axis time of the time series is rescaled. Furthermore, we introduced the angular distance in the phase space reconstruction resulting a recurrence matrix which becomes practically immune to slow amplitude variations in the analyzed signal.

We showed that phase space trajectory reconstruction by time-delay embedding is essentially equivalent to an analysis of the signal on time overlapped windows. Besides it we also introduced other metrics, i.e., the dynamic range distance and the scalar product distance. We made use of them in defining generalizations for the autocorrelation function and for the signal derivation operations. Both of them proved to be more robust to the noise than the classic counterparts.

Is US State Macro Data Synchronous?

Patrick M. Crowley and Chris I. Trombley

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Within currency unions, there should be a high synchronicity between the constituent parts of the union. The US is probably one of the longest standing monetary unions in existence, and is recognized by economists as having a high degree of synchronicity in economic dynamics between US States due to the fiscal sovereignty of the US federal government and a common culture. In this paper we take US State macro data – namely real Gross State Product (GSP), the GSP deflator and unemployment data – and use techniques relating to recurrence plots to measure the degree of synchronicity of movement over time. The data is annual data taken from US official sources, with both real GSP and GSP deflators are expressed in log change form, and unem-

ployment expressed in a rate form. The initial results show that US State data appears to be synchronous at certain points in the business cycle, notably during downturns, and also sometimes during the final stages of growth cycles. A secondary is also obtained that synchronicity in the US appears to have increased over time in certain specific regions.

Recurrence in language: from sounds to meanings

Rick Dale

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Human language is a complex, and sequentially-ordered, behavior. It has many layers of organization, often referred to as "duality of patterning" and "generativity". It is also multimodal, in that any performance of language typically invokes many types of behavior. Consider face-to-face interaction. It involves the deployment of low-level behaviors, like social eye gaze, and higher-level behaviors, such as the sequencing of ideas during conversation – and everything in between. Recurrence analysis can shed light on all of these processes – how they are structured in time – and perhaps even connections between them. I first showcase past work from many researchers studying different levels of organization, from sounds to meanings. I then discuss some recent work suggesting that multiscale analyses will be crucial for uncovering the dynamics of human behavior during language learning and use. Recurrence quantification could be a central toolkit in this fundamental problem of understanding human linguistic behavior, and the control processes that underlie it.

RQA applications to the micro-development of cognitive structure

James A. Dixon

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Developmental systems theory, particularly the work of Gilbert Gottlieb, offers a theoretical framework for understanding development in biological systems. A central thesis of this approach is that development is characterized by a complex web of non-stationary causal relations among multiple, spatiotemporal scales. Evidence in support of this thesis can be found in organisms from all phyla. For higher-order, complex organisms, such as humans, the number of relevant scales is unknown, may be quite large, and may change over time. One approach to investigating development in humans, given these challenging constraints, is to collect data at a very fast rate, decompose the time series into temporal scales, and examine the causal relations amongst them. I will discuss the application of this approach to the development of a new cognitive structure in children using a simple problem solving task. The results show that the macro-scale change in cognitive structure is predicted by changes in the causal relations amongst the micro-scales. The implications for modeling development with recurrence methods and related techniques will be discussed.

Geometric signatures of complex synchronization scenarios – A recurrence network perspective

J. H. Feldhoff, R. V. Donner, J. F. Donges, N. Marwan, J. Kurths

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Synchronization between coupled oscillatory systems is a common phenomenon in many natural as well as technical systems. Varying the coupling strength often leads to qualitative changes in the dynamics exhibiting different types of synchronization. Here, we study the geometric signatures of coupling along with the onset of generalized synchronization (GS) between two coupled chaotic oscillators by mapping the systems' individual as well as joint recurrences in phase space to a complex network. For a paradigmatic continuous-time model system, we show that the transitivity properties of the resulting joint recurrence networks display distinct variations associated with changes in the structural similarity between different parts of the considered trajectories. They therefore provide a useful new indicator for the emergence of GS.

Further reading: J.H. Feldhoff et al., EPL 102, 30007, 2013

Classification of F-Waves by Coupling Principle Component Analysis with Recurrence Quantifications *Poster*

Joshua Gordon, Vijaya Patil, Andrew Keller, Charles L. Webber, Jr., Morris Fisher

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Properly interpreted F-waves have proven to be useful clinical markers for a variety of nerve dysfunctions. F-waves are inherently variable and arise from non-linear and non-stationary processes. We postulated that recurrence quantification analysis (RQA) coupled with principle component analysis (PCA)

would be useful in differentiating patterns of F-wave abnormalities. Patients with polyneuropathies as determined by history, physical examination, and electrodiagnostic (EDX) information seen in the Clinical Neurophysiology Laboratories at the Hines VA Hospital were recruited for the study. Tibial F-waves were recorded from the abductor hallucis muscle using a standard protocol. These F-waves were subjected to RQA from which eight non-linear variables were derived for each subject. Recurrence variables from all patients were assembled into a large matrix and normalized before being subjected to PCA. Finally, by plotting the first principle component as a function of the second, the five patients and four controls could be partitioned into two separate clusters. These results underscore the potential of coupled RQA and PCA in providing a more meaningful classification of peripheral neuropathic dysfunctions than is presently available.

Linguistic Dialog: individual processing, interactive alignment or interpersonal synergy?

