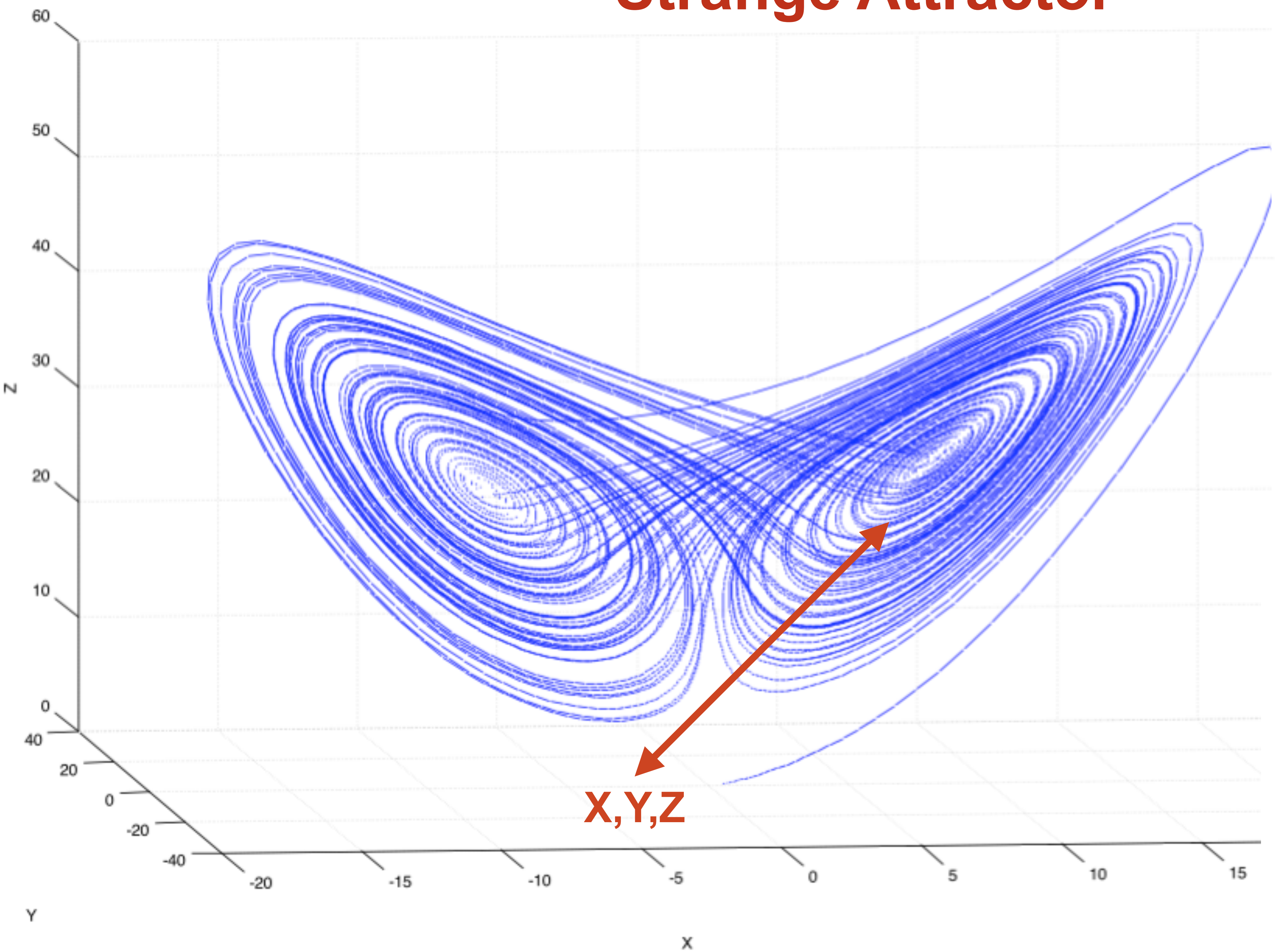
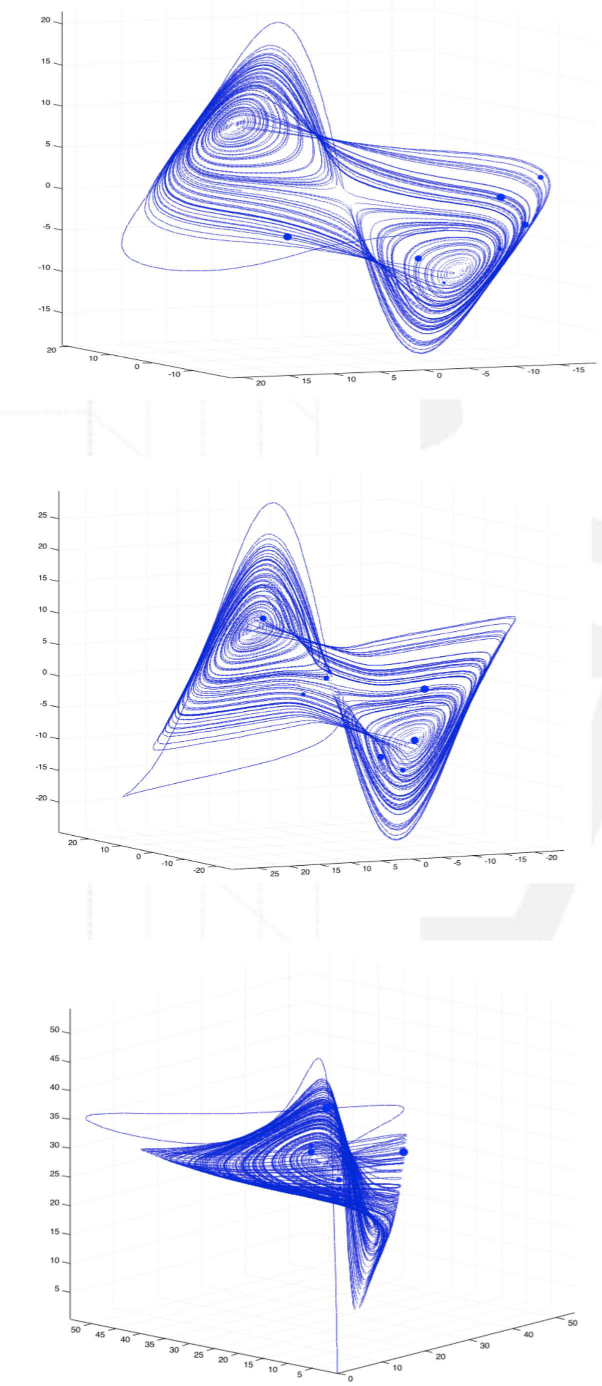
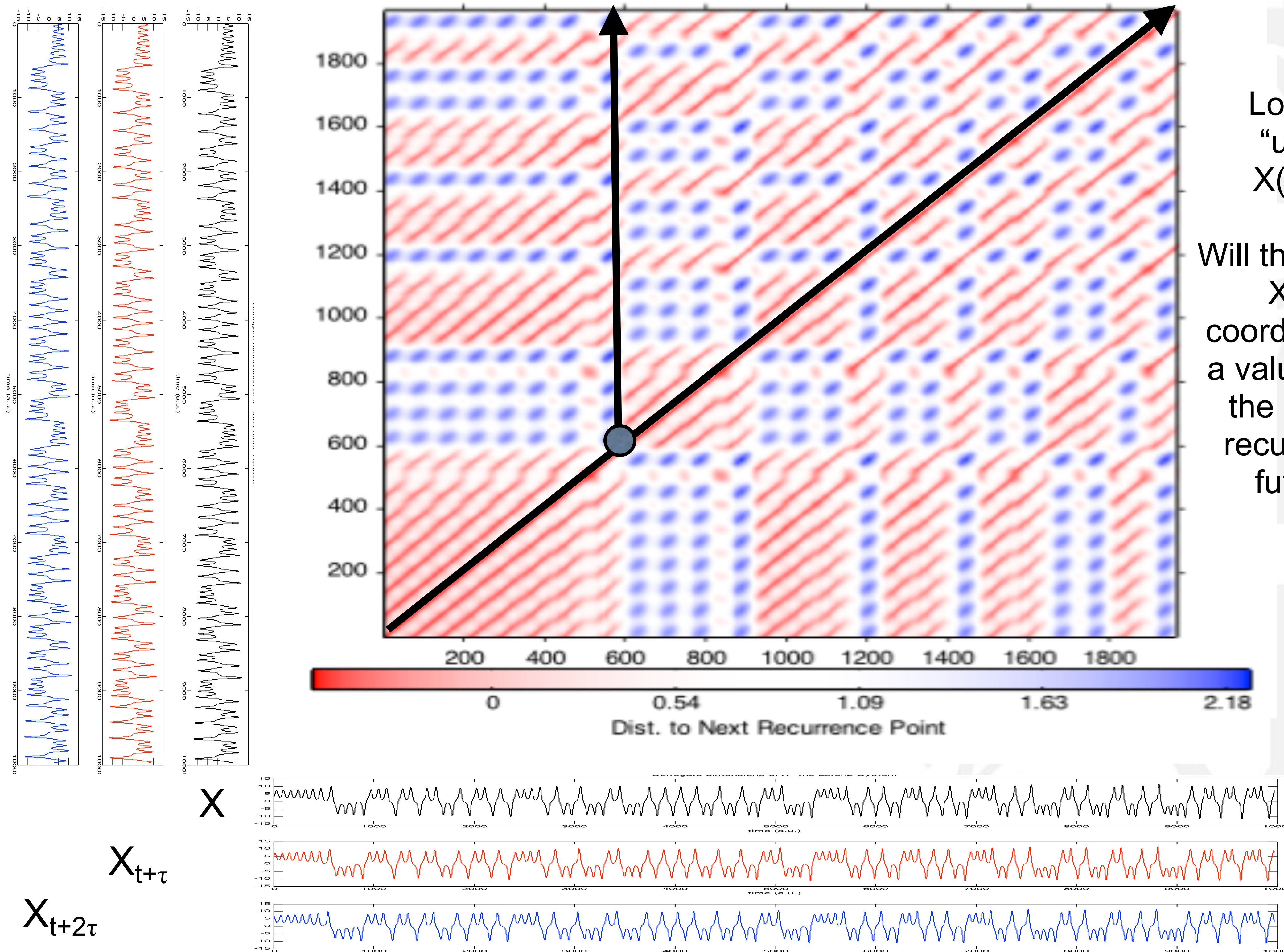
Lorenz system – X,Y,Z State space
Strange Attractor