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In this paper we employ Recurrence Quantification Analysis (RQA) to compare the efficacy of three psycholinguistic models – i) individualist, ii) interactive alignment, and iii) interpersonal synergy – in assessing the quality of linguistic coordination. We operationalize the models' predictions through the notion of "structural organization", that is, the extent (L) and complexity (ENTR) of stable behavioral patterns as measured by Recurrence Quantification Analysis.

According to the individualist model, individuals make themselves predictable to decrease the complexity of the interaction (Vesper, van der Wel, Knoblich, & Sebanz, 2011). Following this line of thinking, the structural organization of individuals' behavior should be the best predictor of the interaction's outcome. According to the interactive alignment model, mutual understanding is reached through reciprocal imitation of linguistic behavior (Pickering & Garrod, 2004). That is, the structural organization between individuals' behavior (CRQA) should be a better predictor of the interaction's outcome. According to the interpersonal synergy model, interactional routines are developed at the level of the interaction, defining recurring roles which might be indifferently enacted by the one or the other interlocutor (Fusaroli, Raczaszek-Leonardi, & Tylén, accepted). Thereby, the structural organization of the overall interaction (not discriminating between interlocutors) should be the best predictor of the interaction's outcome.

We compare these predictions on lexical, prosodic and speech/pause behaviors in an experimentally elicited corpus of joint decision-making (Bahrami et al., 2010), employing a combination of supervised machine learning and Bayesian Information Criterion estimations. The synergy model turns out to be the most adequate in predicting the efficacy of linguistic coordination in all analyses. This suggests that, while currently under-investigated, patterns at the level of the interaction – e.g., interactional routines and complementary dynamics – play a crucial role in coordination, integrating and constraining alignment and individual behaviors. The study paves the way for a systematic use of RQA in the investigation and manipulation of the components of linguistic interpersonal coordination.

Bahrami, B., Olsen, K., Latham, P. E., Roepstorff, A., Rees, G., & Frith, C. D. (2010). Optimally interacting minds. Science, 329(5995), 1081-1085

Fusaroli, R., Raczaszek-Leonardi, J., & Tylén, K. (accepted). Dialogue as interpersonal synergy. New Ideas in Psychology

Pickering, M. J., & Garrod, S. (2004). Toward a mechanistic psychology of dialogue. Behavioral and Brain Sciences, 27(02), 169-190

Vesper, C., van der Wel, R. P., Knoblich, G., & Sebanz, N. (2011). Making oneself predictable: reduced temporal variability facilitates joint action coordination. Experimental brain research. Experimentelle Hirnforschung. Experimentation cerebrale, 211(3-4), 517-530

Recurrence plot analysis of the response to active standing of heart rate, systolic blood pressure and systolic blood volume *Poster*

Hortensia Gonzalez, Oscar Infante, Claudia Lerma

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Backgroud: Recurrence quantitative analysis (RQA) indexes of beat-to-beat heart rate (HR) and systolic blood pressure (SBP), have helped to understand the dynamical response to active standing. The peripheral blood volume is another variable of the cardiovascular control system with a crucial role during active standing, since re-distribution of blood volume is necessary to counteract the gravity and provide enough blood supply to vital organs. Beat-to-beat systolic blood volume (SBV) time series are useful to study the cardiovascular control. However, there are no previous reports of the SBV dynamical response to active standing.

Aims: To identify the dynamical response of SBV to active standing though comparison of RQA indexes evaluated during supine position (resting) and during active standing.

Methods: Non-invasive blood pressure recordings were obtained from 19 healthy volunteers (ages between 20 and 40 years old) during supine position and active standing. Time series of HR, SBP and SBV were obtained during 15 minutes in each position. Embedding delay and embedding correlation were estimated with autocorrelation function and false nearest method, respectively. Recurrence plots were obtained with fixed recurrence rate $< 7\%$ and embedding dimension = 10 (estimated dimension was < 10 in all time series). Normal distribution of RQA indexes was tested with Kolmogorov-Smirnov tests. Mean values of the RQA indexes were compared between supine position and active standing with paired t tests. A p value < 0.05 was considered statistically significant.

Results: In response to active standing there was no change in embedding dimension of all variables, but HR and SBV embedding delay increased significantly. In HR, active standing caused increment in laminarity, trapping time, recurrence time of the first type (T1) and recurrence time of the second type (T2). In SBP, the only changes in response to active standing were: decrease in mean diagonal length and longest diagonal length, and increase in T1. In response to active standing, SBV showed increase in laminarity, T1 and T2.

Conclusions: The dynamical response of SBV to active standing indicates that laminar states of SBV occur more often when facing this physiological challenge. There were similarities in the response of SBV and HR, but the response of RQA indexes was not identical in the 3 evaluated variables. This suggests that despite the known high correlation between these 3 variables, the cardiovascular control exerts different influences on them in response to active standing.

Can Fatigue Levels in Laparoscopic Surgery be deduced through Recurrence Plots and Disorder Index Analysis?