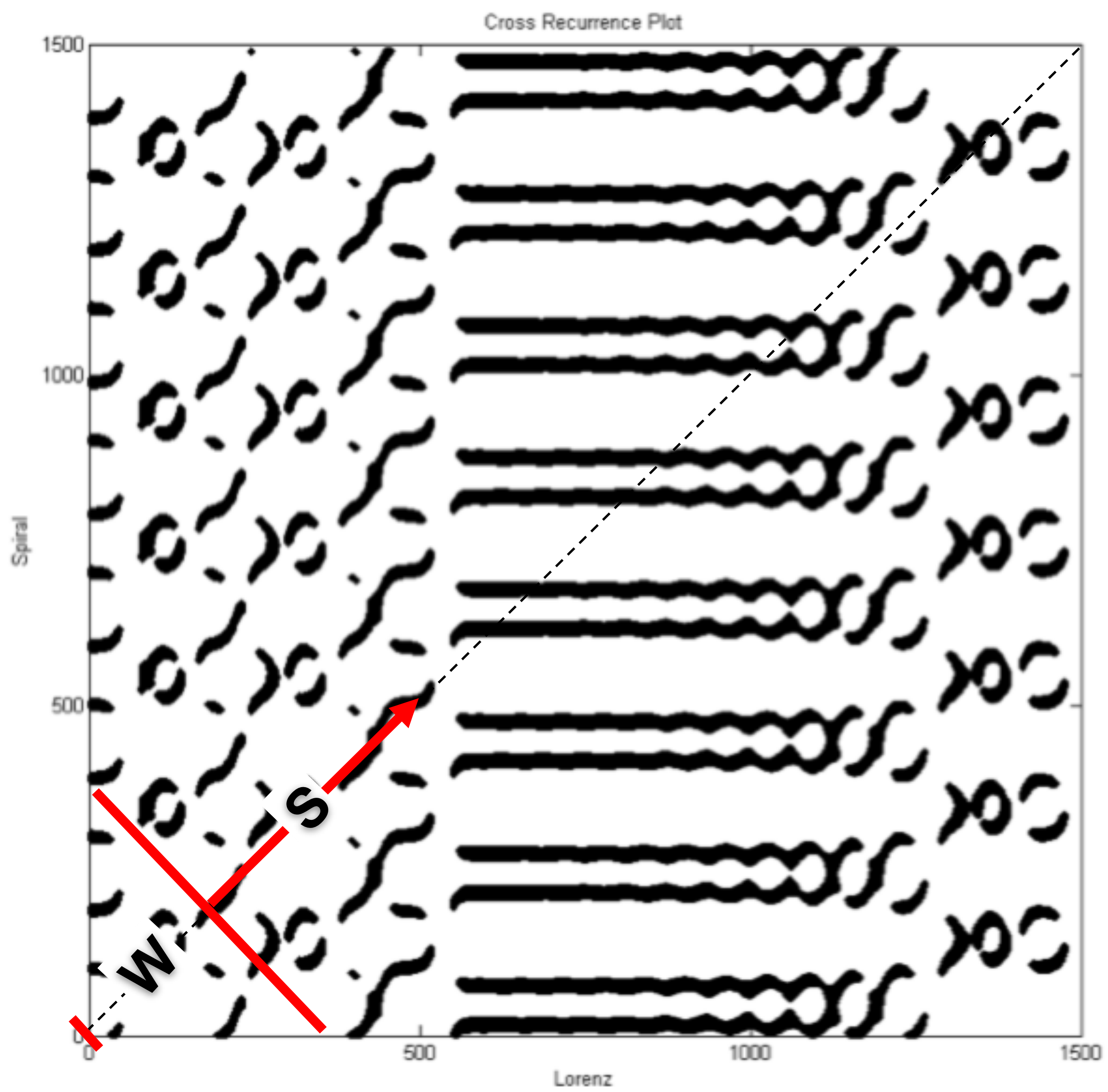
Recurrence Quantification

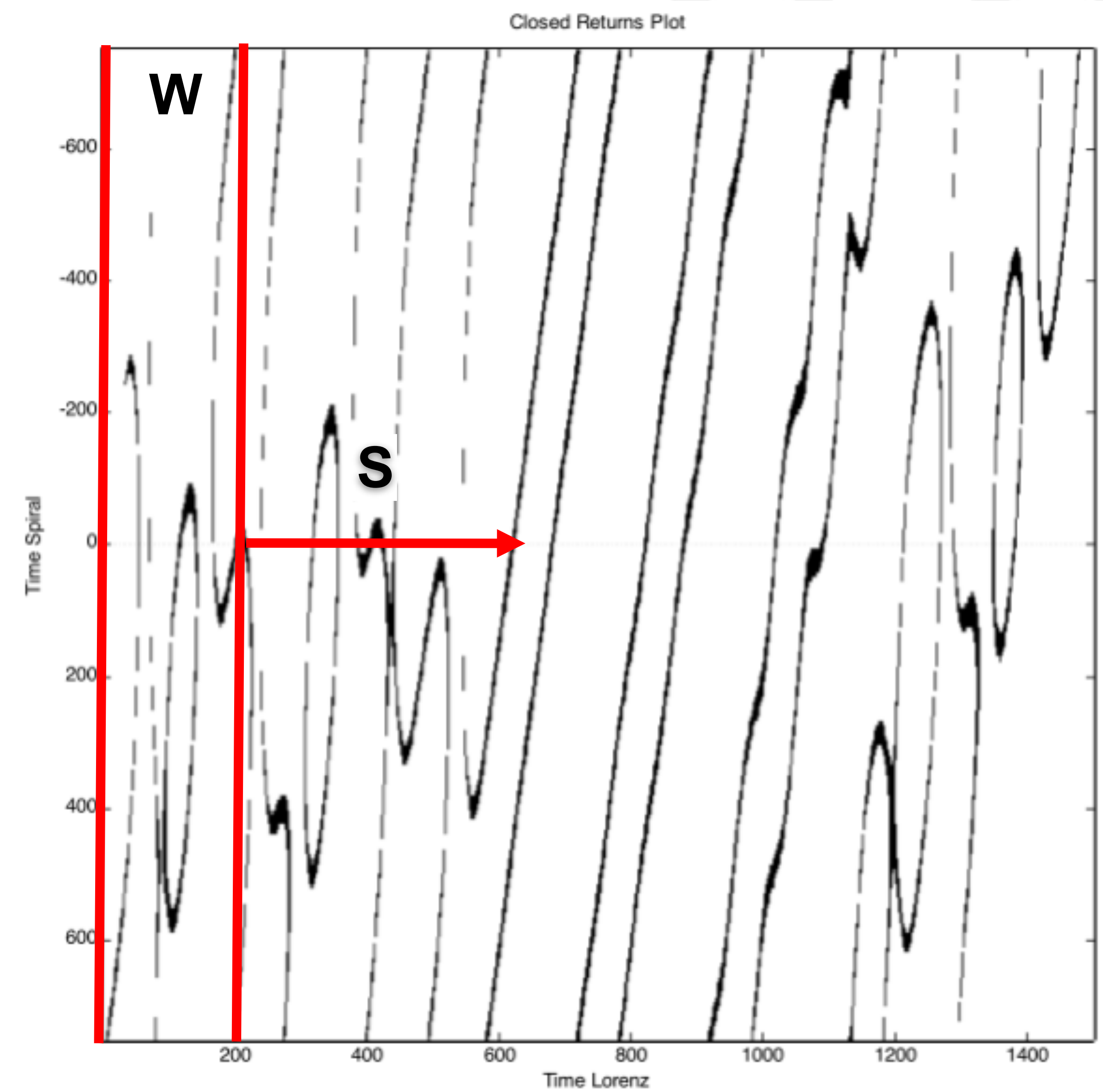


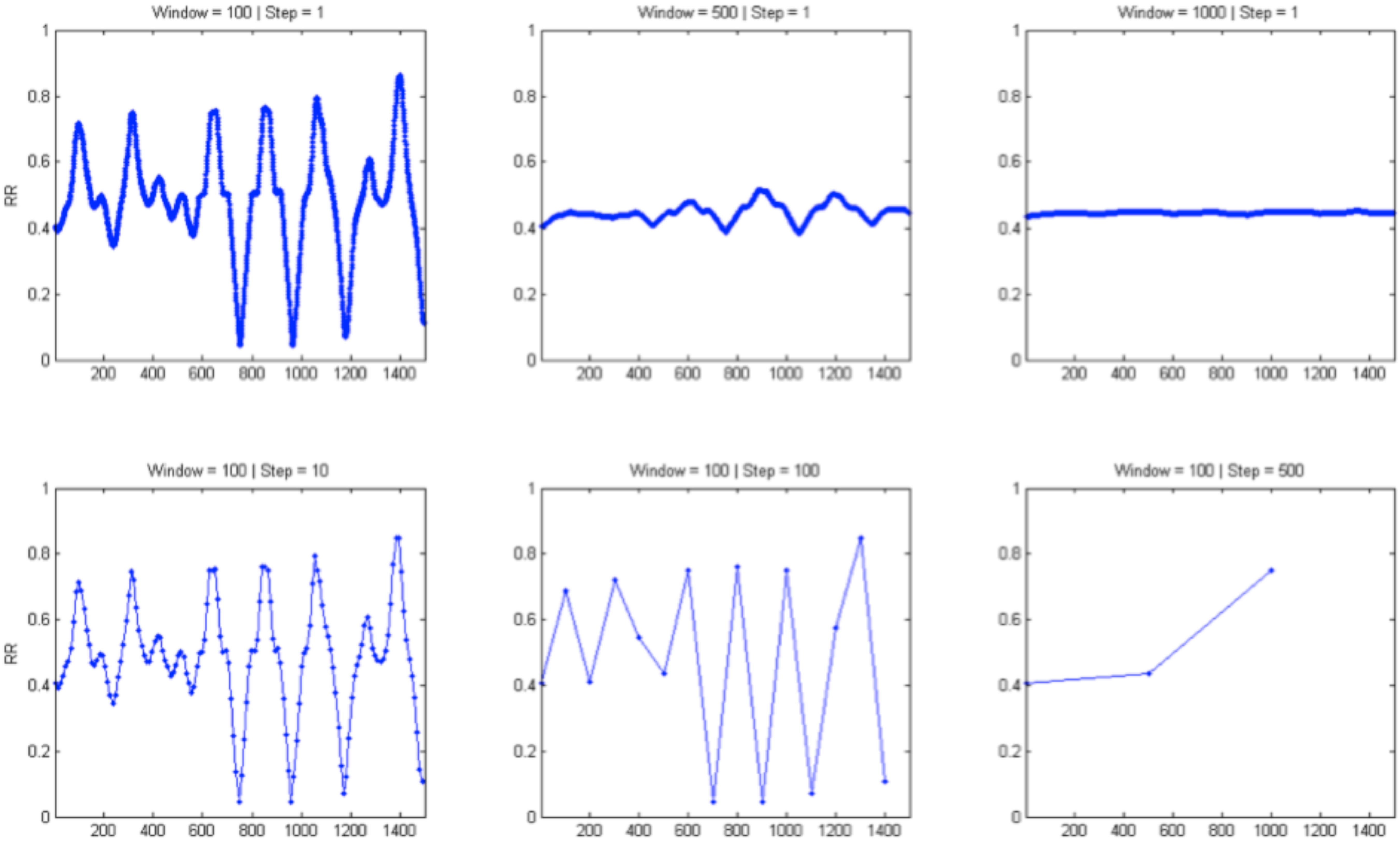
Looking "up" at X(600):

Will the current X,Y,Z coordinate (or a value within the radius) recur in the future?

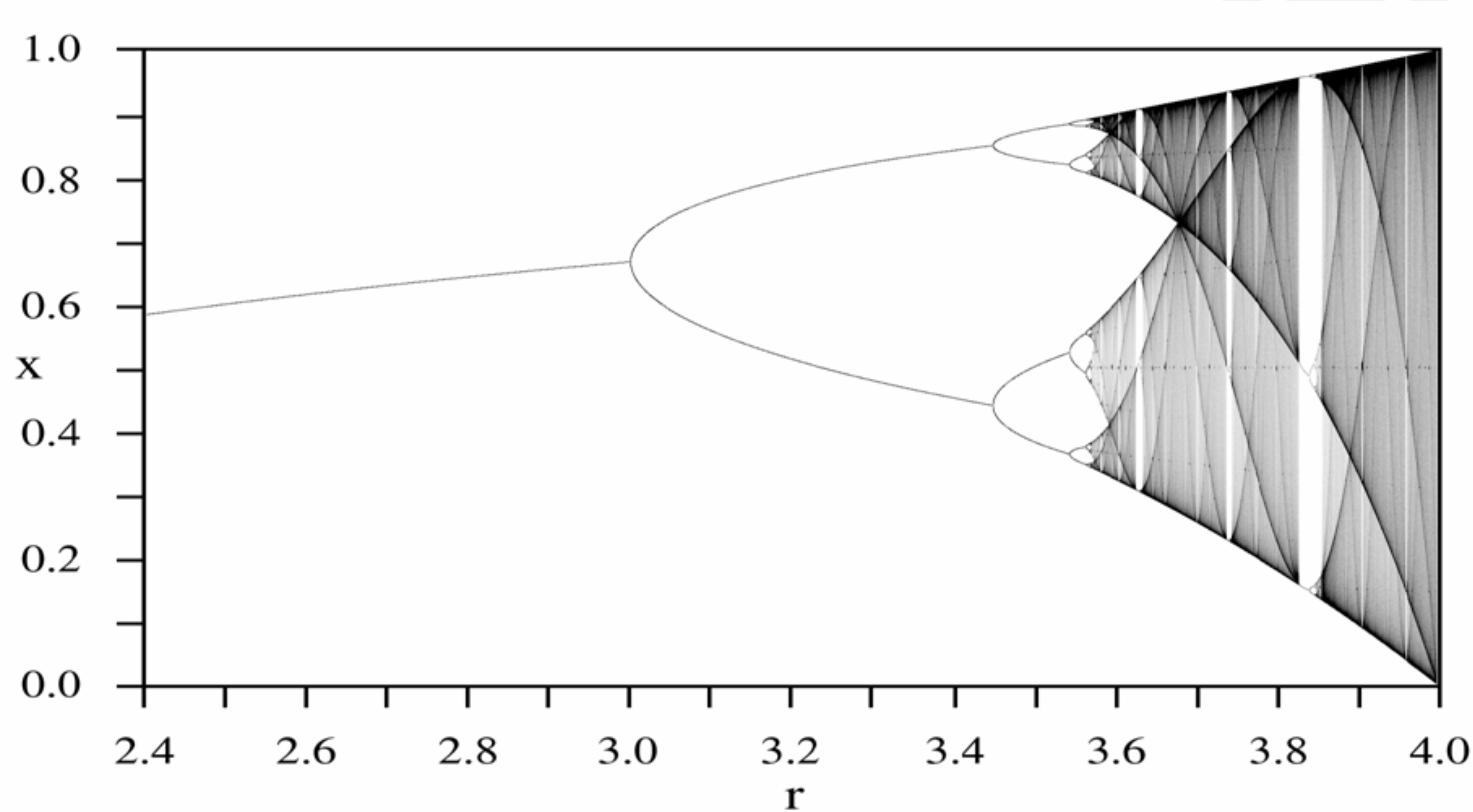
Lagged RQA
move a window of size **W** in **S** steps across LOI





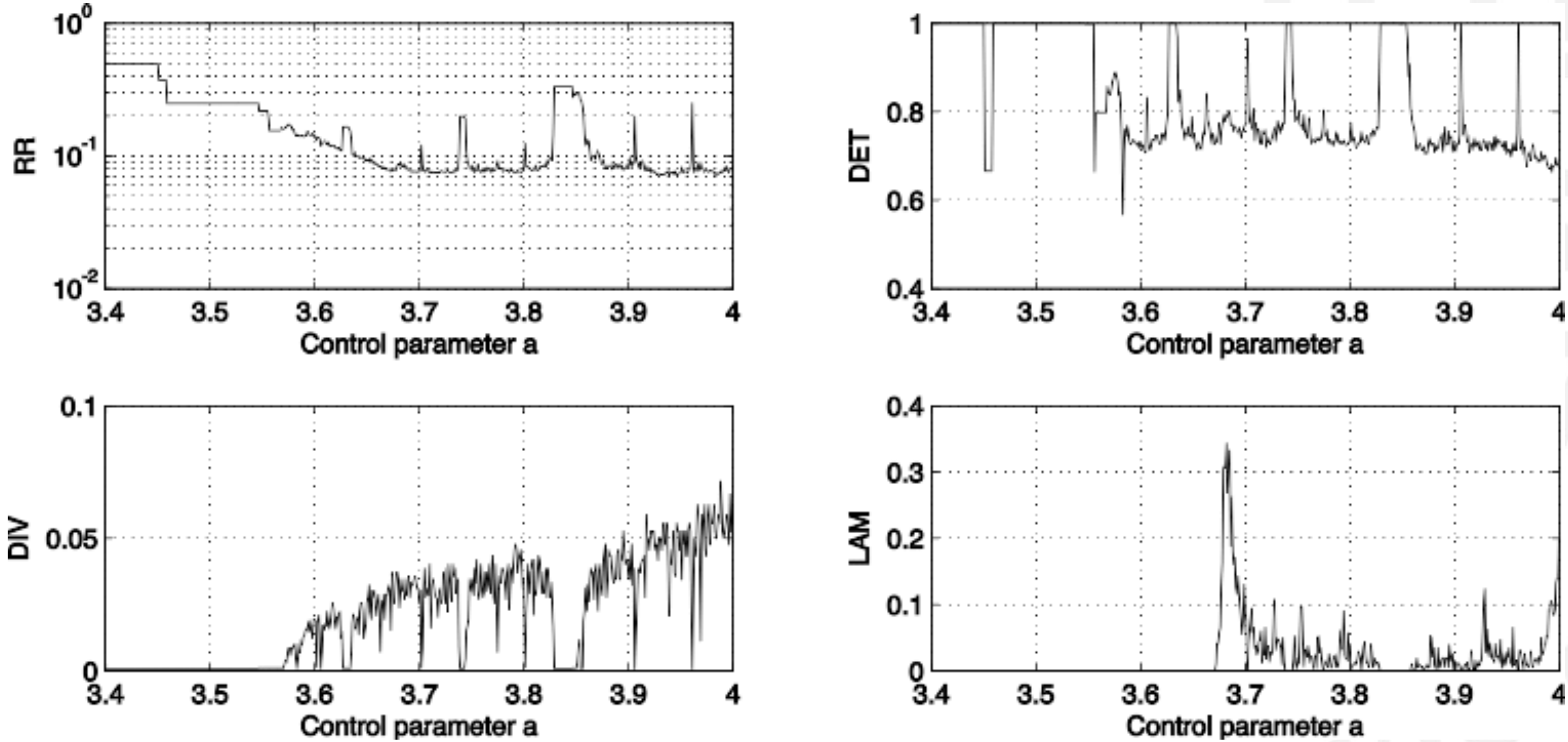

Window = 100 | Step = 1
Window = 500 | Step = 1
Window = 1000 | Step = 1
Window = 100 | Step = 10
Window = 100 | Step = 100
Window = 100 | Step = 500
RR
RR

Logistic map – Transitions revealed by lagged RQA



Logistic map – Transitions revealed by lagged RQA

note: a = r in bifurcation diagram on previous slide



Marwan, N., Romano, M. C., Thiel, M., & Kurths, J. (2007). Recurrence plots for the analysis of complex systems. *Physics reports*, *438*(5-6), 237-329.

Further reading

- The paper by Marwan et al in Physics Reports tells you everything you wanted to know… and more.

274 *N. Marwan et al. / Physics Reports 438 (2007) 237–329*

Table 2
Comparison of RQA measures based on diagonal (*DET*, *L* and L_{max}) and vertical structures (*LAM*, *TT* and V_{max}) regarding periodic-chaos/chaos–periodic transitions (PC/CP), chaos–chaos transitions (band merging—BM and inner crisis—IC) and laminar states

Measure	PC/CP transitions	BM and IC	Laminar states
DET	Increases	—	—
L	Increases	—	—
L_{max}	Increases	—	—
LAM	Drops to zero	—	Increases
TT	Drops to zero	Increases	Increases
V_{max}	Drops to zero	Increases	Increases

Marwan, N., Romano, M. C., Thiel, M., & Kurths, J. (2007). Recurrence plots for the analysis of complex systems. *Physics reports*, *438*(5-6), 237-329.

Order Patterns Recurrence Plot

- Sort of “filter”: not recurrences of values, but order patterns

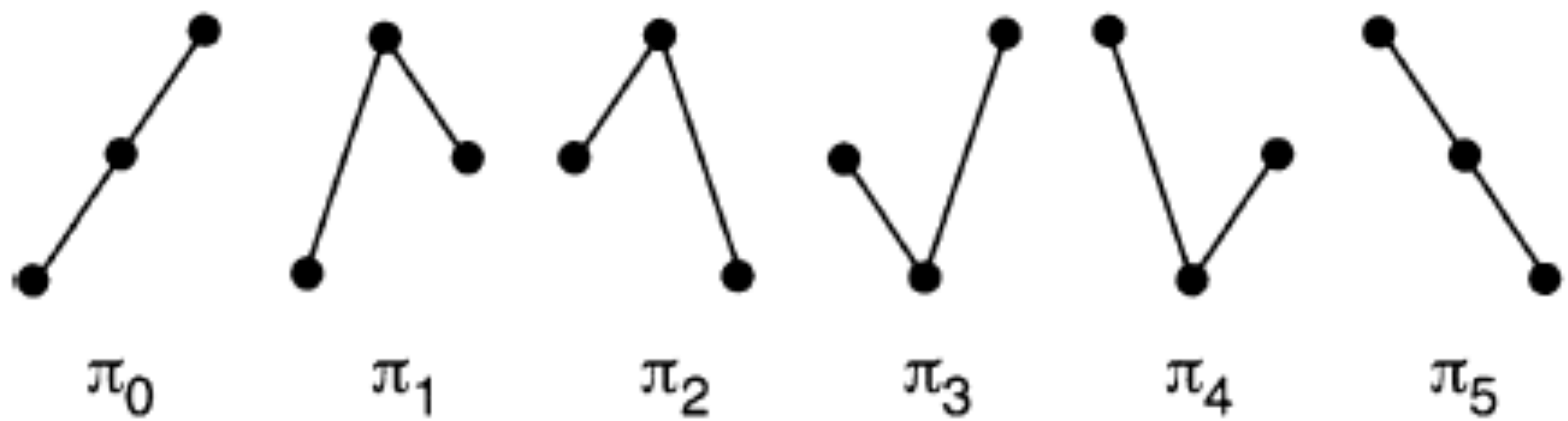
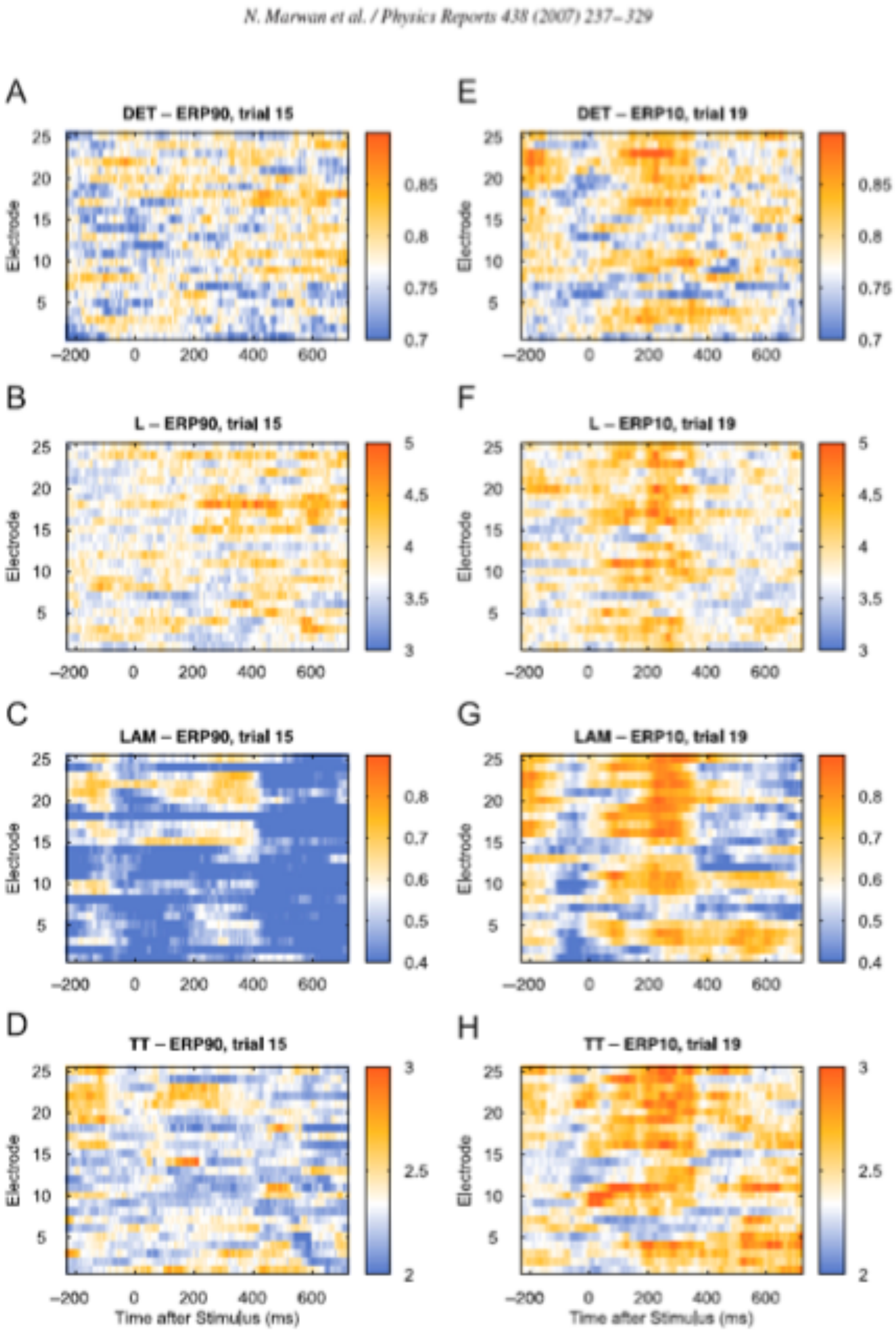


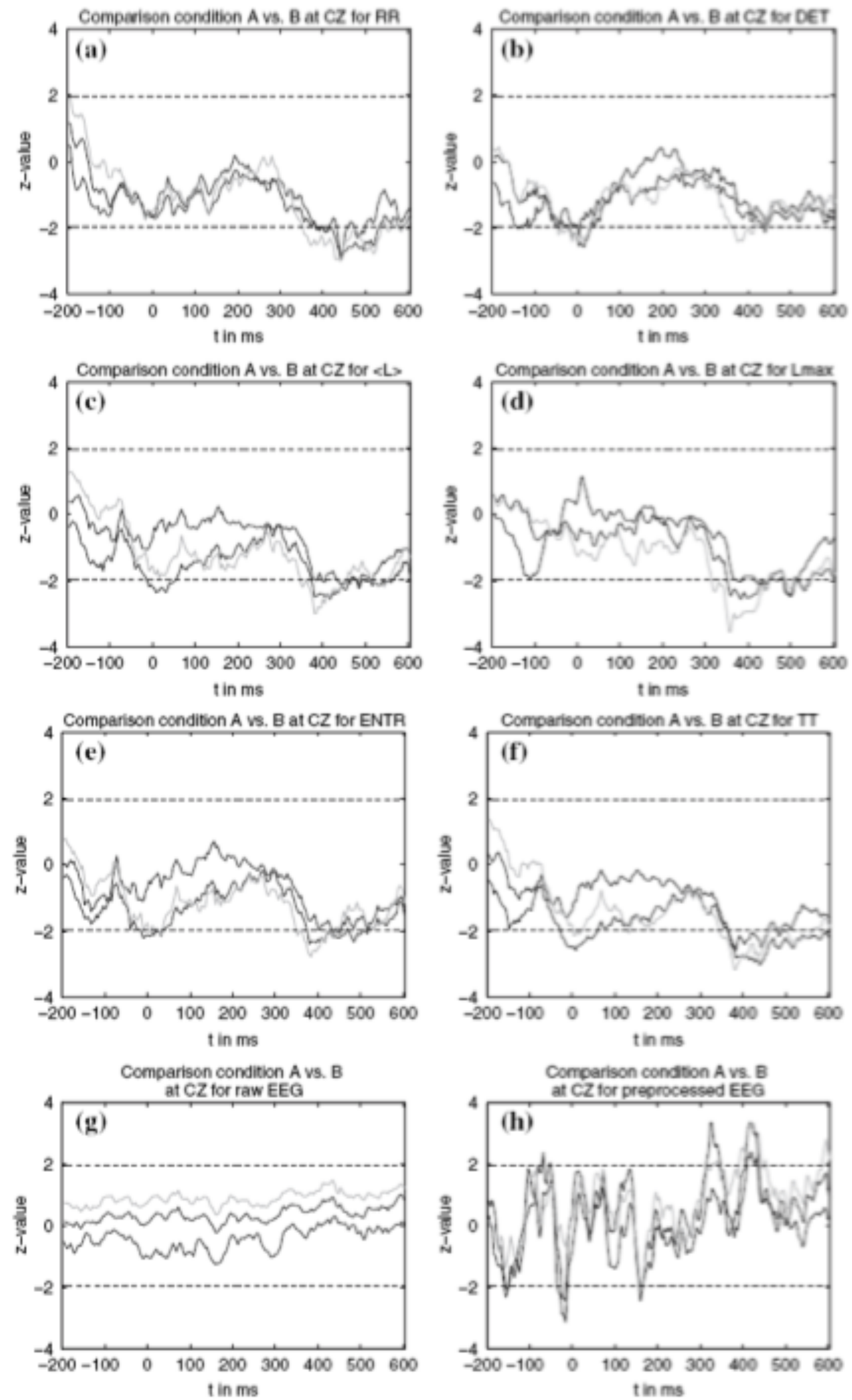
Fig. 2 Order patterns for dimension $d = 3$ (tied ranks $u_i = u_{i+\tau}$ are assumed to be rare)

Order patterns recurrence plots in the analysis of ERP data

Stefan Schinkel · Norbert Marwan · Jürgen Kurths

Schinkel, S., Marwan, N., & Kurths, J. (2007). Order patterns recurrence plots in the analysis of ERP data. *Cognitive neurodynamics*, *1*(4), 317-25. doi:10.1007/s11571-007-9023-z





Schinkel, S., Marwan, N., & Kurths, J. (2009). Brain signal analysis based on recurrences. *Journal of physiology, Paris*, *103*(6), 315-23. Elsevier Ltd. doi:10.1016/j.jphysparis.2009.05.007

Schinkel, S., Marwan, N., & Kurths, J. (2007). Order patterns recurrence plots in the analysis of ERP data. *Cognitive neurodynamics*, *1*(4), 317-25. doi:10.1007/s11571-007-9023-z

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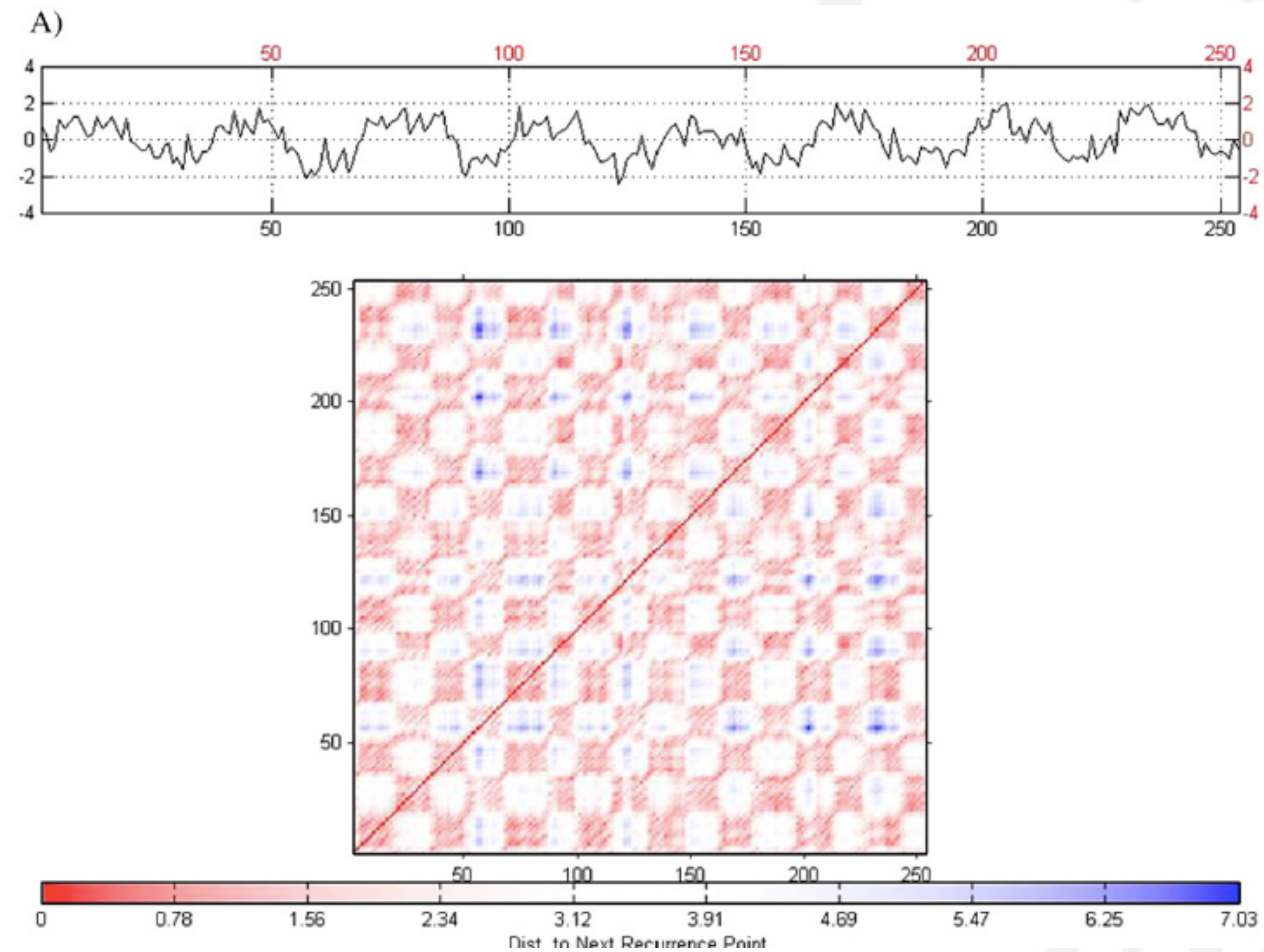
NeuroImage