Ali Keshavarz Panahi, Ikechukwu Ohu, Sohyung Cho, Ahmed M. Zihni, Michael M. Awad

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Minimally invasive surgery (MIS) is considered a difficult surgical procedure to develop expertise in due to its complexity, compared to traditional open surgery. Hence, objective and quantitative skills assessment measures are highly needed, which can also serve as basis for evaluating surgical training programs, with unbiased feedback. We thus propose in this study a most objective, efficient, quantitative and novel skills assessment measure, Fatigue Analysis, which is in turn based on recurrence analysis. The preliminary data used were collected from the performance of twelve different laparoscopic surgical procedures by an expert surgeon at the Washington University School of Medicine, St. Louis, Missouri. One of the best and most objective means of deducing muscle activity is through electromyography (EMG) data, which are either obtained via surface electrodes, or intramuscularly. In our experiments, data collection was done using the former. Pairs of EMG electrodes were attached to eight muscles groups including right and left bicep, tricep, deltoid and trapezius. The EMG data were recorded using a CleveMed software program (Great Lakes NeuroTech. Inc). The time series data collected were processed and classified using custom-written MATLAB programs, while Recurrence Plots were applied to provide deterministic structures to the Fatigue Analysis. In creating the recurrence plots, Visual Recurrence Analysis (VRA) and CRP-Toolbox were applied and used for constructing recurrence point's matrices. Then, the Intensity Analysis approach is implemented on the recurrence matrix in order to quantify the deterministic characteristics of EMG data. To perform intensity analysis, several techniques like Window Sliding, Probability Density Function (PDF), White Gaussian Noise (WGN), and Max-Norm method are used. Finally, a measure called Disorder Index (DI) was driven to quantify the level of determinism in the patterns obtained from the EMG data. In order to compare surgical performance over time, to study the effects of fatigue, the EMG data related to the first and last 10 minutes of each surgical procedure were analyzed for each muscle group. Also, based on different laparoscopic cases with different completion times, the DI values for each muscle group during the first and last 10 minutes of a surgical procedure were studied. Additionally, the effects of fatigue on the muscle groups of the right and left segments of the human body were investigated and compared to each other. The results show that the DI values for right muscle groups are smaller when compared with the left muscle groups. We hypothesis that there is lesser fatigue in right muscles therefore their patterns are more deterministic. As a result, DI plots can be clear indications of the hand dominance of the object. It is also observed that DI values are larger at the beginning of the laparoscopic cases which can serve as indications of the confidence levels of subjects, and certain points in time during a surgical procedure. The results also show that by increasing the completion time of surgical operation the difference between first and last 10 minutes gets higher. Therefore, one of the important deductions can possibly be made on the length of the time of experiments based on the closeness or distances of the DI plots. Irrespective

of the duration of an OR procedure, the muscle group experiencing the least fatigue has close DI values at the beginning and theend of the procedure; for the subject from which data has so far been analyzed, the bilateral trapezius seem to be the least fatigued.

Forecasting nonlinear dynamics of chaotic systems using conceptions of chaos and recurrence plots method *Poster*

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Nonlinear modeling of chaotic processes is based on the concept of a compact geometric attractor, which evolve with measurements. We present an advanced approach to analysis and forecasting nonlinear dynamics of chaotic systems, based on conceptions of chaos and recurrence plots method. As example, a few geophysical systems are studied. Since the orbit is continuously rolled on itself due to the action of dissipative forces and the nonlinear part of the dynamics can be found in the neighborhood of any point of the orbit $y(n)$ other points of the orbit $y_r(n)$, $r = 1,2,\ldots,N$, that arrive neighborhood $y(n)$ in a completely different times than n. Then you can build different types of interpolation functions that take into account all the neighborhoods of the phase space, and explain how these neighborhoods evolve from $y(n)$ to a whole family of points about $y(n+1)$. Use of the information about the phase space in the simulation of the evolution of the physical process in time can be considered as a major innovation in the modeling of chaotic processes. This concept can be achieved by constructing a parameterized non-linear function $F(x,a)$, which transform $y(n)$ to $y(n+1) = F[y(n),a]$, and then use different criteria for determining the parameters a. Further, since there is the notion of local neighborhoods, we can create a model of the process occurring in the neighborhood, at the neighborhood and by combining together these local models to construct a global non-linear model to describe most of the structure of the attractor. In finding the coefficients of a there is a possible encounter a few problems, which at first glance seem to be purely technical, but are related to the nonlinear properties of the system. If the low-dimensional chaotic system, the data that can be used for fitting, normally cover any available locally dimension, but only a certain subspace. Therefore, the linear system of equations to be solved by fitting is "ill-conditioned". However, if the system noise is present, the equations formally are not ill-conditioned, but part of the decision relating to the "direction" of noise points to the future, is not having a sense.

Recurrence plots and randomization possibilities

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The report presents new theoretical aspects of possibilities which give randomizations in the context of recurrence methods. It focuses on new recent developments of authors based on a strong mathematical background. The related field is recurrence time statistics.

When choosing a paradigm of "randomization" in recurrent methods the random selection rules allow to get

1) the solution to a complex problem that requires a large number of searches (for example, the choice of a randomized point selection "view" of three-dimensional images, or random selection of graphics settings);

2) most importantly, if recurrence data output is possible then we can significantly reduce the effects of systematic errors due to randomization of the choice of system parameters, or graphics.

Randomized approach in recurrence methods is fundamentally different from the Bayesian one when problem uncertainties are "attributed to" the statistical properties.

In a Bayesian approach the probability is a part of the problem model. In contrast, the probability in a randomized approach is selected artificially. It exists only in our method, and therefore, there is no a traditional problem of "a bad model" as can happen with the Bayesian approach.

Further insights on the connectivity between money supply and interest rates

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The emergence of a new field of research found at the intersection of macroeconomics and finance supported the intrusion of complex dynamics in the money supply process, as well as its direct or indirect impact on economic and financial variables. This connectivity started exhibiting more interesting properties with the exorbitance of financial innovation, the stance of monetary policy and credit conditions. The dynamic role of money within the complex macro-financial network has recently pointed out by da Cruz and Lind (2012). The money creation and circulation processes take place through heterogeneous agents, so that its

flow is subject to the complex interactions of the network. Under circumstances of nonlinear relationships, the money supply can easily behave explosively, out of the boundaries that monetary policy fixes. Insofar as the overall structure of the entire economic environment adversely influences money supply, notable issues may arise regarding its contribution in achieving policy goals.