www.elsevier.com/locate/ynimg
NeuroImage 37 (2007) 489–503

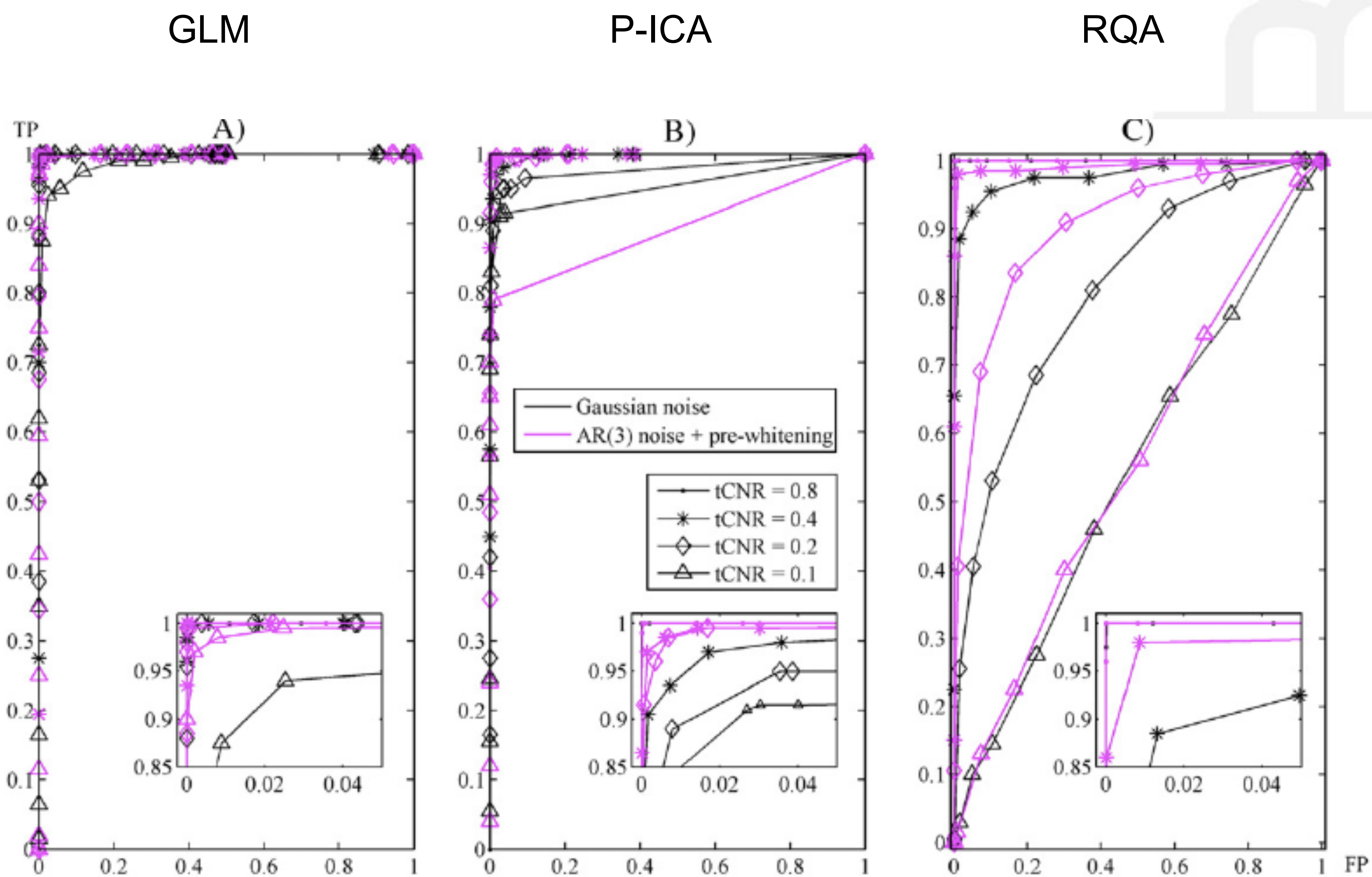
Model-free analysis of brain fMRI data by recurrence quantification

Marta Bianciardi,[a] Paolo Sirabella,[b] Gisela E. Hagberg,[a] Alessandro Giuliani,[c]
Joseph P. Zbilut,[d] and Alfredo Colosimo[b,*]

Comparison of RQA with GLM and P-ICA



Ability of three analyses to distinguish between noises in fMRI signal (ROC analysis)



Bianciardi, M., Sirabella, P., Hagberg, G. E., Giuliani, A., Zbilut, J. P., & Colosimo, A. (2007). Model-free analysis of brain fMRI data by recurrence quantification. *NeuroImage*, *37*(2), 489-503. doi:10.1016/j.neuroimage.2007.05.025

Summary

RQA(TM) - now comes with an errorbar


Physics Letters A 373 (2009) 2245–2250

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

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Confidence bounds of recurrence-based complexity measures

Stefan Schinkel[a,*], N. Marwan[a,b], O. Dimigen[c], J. Kurths[b,d]

http://www.agnld.uni-potsdam.de/~schinkel

Schinkel, S., Marwan, N., Dimigen, O., & Kurths, J. (2009). Confidence bounds of recurrence-based complexity measures. *Physics Letters A*, *373*(26), 2245-2250. Elsevier B.V. doi:10.1016/j.physleta.2009.04.045

Complexity Methods for Behavioural Science

Cross-Recurrence Quantification Analysis and other flavours of RP's

Fred Hasselman
f.hasselman@bsi.ru.nl

Behavioural Science Institute
Radboud University Nijmegen

Rescaling *before* Reconstruction

- You could also rescale the time series *before* you do the reconstruction:

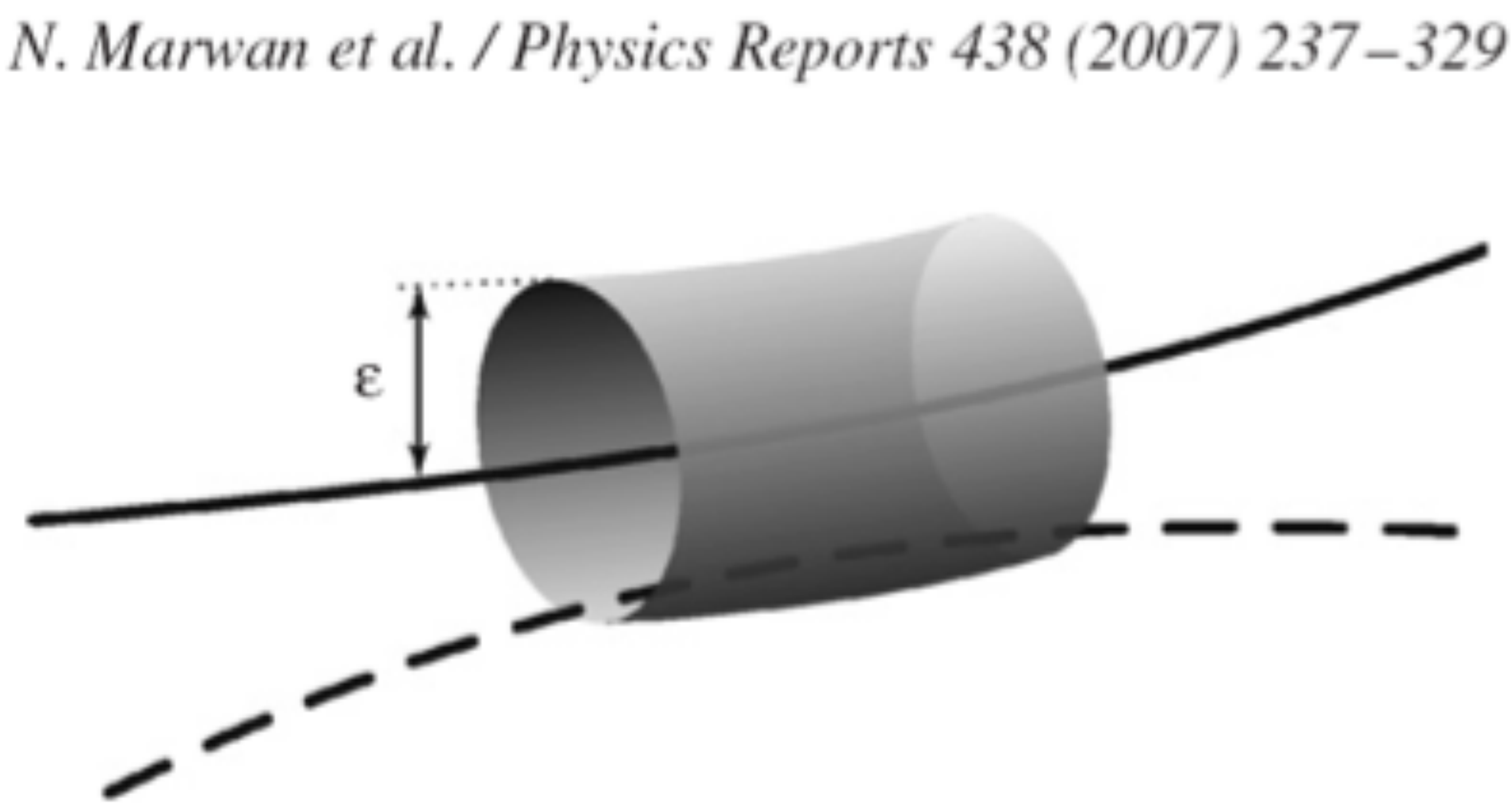
- **Max distance** -> unit scale $\mathbf{X}_{\mathbf{unit}} = (\mathbf{X}\text{-min}(\mathbf{X})) / (\text{max}(\mathbf{X})\text{-min}(\mathbf{X}))$

  Scale of 0-1 (in package *casnet* you can use the **elascer** function)

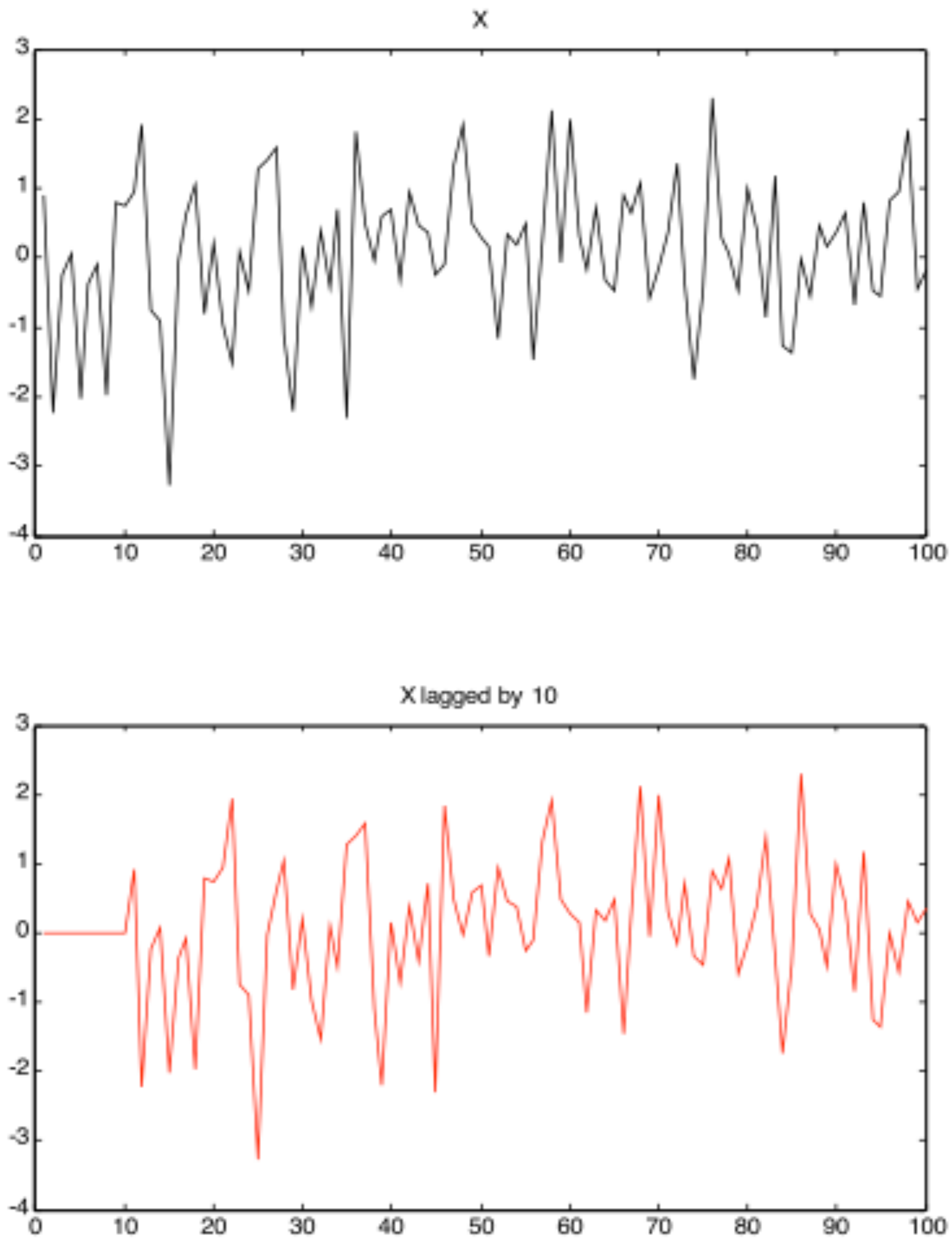
- **Mean distance** -> z-score $\mathbf{X}_{\mathbf{z}} = (\mathbf{X}\text{-mean}(\mathbf{X})) / \text{std}(\mathbf{X})$

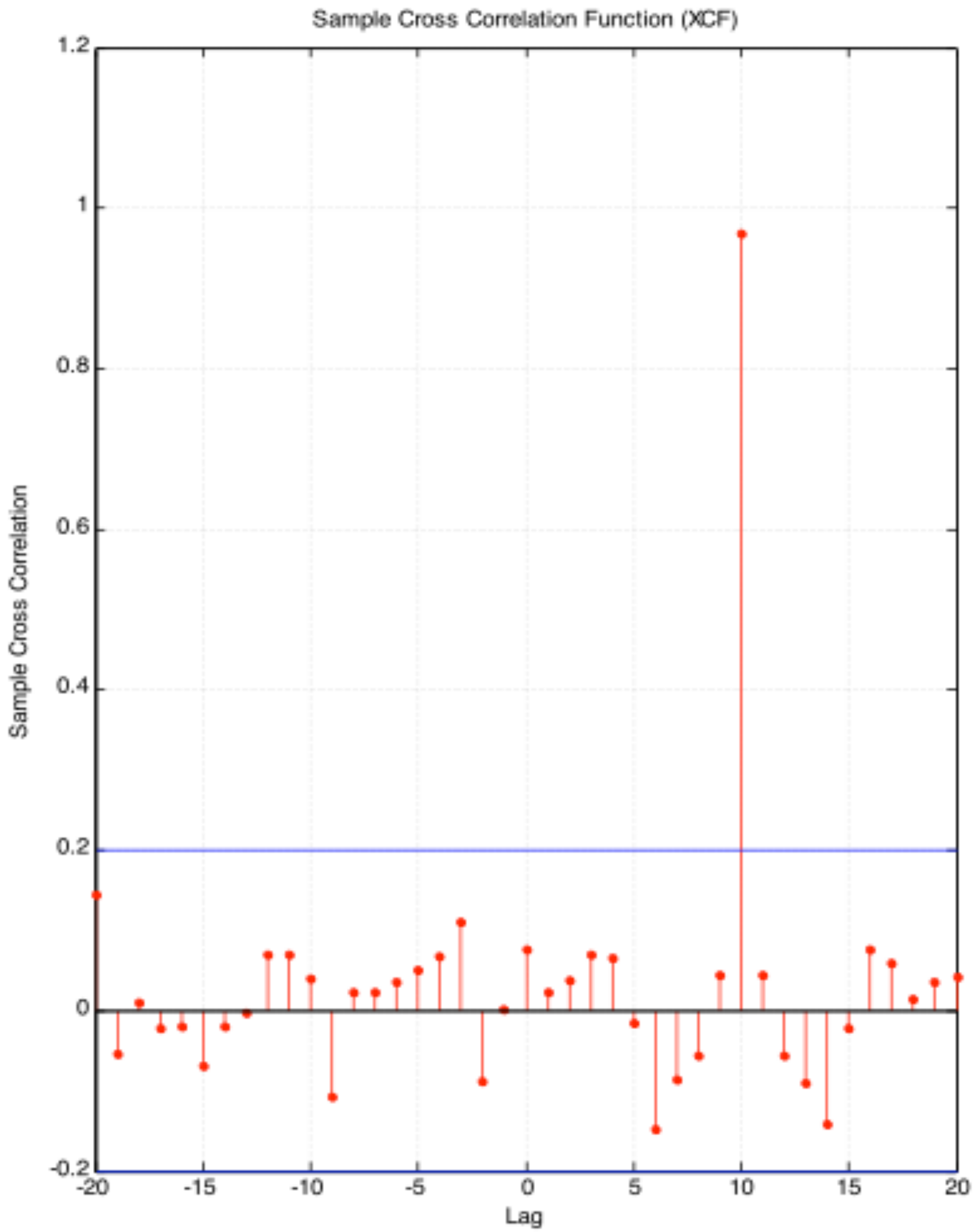
  Z-score scale (in package *casnet* you can use the **ts_standardise** function with: **adjustN = FALSE**)

Within radius / threshold = shared trajectory

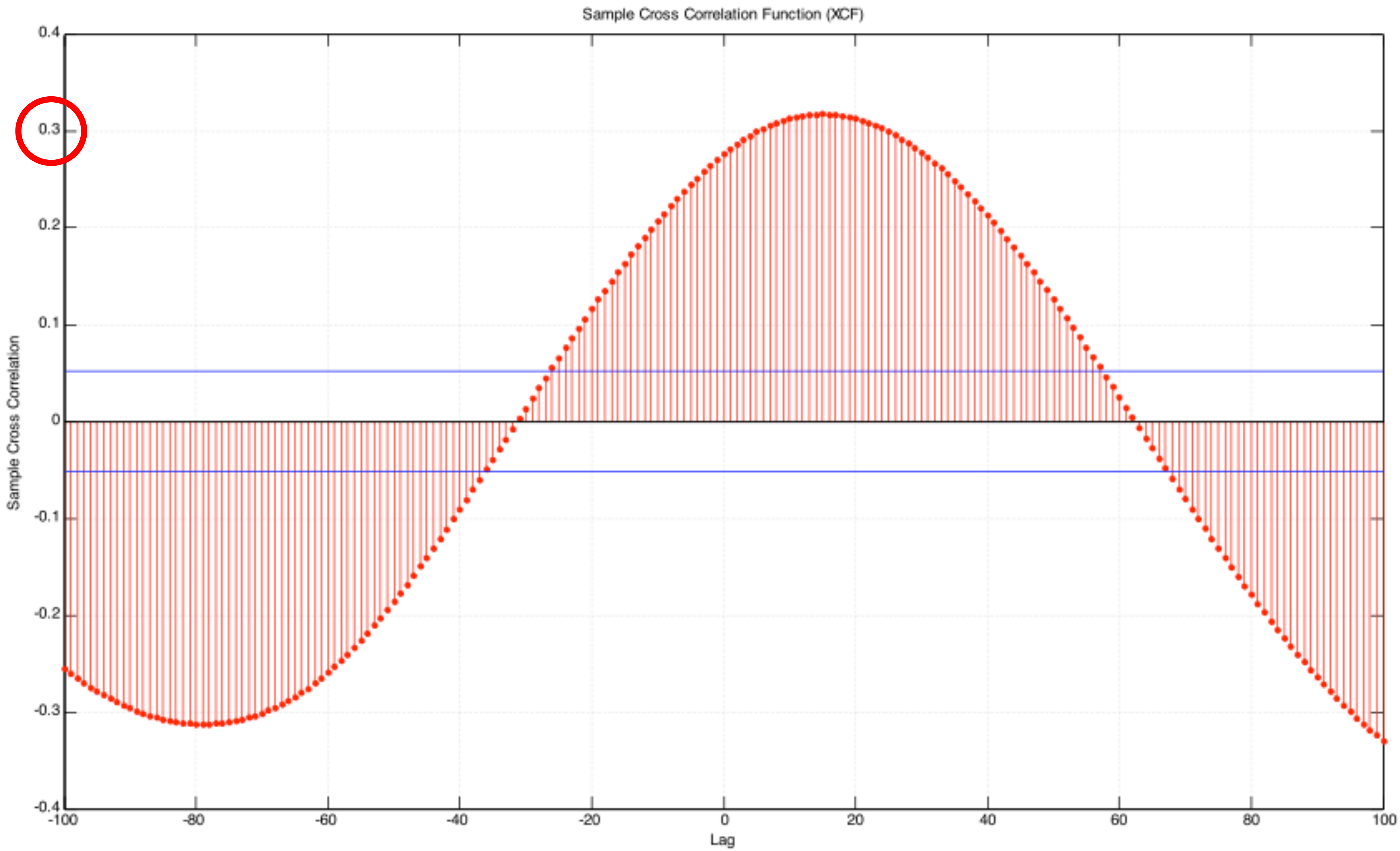


Intuitive notion of synchronisation – Cross Correlation

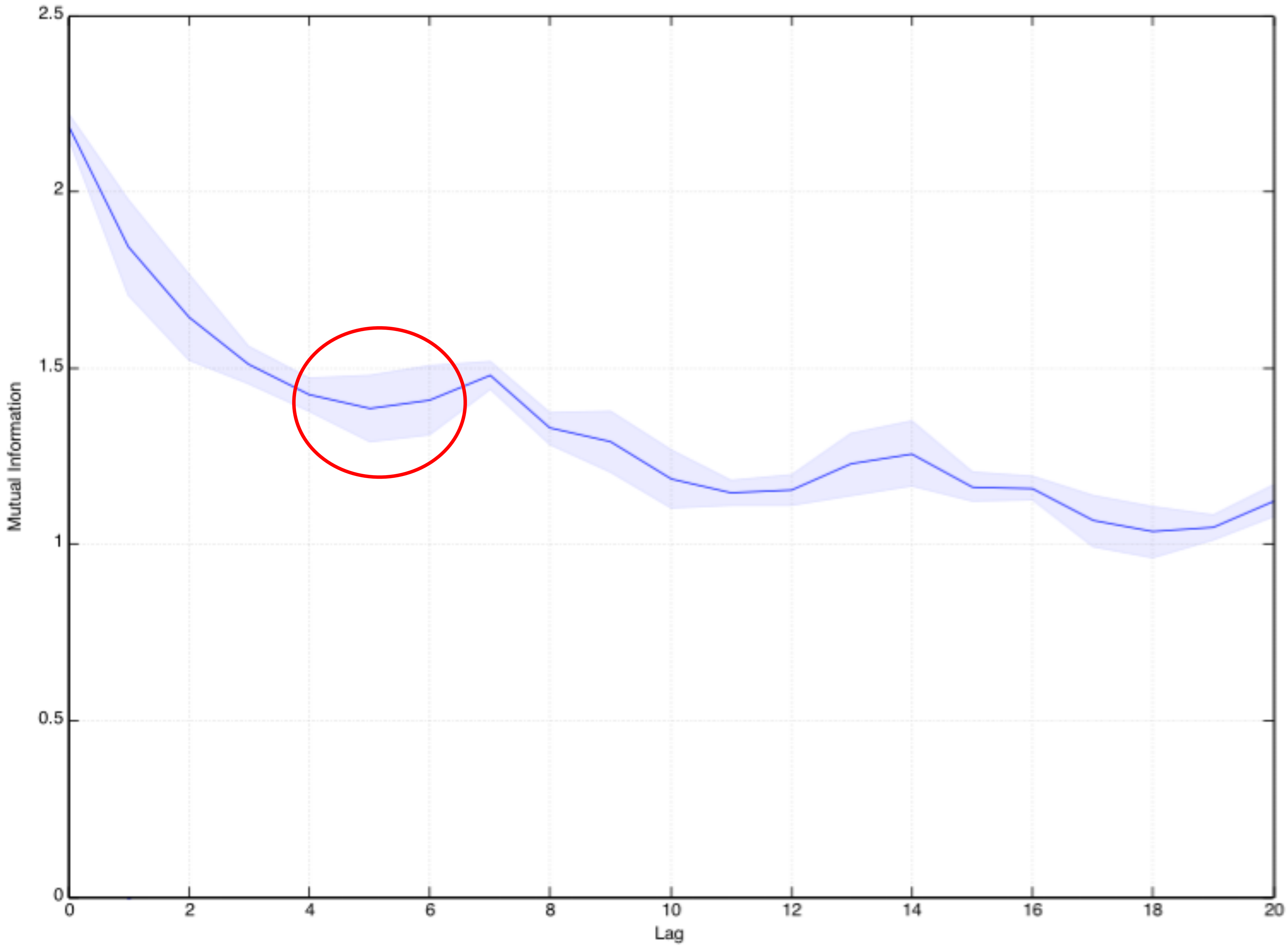


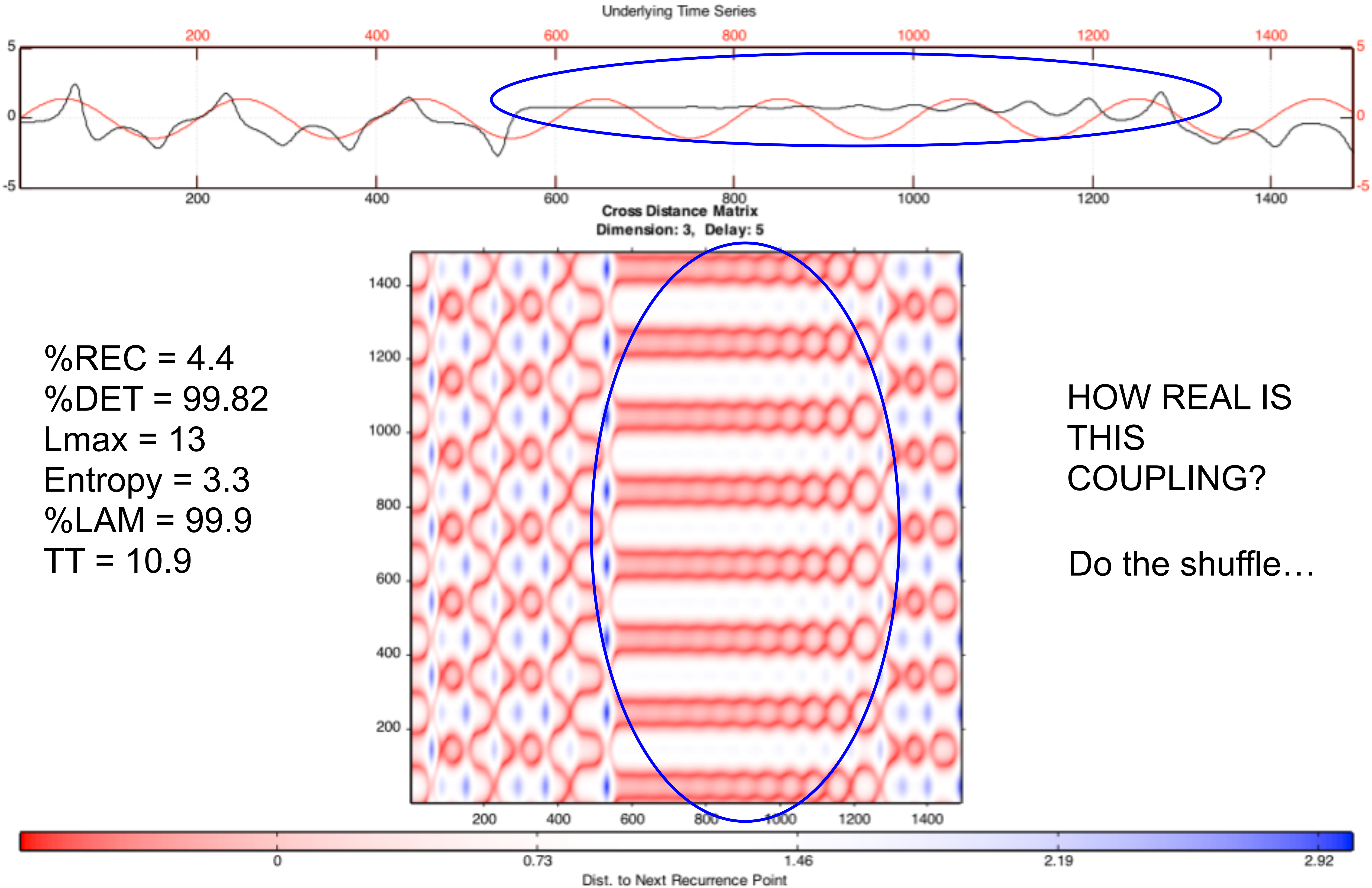


Intuitive notion of synchronisation – Cross Correlation



Lorenz and Spiral – Mutual Information

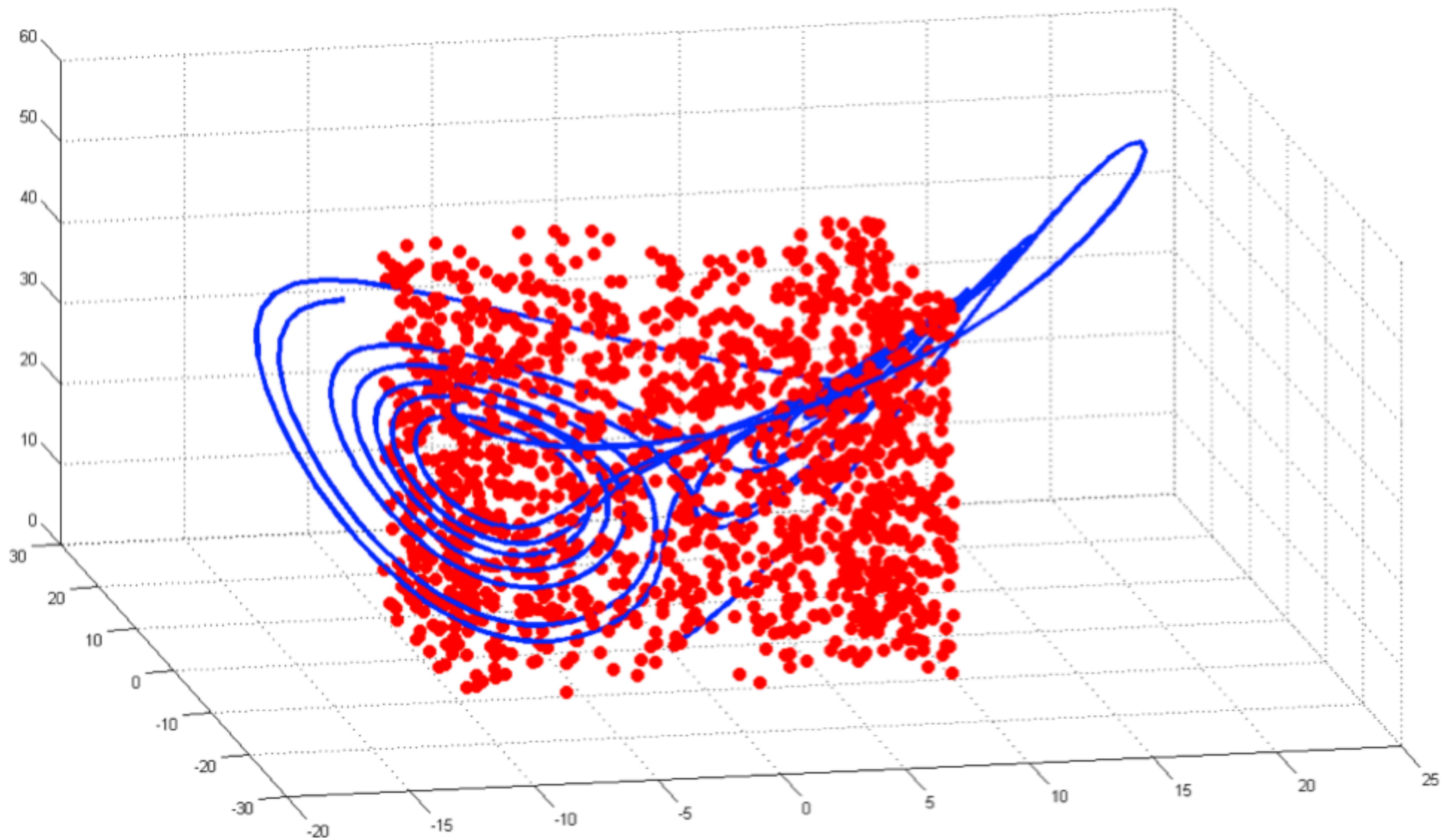


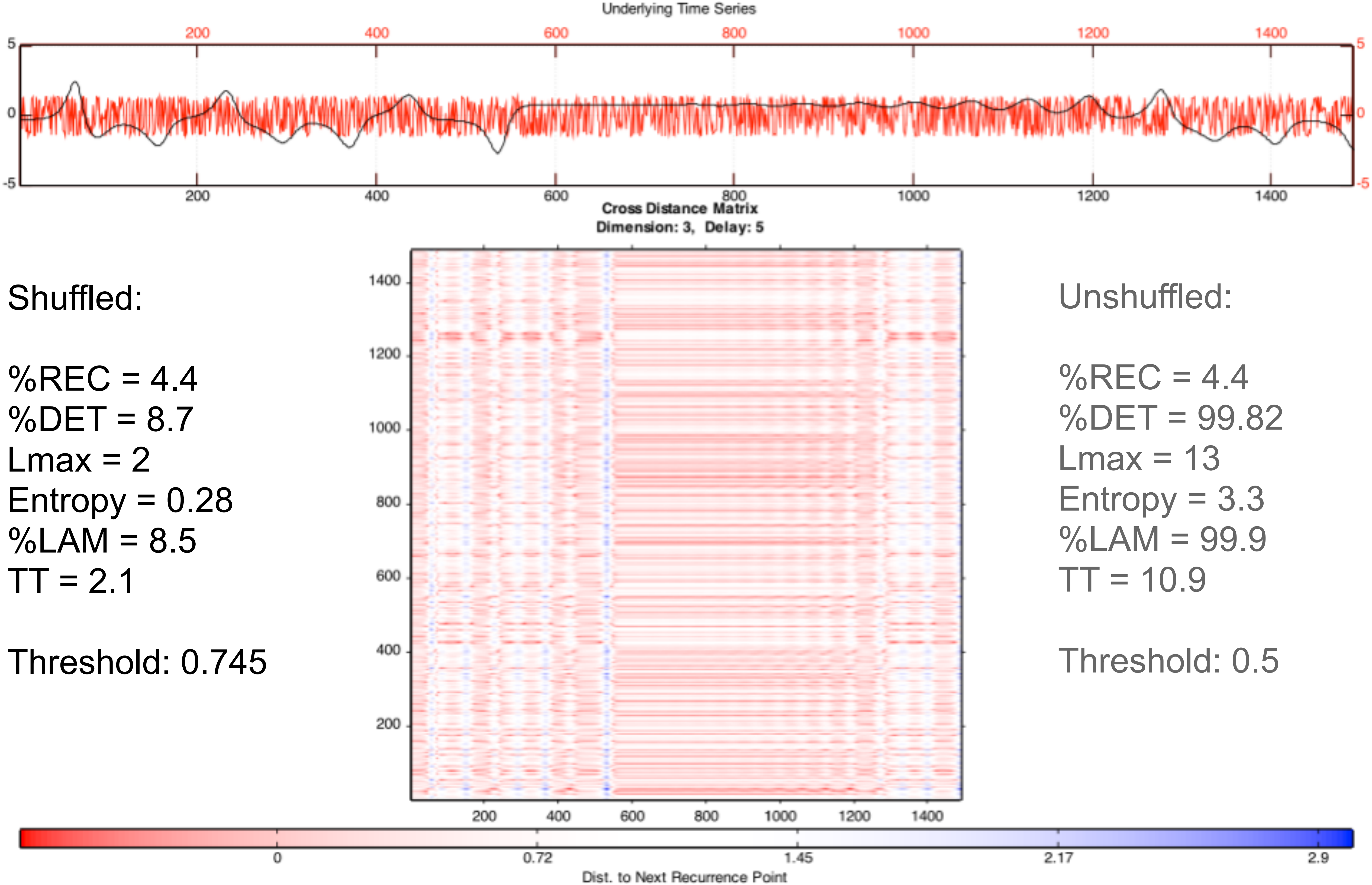


%REC = 4.4
%DET = 99.82
Lmax = 13
Entropy = 3.3
%LAM = 99.9
TT = 10.9

HOW REAL IS THIS COUPLING?

Do the shuffle…


60
50
40
30
20
10
0
30
20
10
0
-10
-20
-30
-20
-15
-10
-5
0
5
10
15
20
25



Shuffled:

%REC = 4.4
%DET = 8.7
Lmax = 2
Entropy = 0.28
%LAM = 8.5
TT = 2.1

Threshold: 0.745

Unshuffled:

%REC = 4.4
%DET = 99.82
Lmax = 13
Entropy = 3.3
%LAM = 99.9
TT = 10.9

Threshold: 0.5

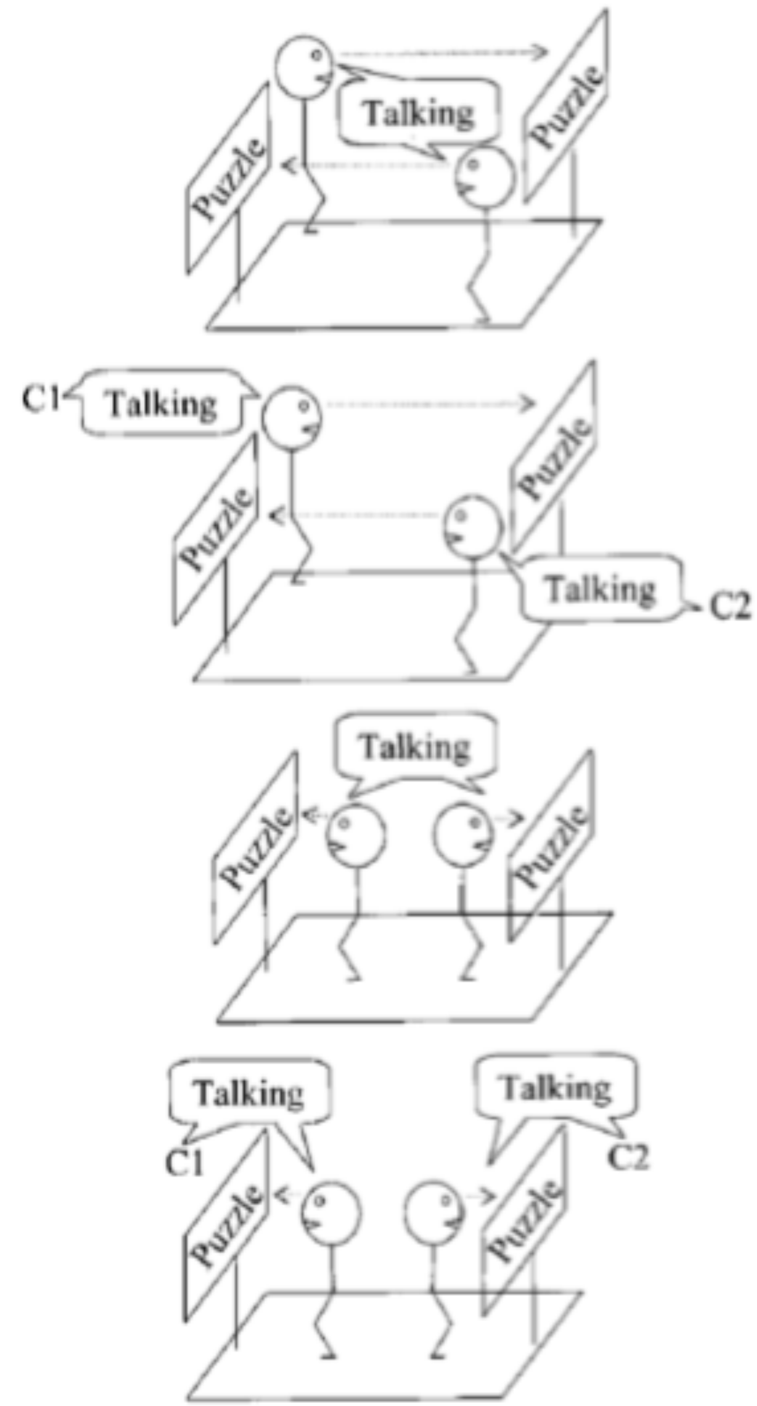
Some Applications

- Coupling of postural sway through communication
- Coupling of language development between infant and caretaker
- Coupling of eye movements to communication

Coupling of postural sway through communication

- Postural sway measured by force plate

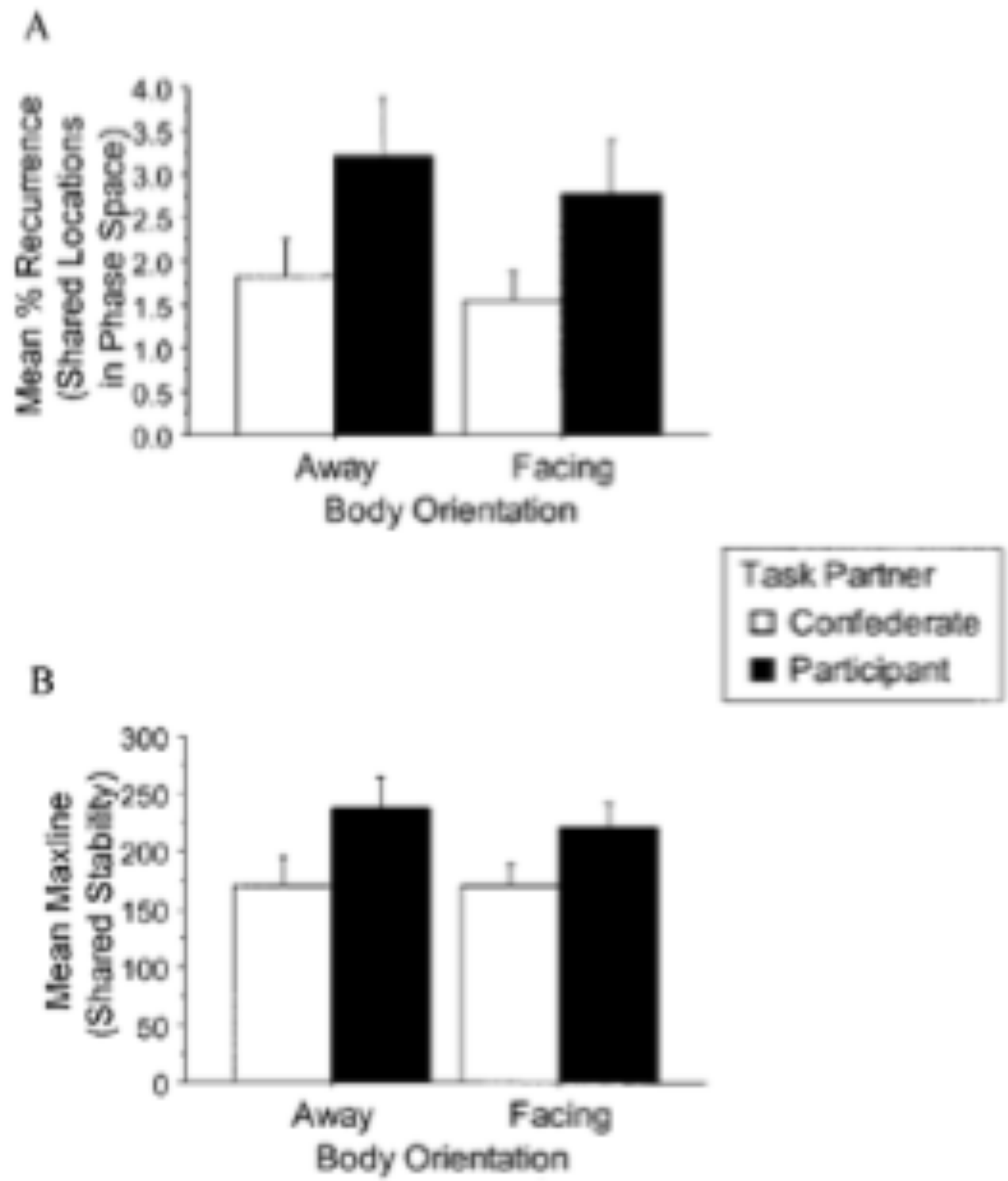
- Level of direct communication manipulated by talking directly or to confederate / visibility