Systematic and multiple shocks on the money supply during the financial breakdown have crucially determined the response of key-interest rate variables. Despite the significance of this mechanism only a very limited number of papers tried to explore the empirical puzzles. The present work aims to put forward the nature of connectivity between money supply as measured by M2, Fed funds interest rates and 10-years Treasury bond by implementing jointly a newly launched multivariate direct causality test (PMIME) (Vlachos and Kugiumtzis, 2010) and the cross-recurrence quantification analysis (CRQA) (Marwan and Kurths, 2002), both in rolling windows.

The empirical findings reveal that connectivity changes significantly over the window including the unfolding of financial crisis and the zero-bound interest rate regime. The PMINE detects nonlinear direct causality running from the M2 to the Fed funds and from the Fed funds to the longer-term interest rate. The calculation of entropy between the above couplings, over time-varying epochs, shows that the M2-Fed funds connectivity starts becoming unstable and highly nonlinear in early 2007 that coincide with the Feds expansionary monetary period in the effort to rapidly address potential credit constraints and default. During the last period of the sample, money supply was filled by unconventional monetary policy that caused Feds balance sheets to dramatically increase. The asymmetric expansion of the monetary base, in comparison with the M2, provoked a significant decrease in the M2 multiplier supporting strong evidence that the impact to the Fed funds came from the supply of reserves i.e. Fed's liabilities.

Application of recurrence and cross recurrence analysis to the study of nonstationary signals from speech production

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Many recurrence and cross-recurrence based measures are sensitive to variations in the rate of change of the signals. Moreover non-stationarity affects the results of time-delay embedding. Critically, non-stationarity can be a potential source of consistent bias in the analysis. In speech production, our main research area, as in general in motor control, this is a strong limitation because the signals under study need often to be considered as non stationary. Many of the artifacts produced by non stationarity result in structures which can be identified in (cross) recurrence plots (eg. lines of variable thickness and down-warding lines) and that therefore can be safely removed. We propose to conduct measures on the properties of the remaining straight and bowed line structures in the plots. This approach can attenuate the effects of using non appropriate values for the embedding parameters, strongly simplifying the analysis. Importantly lack of embedding can be seen as an extreme case of inappropriate parameter setting. Therefore, depending on the kind of signals analyzed and on the precise objective of the analysis, embedding can be skipped. The results are less dependent on variations of the rate of change of the signals and on fine tuning of the analysis parameters. We proceeded along these lines in a number of case studies on speech motor behavior observed at different time scales (going from milliseconds to dozens of seconds). We could successfully characterize 1) the amount of regularity of the rapid vibration of the vocal folds; 2) the variability of the slower motion of the other articulators as the jaw, the lips and the tongue, during the production of vowels and consonants and 3) the dependencies between the breathing signals recorded from 2 speakers involved in dialogues lasting several minutes. Trough the analysis of both simulated data sets and of data recorded from real speakers we will show how our approach can be adopted in the analysis of univariate and multivariate time series with different advantages and limitations.

Recurrence quantification and recurrence network analysis of remote sensing data

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We investigate time series of remote sensing products with global coverage reflecting climate and vegetation activity. Carbon uptake by plants is related to the fraction of absorbed photosynthetically active radiation (fapar), which is provided by several satellite missions. Here, a set of more than 30000 time series with a length of 14 years at 10-days resolution for fapar, temperature, precipitation and shortwave radiation is analyzed by means of RQA and RNA. These are covering all terrestrial ecosystems and climates apart from the arctic and major deserts. RQA and network variables are calculated either for individual time series using identical recurrence parameters, or

bivariate by performing a joint recurrence analysis to quantify the synchronization between fapar and temperature or fapar and precipitation. We discuss the potential of these measures towards a new classification of the terrestrial biosphere based on the nonlinear dynamical properties of the time series, which can be compared to existing classifications based on static or linear climate and/or vegetation properties.

Recurrence plot analysis of heart rate and systolic blood pressure: a strategy for embedding parameters estimation

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Objectives: To analyze several indexes obtained with recurrence quantitative analysis (RQA) of beat-to-beat heart rate (HR) and systolic blood pressure (SBP) time series, in order to: (1) assess the influence of the embedding parameters estimation on RQA indexes, (2) identify the RQA indexes that change in response to active standing, and (3) to compare the results with a correlated Gaussian noise model.

Methods: Ten healthy volunteers (ages between 20 and 40 years old) were included. Non-invasive beat-to-beat blood pressure recordings were obtained during supine position and also during active standing, 15 minutes in each position. HR and SBP analysis included conventional indexes (statistical and spectral) and RQA indexes. Embedding parameters (delay, dimension and threshold) were estimated with different methods: autocorrelation function, mutual information function and Poincaré plot (for delay estimation), false nearest neighbors and correlation dimension (for dimension estimation), scaling region criteria, fixed determinism criteria and identification of "minimum" and "saturation" regions (for threshold estimation). The correlated Gaussian noise was analyzed with the same methods that were used in the real time series, in order to compare the recurrence plot and RQA indexes against the HR and SBP results.