Shockley, K., Santana, M-V., Fowler, C. (2003). Mutual Interpersonal Postural Constraints Are Involved in Cooperative Conversation. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 326-323.

Coupling of postural sway through communication

Speech can be a "coupling tool" for coordination of previously autonomous bodies



Shockley, K., Santana, M-V., Fowler, C. (2003). Mutual Interpersonal Postural Constraints Are Involved in Cooperative Conversation. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 326-323.

Coupling of language development between infant and caretaker

Dale, R., & Spivey, M.J. (2006). Unraveling the dyad: Using recurrence analysis to explore patterns of syntactic coordination between children and caregivers in conversation. *Language Learning, 56(3)*, 391–430

Rick Dale has introduced some interesting applications of Recurrence Analysis:

- CRQA on categorical/nominal data
- "LOS"-profile, as a measure of who's leading and who's trailing

Categorical (C)RQA:

- The RP's of the poems are an example of recurrence plots on categorical data. The recurring values represent an arbitrary category.

- Dale examined transcriptions of conversations between children and caregivers (CHILDES). The unit of analysis was syntactic structure

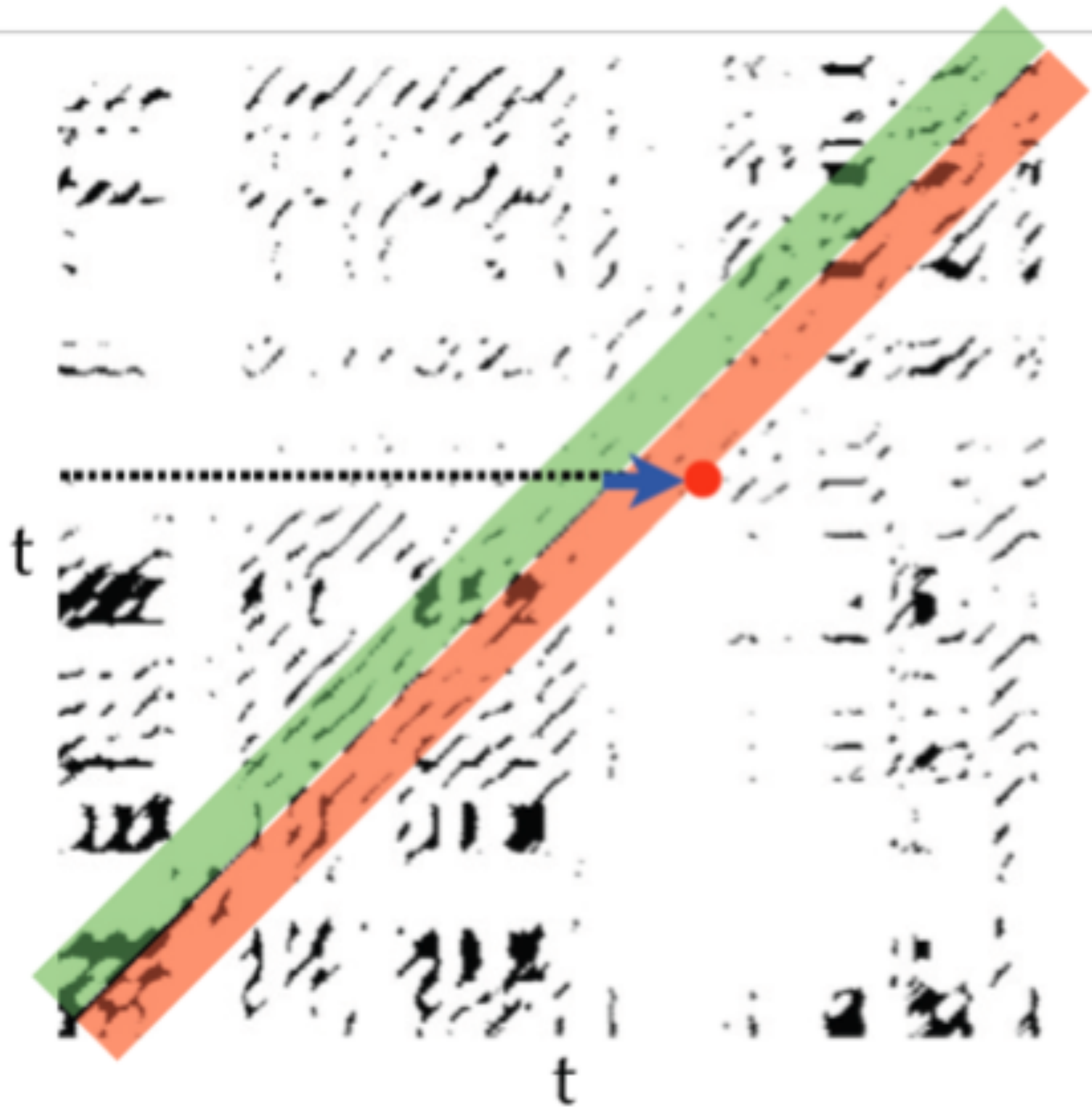
The RQA parameters become extremely simple, no need for estimation:

Lag = 1, Embedding = 1, Threshold / Radius = 0

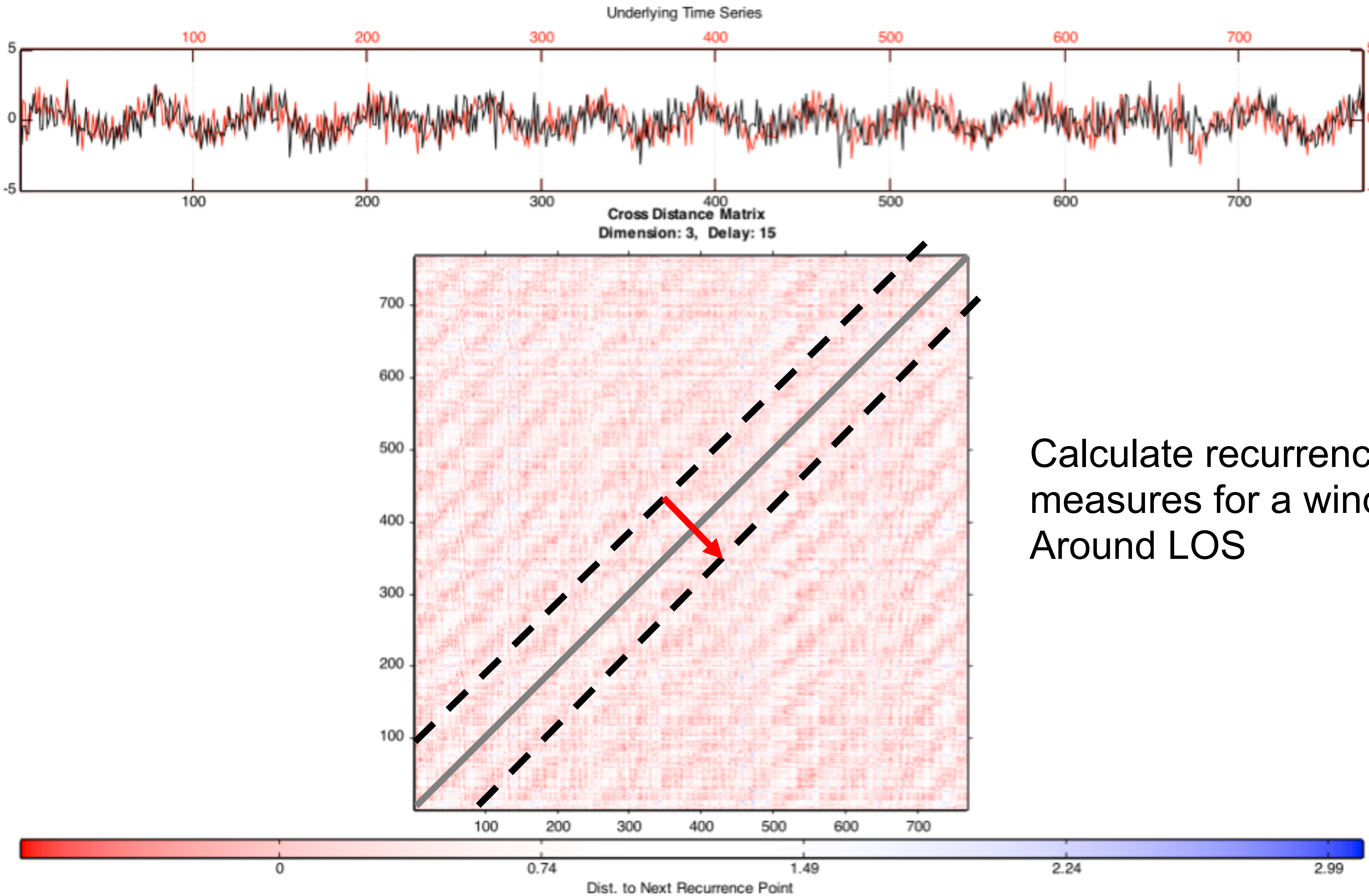
Who leads?

Time Series
On Y-axis
leads at red dot:

The category- / word- / syntactic- / pattern first occurred there,
in the X-axis series
it occurred later

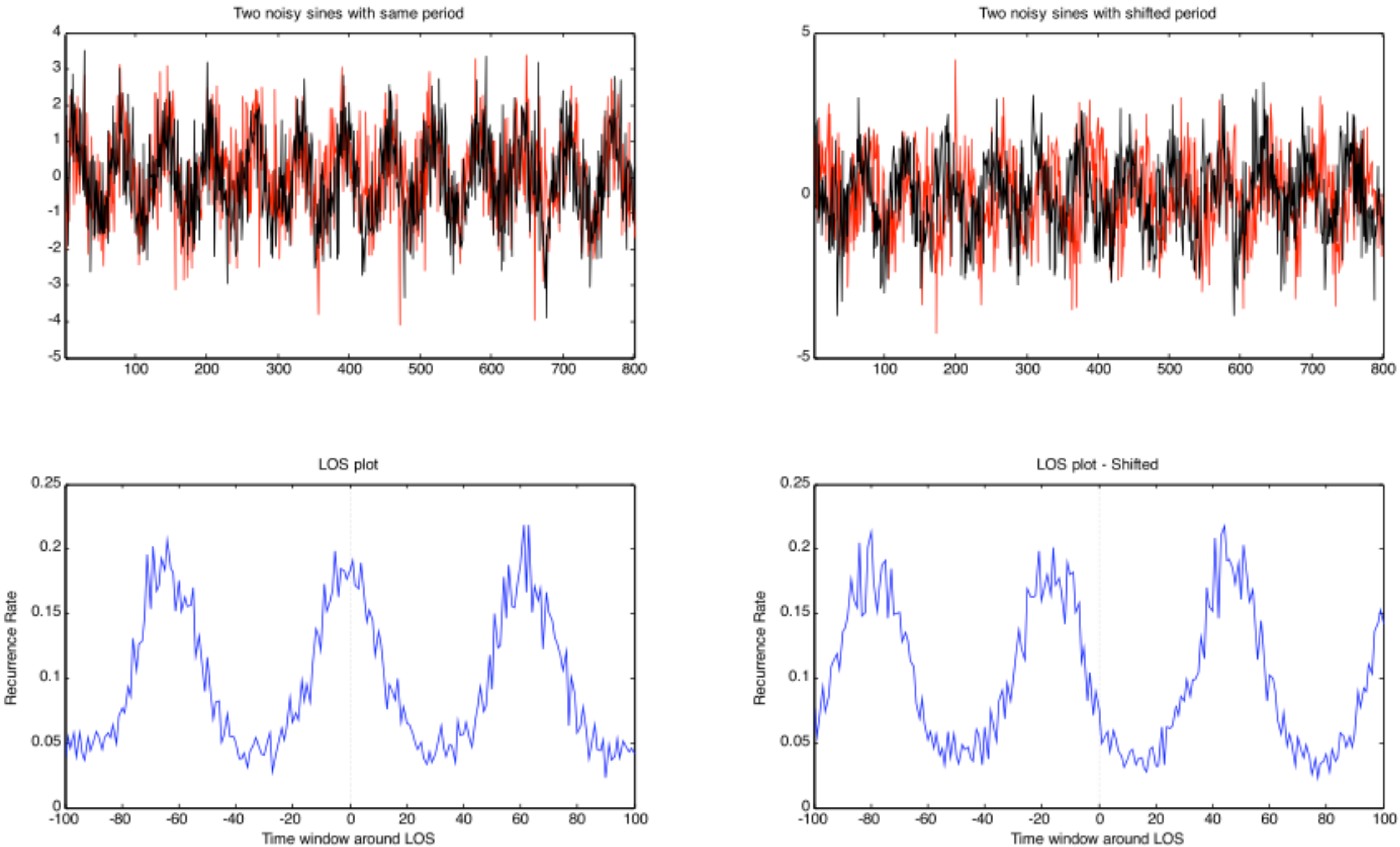


Diagonal Recurrence Profile



Calculate recurrence measures for a window Around LOS

Diagonal Recurrence Profile



Behavioural Science Institute
Radboud University Nijmegen

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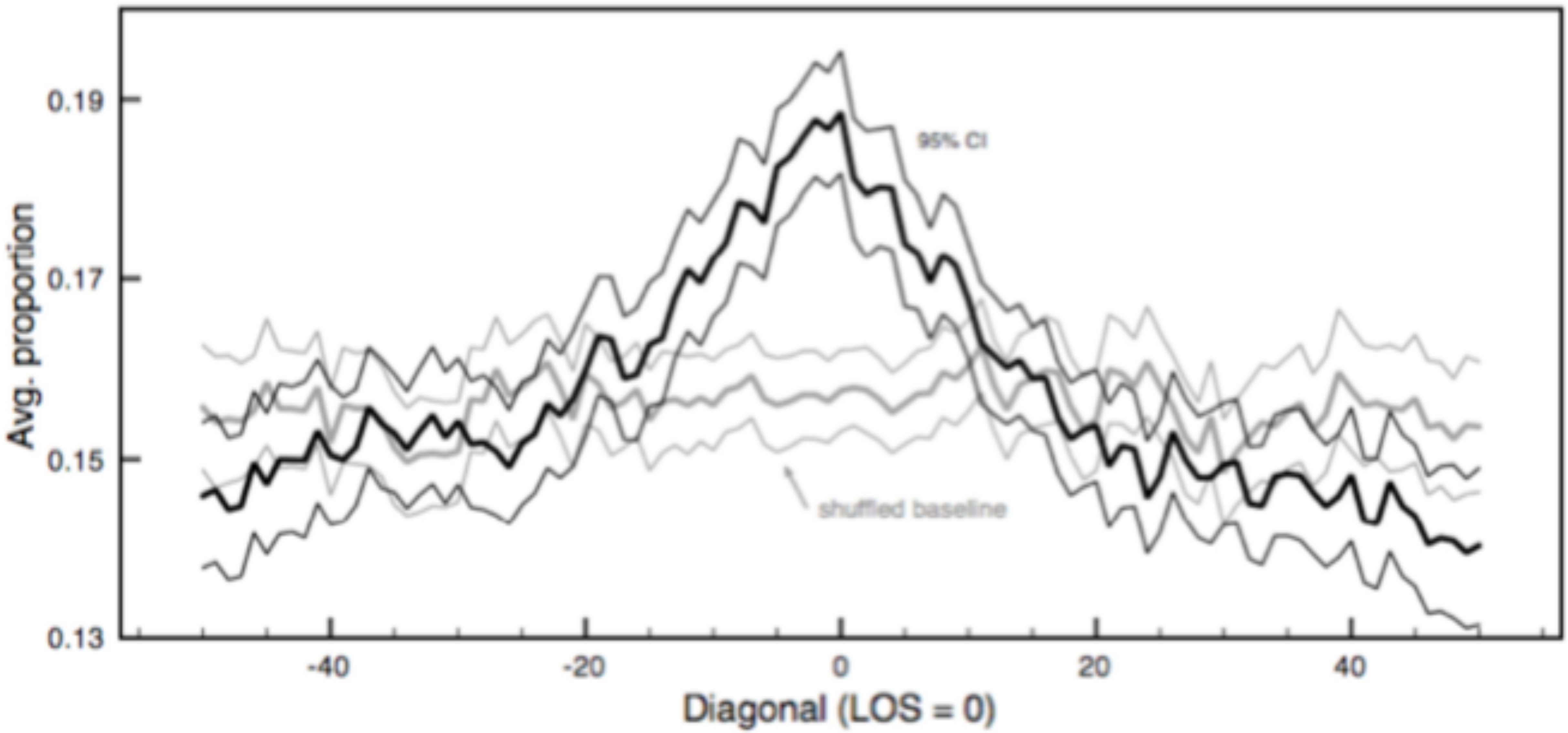

Coupling of language development between infant and caretaker

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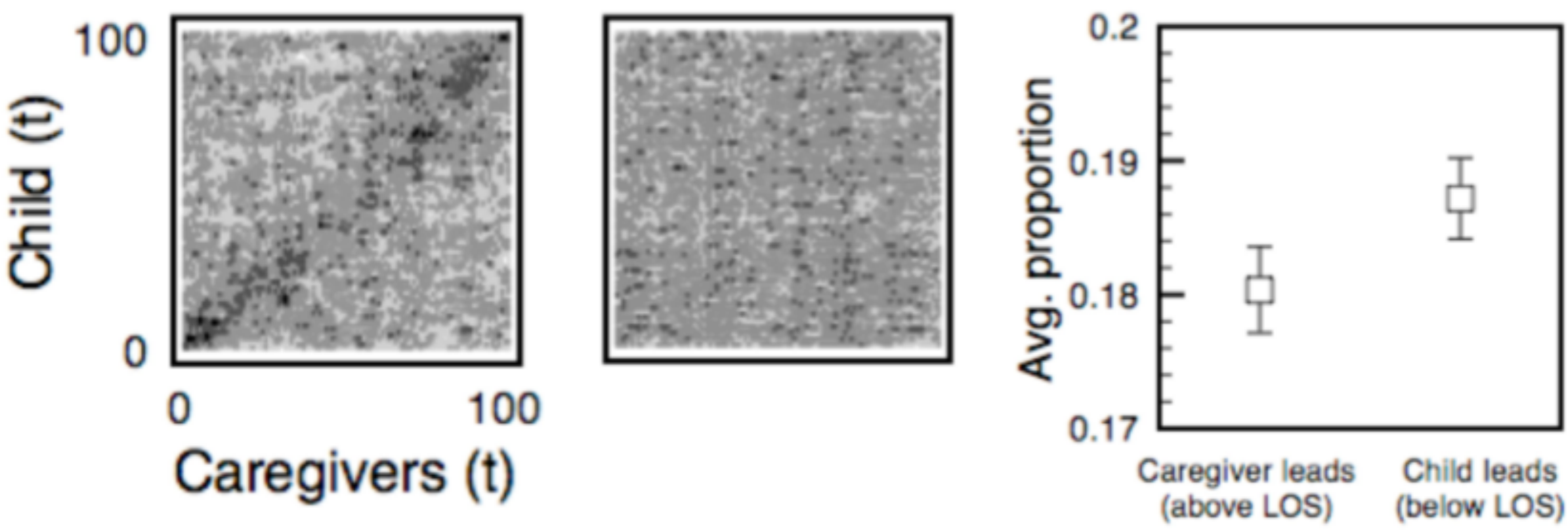
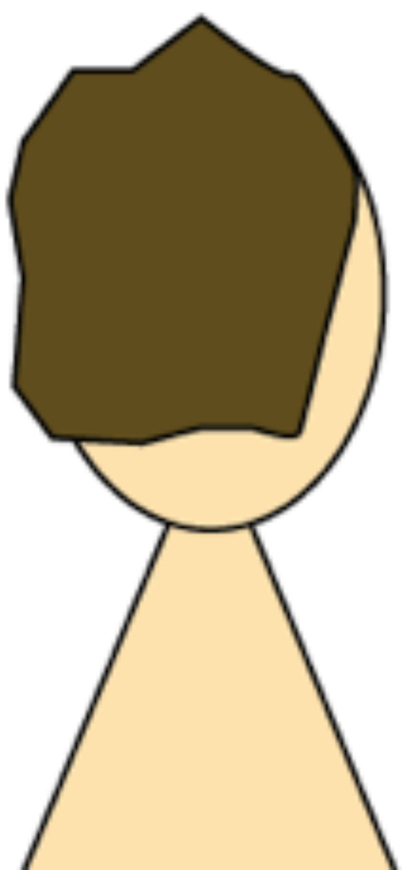