Results: (1) The embedding delay value of each time series must be chosen individually since the 3 tested methods provide complementary information. For estimation of embedding dimension and threshold there is a range of selectable values between the minimum and the saturation regions. Individual values of embedding dimension and threshold will produce different RQA indexes. However, for all parameter values which are chosen within the mentioned range, there is a significant change in response to active standing of several RQA indexes. (2) The following indexes increase in response to active standing: determinism, laminarity and maximum diagonal length, with a statistical significance < 0.05. (3) The correlated Gaussian noise shows similar recurrence plot and RQA indexes than HR and SBP. Also the curves obtained with the parameter estimation methods for the correlated Gaussian noise are similar curves to the ones obtained for HR and SBP.

Conclusions: Significant change in response to active standing of HR and SBP RQA indexes can be detected for a range of embedding dimension and threshold, which suggest that estimation of these parameters is robust. However, estimation of embedding delay depends on the individual characteristics of each time series. The correlated Gaussian noise is an attractive simple theoretical tool for further studies of HR and SBP dynamics.

Spectra of recurrence times in the chaotic region of the logistic map *Poster*

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The chaotic region of the logistic map, $X_{n+1} = aX_n(1 - X_n)$, is defined by $a \in (3.569946, \ldots, 4)$. This region is characterized by a set of strange attractors which are defined by a 2^n-band structure. For a given value of the parameter a these bands are permutated under iteration. We show that the spectra of recurrence times for these attractors is determined both by the period of such permutations and for the bifurcation process.

Quantifying the complexity in a recurrence plot

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Recurrence plot (RP) is considered to be one of the most powerful techniques for nonlinear data analysis. Fundamentally it provides a graphical visualization for the data series that allows one to proper extract the key properties related to the underline process that generates the time series. It can be successfully applied even to nonlinear and nonstationary process. To allow a systematic interpretation of the information that appears in a recurrence plot, providing a proper quantification of important aspects revealed by the plot, the recurrence quantification analysis (RQA) was introduced. They define dynamical measures based on recurrence point density and diagonal segments. In special on of this measure is known as RQA-Entropy. Here, based on

the RQA-entropy we introduce a new quantifier. This quantifier, which is called RQA-Complexity, is based on the LMC measure, and consider two complementary measures, disorder and order, that are combined into a single expression to proper quantify the system's complexity. We present examples that allow us to proper validate this new RQA-quantifier.

Recurrence Quantification Applied to the Analysis of Brain Electrical Activity

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The scalp electroencephalogram (EEG) is a continuous non-stationary output signal of the brain, the ultimate complex dynamical system. The EEG is an emergent property of the brains organization, and has long been assumed to contain important physiological information. But the problem of devising reliable methods for extracting the putative information had been essentially unsolved. The invention of recurrence quantification analysis by Webber and Zbilut (WZ) provided a new strategy for gleaning physiological meaning from biological time series. Recent results indicated that analysis of brain recurrence (ABR), the statistical evaluation of specific WZ variables derived from EEGs recorded under controlled conditions, is a solution to the problem of interpreting the EEG. ABR directly detects and quantifies temporal patterns whose existence entails the operation of non-autonomous differential law in the brain. Present applications of ABR include discovery of a human magnetic sense, objective characterization of the depth of human sleep and the extent of sleep fragmentation (a basic phenomenon responsible for poor quality sleep), the diagnosis of degenerative neurological disease such as multiple sclerosis, and detection of changes in brain metabolism caused by weak environmental stimuli previously believed incapable of affecting the brain. ABR is well-suited to the task of extracting information from the EEG and, in the context of appropriate experimental and statistical design, seems certain to have a beneficial impact in the fields of clinical and experimental neuroscience.

Potential Pitfalls in Recurrence Plot Analysis

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After 25 years, recurrence plots have become a well-known and promising tool in many scientific disciplines, what is reflected by the growing number of applications and publications. Recurrence based methods have on the one hand a deep foundation in the theory of dynamical systems and are on the other hand powerful tools for the investigation of a variety of problems. The increasing interest encompasses the growing risk of misuse and uncritical application of these methods. Therefore, in my talk I would like to point out potential problems and pitfalls related to different aspects of the application of recurrence plots and recurrence quantification analysis.

Informational content of Monday returns and the role of dynamic invariants

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Calendar effects had always been recognized as one of the major pitfalls of the Efficient Market Hypothesis. Many authors attempted to accommodate them in the context of statistical errors. Others concluded that this kind of anomalies, when identified, is immediately incorporated into stock prices. The most cited explanations for the existence of calendar effects include investors' behavioral biases, microstructure effects, time-varying spreads, short-selling or macroeconomic risk. These behavioral imperfections as well as the real properties of trading schemes may explain why interactions between financial agents are complex. Thus, fluctuations in stock prices can be thought as the synergetic action of endogenous dynamics and noise, residing in a no-constant financial environment. In this context, methods accounting for calendar effects with means of linear/non-linear regressions including dummy variables, might fail. To overcome these potential biases we proceed differently. First, we decompose the daily prices of ATHEX into separate time series for each day of the week. Then, using the RQA tools, we aim at disentangling the behavior of the dynamic invariants of each time series in order to capture the inherent complexity and persistence of the trading patterns.

As entropy is a tool employed to quantify disorder and uncertainty in a system, its application in relation with the rich informational content of our constructed series can provide deeper insights on the origins of market fluctuations related to the Keynesian "animal spirits".

Our approach is built on Karagianni and Kyrtsou (2011), suggesting that in highly complex and noisy systems the use of dynamic invariants, instead of prices, is more accurate computationally and may help identify hidden economic phenomena. The empirical findings show that, prior to 2007, the bull phase of ATHEX is accompanied with a sharp decrease in entropy val-

ues of Monday time series. On the contrary, during bear territory of the stock index, Monday returns move to a high entropy regime. The observed "leverage effect" has been explicitly discussed by Koutmos (1997) who argue that: "when market declines, positive feedback trading is stronger due to portfolio insurance strategies, and the use of extensive stop-loss orders." More interestingly, the latter regime is associated with high market volume, implying strong trading activity. This result is in line with Fishe et al. (1993) concluding that "lower Monday returns are primarily a function of particularly bad news being released over the weekend since the most significant differences occur in a high volume bad news environment."

Robustness of cross-recurrence results in a social interaction experiment

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In an experiment modeling an organizational context, we have examined the effect of emotions on group decisions. We applied Cross-Recurrence Quantification Analysis (CRQA) to psychophysiological measures of arousal (skin conductance and heart rate) from this experiment in order to test if CRQA measures correlate with group outcomes such as performance and group decision-making. CRQA has previously been used to measure the degree of synchronization of arousal levels in e.g. high arousal religious rituals (Konvalinka et al. 2011). Our emphasis in the presentation is on testing the robustness of the CRQA results with respect to the parameters in the cross-recurrence quantification analysis: data sampling rate, time delay, embedding dimension, and recurrence rate, as well as the distance measure (Euclidean or maximum norm). The robustness analysis reveals systematic dependencies on the parameters, and gives us an indication of what we can reliably conclude from a cross-recurrence quantification analysis of such data.

B(eo)W(u)LF: Facilitating multi-level recurrence analysis in language

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Researchers interested in language have used recurrence for decades (e.g., for orthographic-level analysis; Orsucci, Walter, Giulianai, Webber, & Zbilut, 1997, 2008), though it remains a relatively rare domain in which these important new techniques are applied. Given the variability of transcript formats, sources of digital language data, and so on, it may be useful to facilitate dynamic analysis of language by using a standard format. We introduce a data format called the "by-word long-form" or "B(eo)W(u)LF", with accompanying software. B(eo)W(u)LF structures linguistic data into an expanded word-by-word matrix with researcher-defined variables that permits the analysis and visualization of data across multiple time scales, from single word to entire corpus. In this talk, we describe B(eo)W(u)LF, provide access to free programmable tools to create the by-word long-form matrix, and give a few demonstrations of the method using common texts.

Quadrant Scanning Recurrence Diagrams: Identifocation of Transitions in Central Nervous System Behavior

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Quadrant scans provide a time-dependent quantification of the relationship between a system's past and its future as identified by the implicit diffeomorphism created by an embedding. A quadrant scan is a continuous function that has local maxima at transitions in dynamical behavior. They have been applied to waveform data, specifically EEGs, and to maps, for example heart interbeat-interval sequences. These results indicate that it is possible to use these functions to identify hierarchies in transition behavior. These transitions can be identified by direct examination of the quadrant scans. Additionally, change point detection algorithms can be applied to the scans.

Recurrence Quantification Analysis of Clinical Data *Poster*

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Clinical models do not fit the simplest known states and symptoms of disease; further clinical data is highly variable and often missing values. A combination of low-level features and high-level attributes can provide better combined expressiveness of descriptors, such as static, sequential, and overlaps in data. Adaboost weight vectors have been shown able to distinguish easy from hard classification points. Adaboost provides global coverage over the clinical feature space, as well. Re-

cently, we were involved with a telehealth, at-home monitoring study, which recorded patient vital sign readings, twice daily, for an approximate several month interval. The publicly available MIMIC dataset is sampled as well for comparative analysis. The RQA metrics, order patterns, Renyi and permutation entropy, are combined over the data sets for best classification accuracy. Recurrence plots provide visual information relating clinical states, and are displayed during expert labelling of classification state. In this work, recurrence quantification and plots are shown to provide needed improvements in clinical models of real-world data.

Unthresholded recurrence plots for complex-valued representations of narrow band signals *Poster*

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We address the information content of unthresholded recurrence plots (URPs) for complex-valued signals admitting a Fourier series representation (including periodic and sampled signals). Recurrence plots of complex-valued signals are related to joint recurrence plots [1] which allows studying the relationship between different real-valued signals. The graph theoretic procedure in our recent work [2], which was developed to analyze the impact of the choice of the embedding parameters on information content, is extended to the class of complex-valued signals. This provides uniqueness conditions on the embedding parameters which guarantee that a zero mean complex-valued signal can be uniquely recovered from its URP up to conjugacy and a unimodular factor.

The analytic signal is a well-known complex-valued representation for real-valued signals. We show how analytic signals provide alternative ways to employ URPs for analyzing narrow band signals. A narrow band signal can be considered as an amplitude modulated sinusoid. The amplitude of the narrow band signal can be expressed through the magnitude of the corresponding analytic signal.

The main results and their practical potential are clarified by two examples. The first example illustrates the interplay between the frequency content of complex-valued signals and the embedding parameters in determining the information content of the resulting URPs. We show that if the uniqueness conditions on the embedding parameters are not satisfied then signals with morphologically different magnitudes can exhibit identical URPs. In the second example we consider an application in EEG analysis in which an EEG signal is decomposed into five narrow band signals corresponding to the delta (0.1-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz), and gamma (30-100 Hz) frequency bands [3]. These basic EEG frequency bands are assumed to reflect different functional processes in the brain.

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Redundancy and the information content of lines in unthresholded recurrence plots *Poster*

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We address redundancy in the information content of unthresholded recurrence plots (URPs). This is of importance for relating subpatterns in a URP to localized (morphological) properties of the underlying signal. The theory of framework rigidity is employed to explain geometrically the redundant distance information in a URP. We show how from the information content of horizontal and vertical lines in a URP the remaining part of that URP can be constructed. New time quantities are introduced to represent distance information near a contourline of a URP. This contour line and its corresponding time quantities can be encoded in a two-dimensional representation. We also show how this new two-dimensional representation determines redundant information in a URP.

These results may be useful not only to improve existing recurrence plots based methods and algorithms, but also to develop new algorithms for the detection of similar signal segments.

Examples and an application from EEG analysis clarify the theoretical results and demonstrate their practical potential. These results show that information in a URP can be reduced to lines in that URP.

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A Recurrence-Based Feature Extraction Approach for Brain-Computer Interface Systems

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Brain-computer interfaces (BCIs) provide new alternative channels for human communication, being of particular importance as assistive instruments for severe disable people. Such undoubtedly relevance led to the development of several BCIs working paradigms as the ones outlined by motor imagery or by steady-state visual evoked potentials (SSVEP).

In the present work, we have analyzed the classification performance of two individuals for a five command SSVEP – BCI system concerning attributes obtained by recurrence quantification analysis (RQA) and spectral analysis of time series provided by a 16 channel EEG system. In this case, the classification error provided by a linear classifier was compared for a BCI system with features defined by classical recurrence measures and a BCI system with features based on the spectral power density coefficients obtained by the Welch method. Both the recurrence-based and spectral attributes were selected based on a cluster measure given by the Davies-Bouldin index, which aimed to identify the most discriminant attributes.

As a main result, we found that the attained resolution ε of the recurrence plot for a recurrence rate of 2.5 % defined the key discriminant feature, typically providing a classification error less than 2 % when information of 4 electrodes is used. Such classification error is only attained with power density coefficients when 17 attributes (and not just 4 as in the case of RQA) are used for the first individual and more than 40 attributes are employed for the second. These results strongly support the promising capability of RQA for efficient feature extraction in the BCI context.

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A Recurrence Plot-based Distance Measure for Time Series Clustering

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Given a set of time series, our goal is to identify prototypes that cover the maximum possible amount of occurring subsequences regardless of their order. This scenario appears in the context of the automotive industry, where the goal is to determine operational profiles that comprise frequently recurring driving behavior patterns. This problem can be solved by clustering, however, standard distance measures such as the dynamic time warping distance might not be suitable for this task, because they aim at capturing the cost of aligning two time series rather than rewarding pairwise recurring patterns. In this contribution, we propose a novel time series distance measure, based on the notion of recurrence plots, which enables us to determine the (dis)similarity of multivariate time series that contain segments of similar trajectories at arbitrary positions. We use recurrence quantification analysis to measure the structures observed in recurrence plots and to investigate dynamical properties, such as determinism, which reflect the pairwise (dis)similarity of time series. In experiments on real-life test drives from Volkswagen, we demonstrate that clustering multivariate time series using the proposed recurrence plot-based distance measure results in prototypical test drives that cover significantly more recurring patterns than using the same clustering algorithm with dynamic time warping distance.

Hearts & Minds: Physiology, Emotions, & the Readiness-to-Learn

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Using Recurrence Quantification Analysis (RQA) to examine heart-rate variability (HRV) data, Torre found a recurrence point difference of approximately seven percent between monolingual (English) and bilingual (Spanish dominant) students in affective-perceptive activity and in cognitive activity in which the teaching/learning process was conducted in English. However, there was virtually no difference between the two groups of students in pragmatic (hands-on) activity. These findings demonstrate that advanced, nonlinear analytical methods can provide more comprehensive means of examination than standard techniques alone when applied to physiological systems. It also serves as initial evidence of how different educational

(teaching) methodologies can affect physiological/emotional responses and, perhaps, students' ability to learn and develop.

Through the use of Holter monitors and Recurrence Quantification Analysis (RQA), Torre's research seeks to identify characteristic patterns in the autonomic nervous system associated with specific emotions. His work explores the emotions children experience as they learn and examines how different educational processes and activities mediate the experience of emotions and how these emotions encourage or restrain children's ability to learn. In particular, he is interested in the complex nature of thinking, problem solving, teaching and learning, and the effects of language and culture on these processes.

How CRQA can shed light on two-person anticipatory systems

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Handshakes, passing plates, carrying pianos, and conversations are all examples of joint action' actions carried out by an ensemble of people (Clark 1996). Similarly, left and right brain hemispheres work together to accomplish motor tasks that demand coordination and anticipation of multiple limb movements. For example, if one removes a heavy book from their right hand by using their left, the right hand moves slightly upward, as ones motor system seems to anticipate the shift in weight from right to left. However, if another person were to remove the book, the hand would move drastically upward. The common explanation for this difference is that the motor system sends an efference copy of the current movement commands to the peripheral nervous system which may be used to perceptually anticipate the effects of ones own motor movements. We present an approach to this problem that explores how two people come to anticipate each others movement effects. If they do, they would, in a real sense, come to exhibit anticipatory processes akin to those seen in the individual. Importantly, recurrence methods may help shed light on these dynamics. By tracking the arm movements of people exchanging objects over the course of time, distinct signatures such as RR, DET, and Lmax exhibit a stabilizing two-person motor system (Marwan et al. 2002). Such an approach has been used to show differences between intra and interpersonal coordination in limb movements (Richardson et al. 2008) and the influence of conversation on postural sway (Shockley et al., 2003, 2007). Thesemeasurementsmight also be effective tools in addressing how similar one's movements are in a task accomplished via joint action compared to movements involved in the same task accomplished independently.We detail this approach to two-person anticipatory systems, and offer preliminary analysis using CRQA.

Quantifying degree and directionality of coupling using cross recurrence analysis. *Poster*

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People continuously coordination their movements and actions with those around them. Such coordination can occur both intentionally and unintentionally with visual and auditory information coupling the behaviors of co-actors. In many instances this coupling is not always symmetric, with asymmetries in interpersonal coupling leading to complimentary patterns of coordination and the emergence of social roles. Here we explored data from a range of visual and interpersonal coordination studies that involved various uni- and bi- directional coupling manipulations, in order to examine whether cross recurrence analysis could be employed to index asymmetries in coupling strength as well as the directionality of coupling during interpersonal coordination. Results revealed that differences in the amount and structure of recurrent activity between the two triangular halves of a cross recurrence plot can be used to quantify the symmetry of coupling. The relationship between different recurrence quantifications and existing measures of coupling directionality was also explored. The advantages of using cross recurrence analysis to explore the stability of interpersonal and visual coordination is discussed.

Recurrence Categorization of Immunohistochemical Stainings of Her-2/neu in Breast Cancer

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Her2/neu is a biomarker for drug therapy with Herceptin which specifically targets cancer cells expressing this oncogene. Positive Her-2/neu expressions are determined by either immunohistochemistry (IHC) or fluorescence in situ hybridization (FISH). Specimens of breast cancer were stained for the Her2/neu by IHC in this study. Pathologists examined IHC

stained histological sections microscopically and assigned integer scores to each (0 and 1+ = negative; 2+ = equivocal; 3+ = positive). This method of categorization is very subjective with large personal variation, especially in equivocal cases. Tissue samples with 2+ scores were submitted for FISH to test for the presence of the Her2/neu gene. Nevertheless, some of results remained ambiguous. In our study, JPEG color images from all categories of Her2/neu stainings were converted pixel by colored pixel into hexidecimal numbers and mapped over the range from 0 to 1000. Square numeric matrices $[400, 400]$ were treated as cross recurrence plots using a fixed radius of 500 (mid-range) from which 8 recurrence variables were extracted. Histograms with 101 bins were computed for the 160,000 points from each square image. A single continuous-scale metric describing the histogram contours was defined for its ability to strongly correlate with the discontinuous histological scores. Recurrence variables were then correlated with this metric to report on the complex structuring of the histological images. Diligent efforts are continuing with the aim of automating histological slide readings for cancer patients using combined histogram and recurrence strategies.

Multiscale analysis of recurrence patterns

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Sensor technology in the 21st century is capable of monitoring complex nonlinear systems in real time and high precision, leading to the proliferation of monitoring signals. With massive dynamic signals readily available, there is dire need for the extraction of knowledge pertinent to nonlinear systems, thereby improving the integrity and performance of process monitoring and control. We intertwined the approaches of physics-based modeling and sensor-based data fusion to promote the study of nonlinear system informatics and control. First, we will present an approach of multiscale recurrence analysis to characterize and quantify nonlinear system dynamics in the space-time domain, as opposed to the conventional time-delay reconstructed phase space. The integration of wavelets and nonlinear recurrence methods was experimentally shown to facilitate the prominence of hidden nonlinear characteristics properties that are usually buried in a single scale view. Second, we simulate the recurrence network as a physical system by treating the edges as springs and the nodes as electrically charged particles. Then, force-directed algorithms are developed to automatically organize the network geometry by minimizing the system energy. As a result, this research addresses a question, i.e., "What is the geometry of a recurrence network?", and provides a new way to reproduce the attractor or time series from the recurrence plot. Finally, future research directions in the area will be discussed.

Improving reliability of recurrence plot analysis through nonlinear separation of signal components

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Recurrence plot analysis is a well-established tool in the nonlinear dynamics community, where it is used to detect nonstationarity and hidden patterns in time series data. However, in the last decade recurrence plot analysis has also gained popularity in applied fields such as the analysis of physiological time series. Typical applications are characterization of breathing patterns for the detection of sleep apnea or the analysis of ECG signals. However, interference from unwanted signal components can disturb the results of recurrence plot analysis. Baseline wander is especially problematic, since it interferes with the neighbour search, causing similar waveforms to appear to be far away in phase space due to a different offset.

Removal of baseline wander with linear filters can be difficult since their spectra sometimes overlap with that of the signal and their spectral properties are often unknown and not constant.

We have adapted a nonlinear noise reduction method based on local Principal Component Analysis to the task of separating respiratory baseline wander from the cardiac component of Ballistocardiograms, a method for registering the mechanical heartbeat activity. Ballistocardiography has sparked a renewed interest in context with the current trend towards telemedicine, as it provides an unobtrusive way to obtain information on cardiorespiratory activity.

After removal of the respiratory component a recurrence plot analysis is much more likely to reveal information about the physiological process behind the cardiac component. Furthermore, the respiratory component itself can also be subject to recurrence plot analysis, e.g., with the aim of detecting and classifying apnea. We intend to combine the information from both components via synchronisation analysis. Currently, tests are being carried out and first results will be obtained soon.