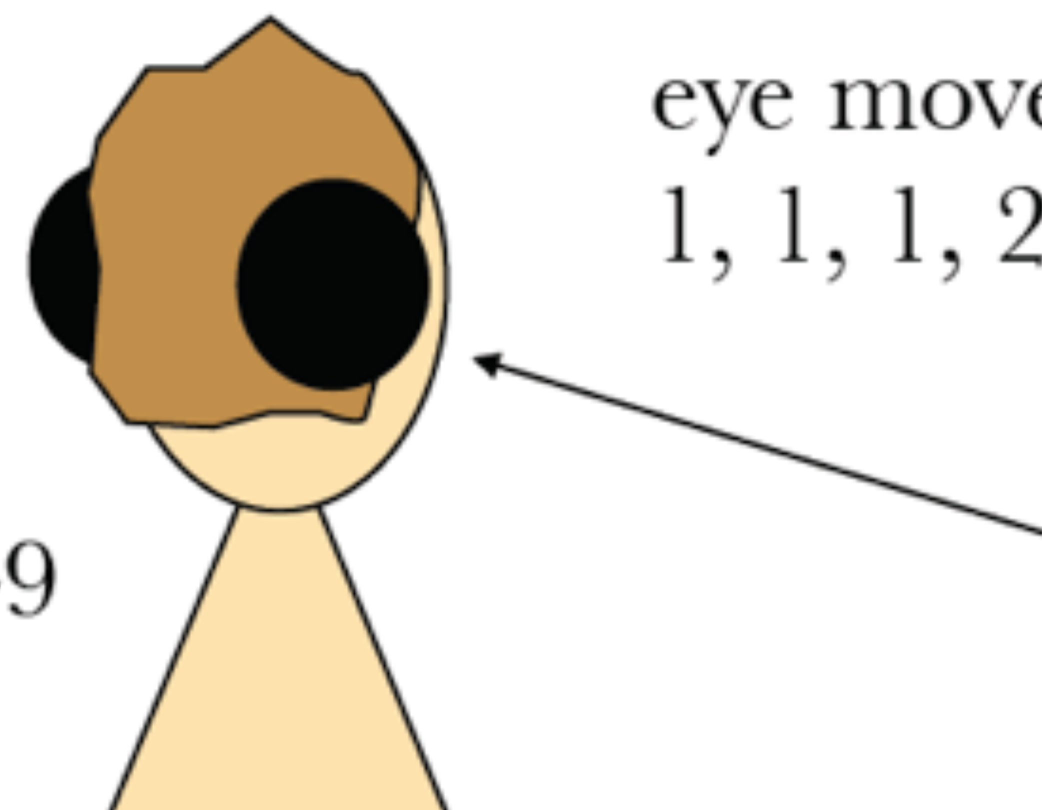


eye movement patterns...

1, 2, 2, 2, 2, 4, 4, 5, ...

"blah blah blah..."

N = 4



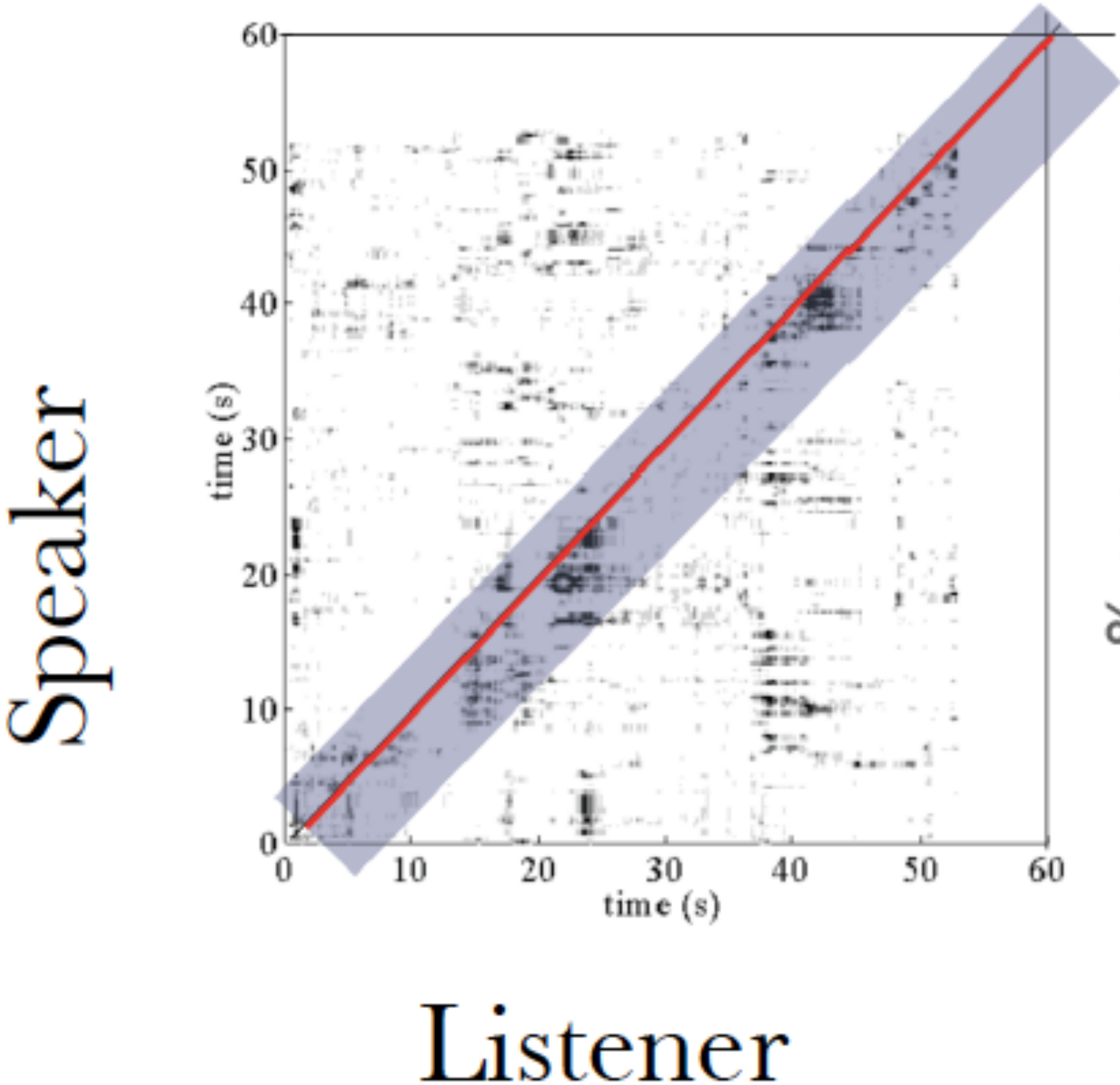
eye movement patterns...
1, 1, 1, 2, 2, 2, 2, 4, ...

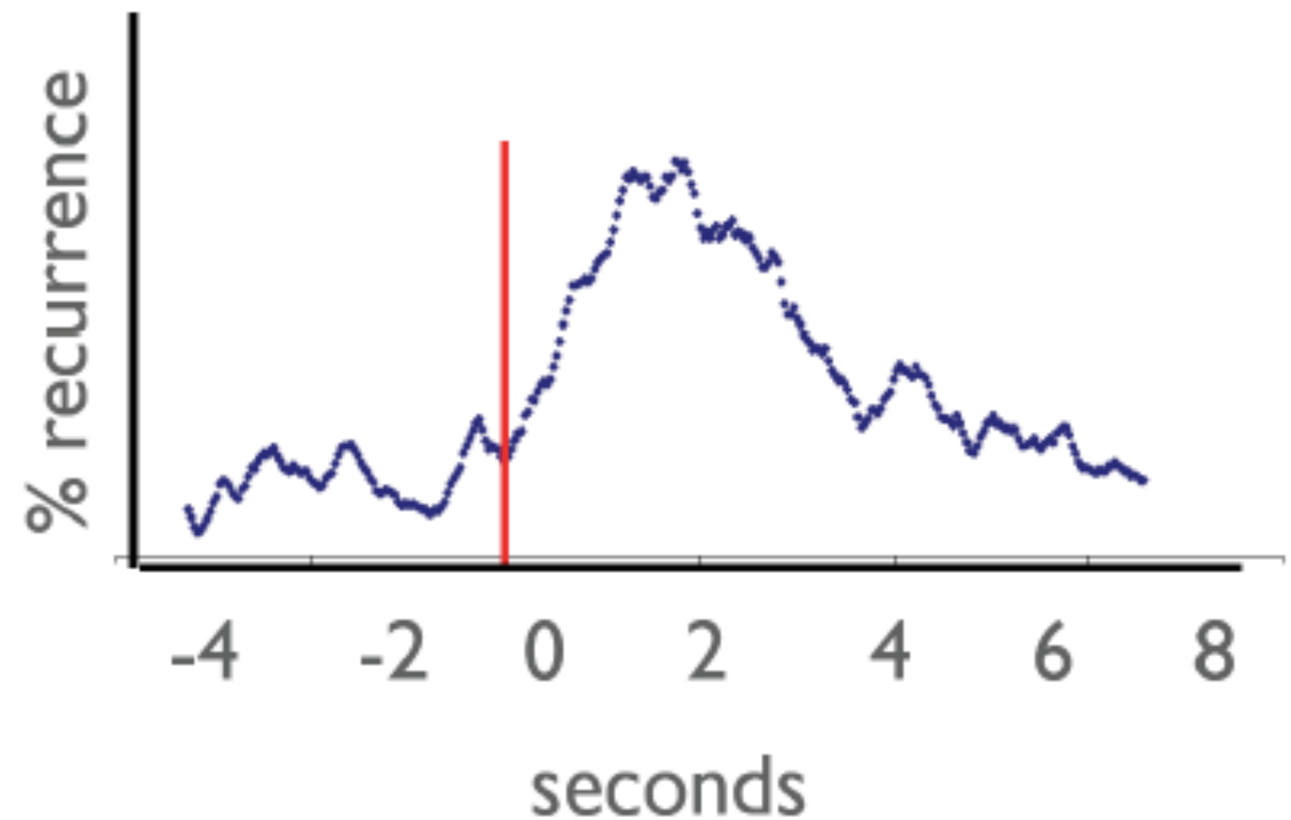
“blah blah blah...”

N = 49

Coupling of eye movements to communication

Richardson, D.C., Dale, R., Kirkham, N.Z. (2007). The art of conversation is coordination. *Psychological Science*, *18*, 407-413.



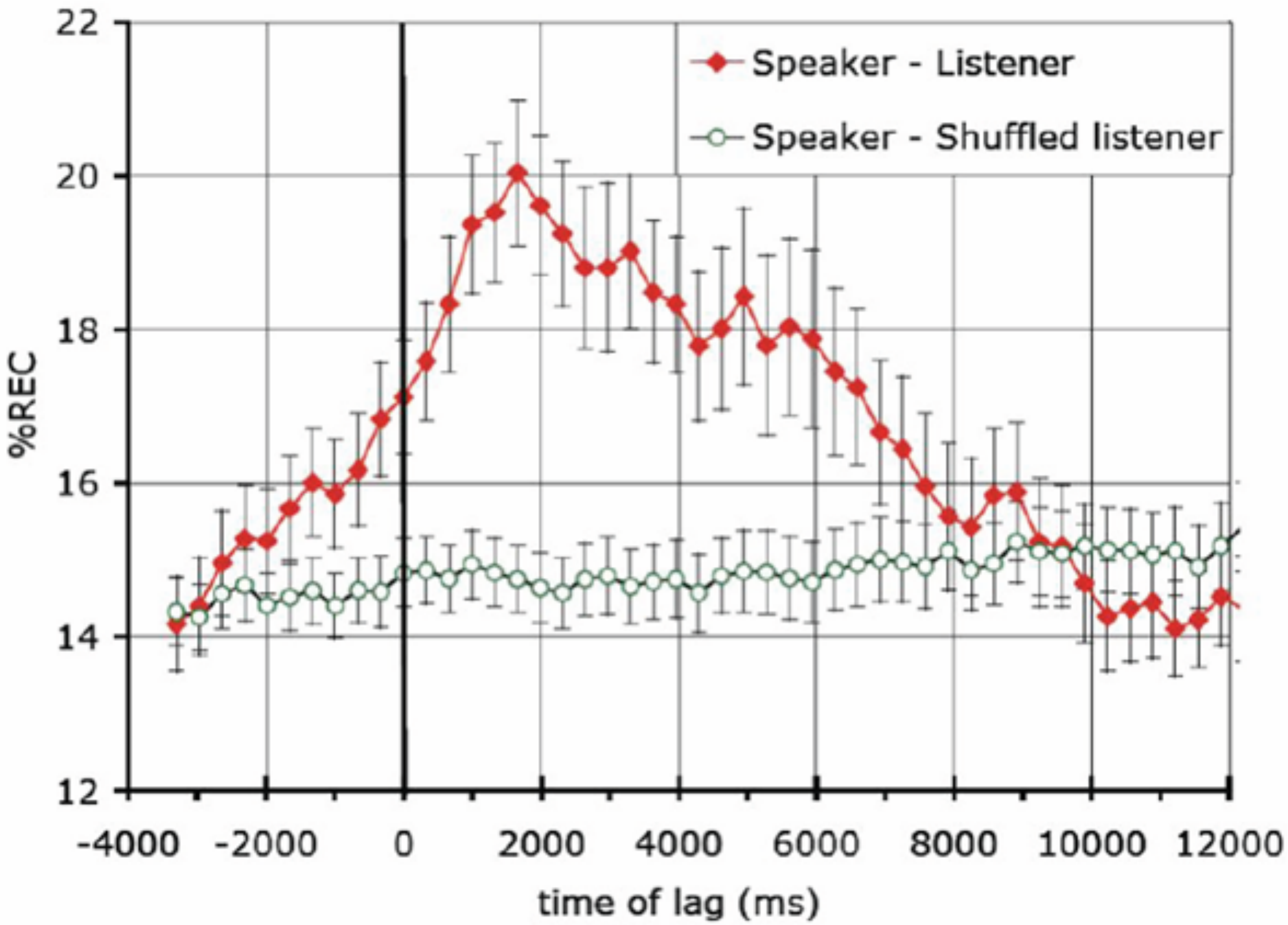


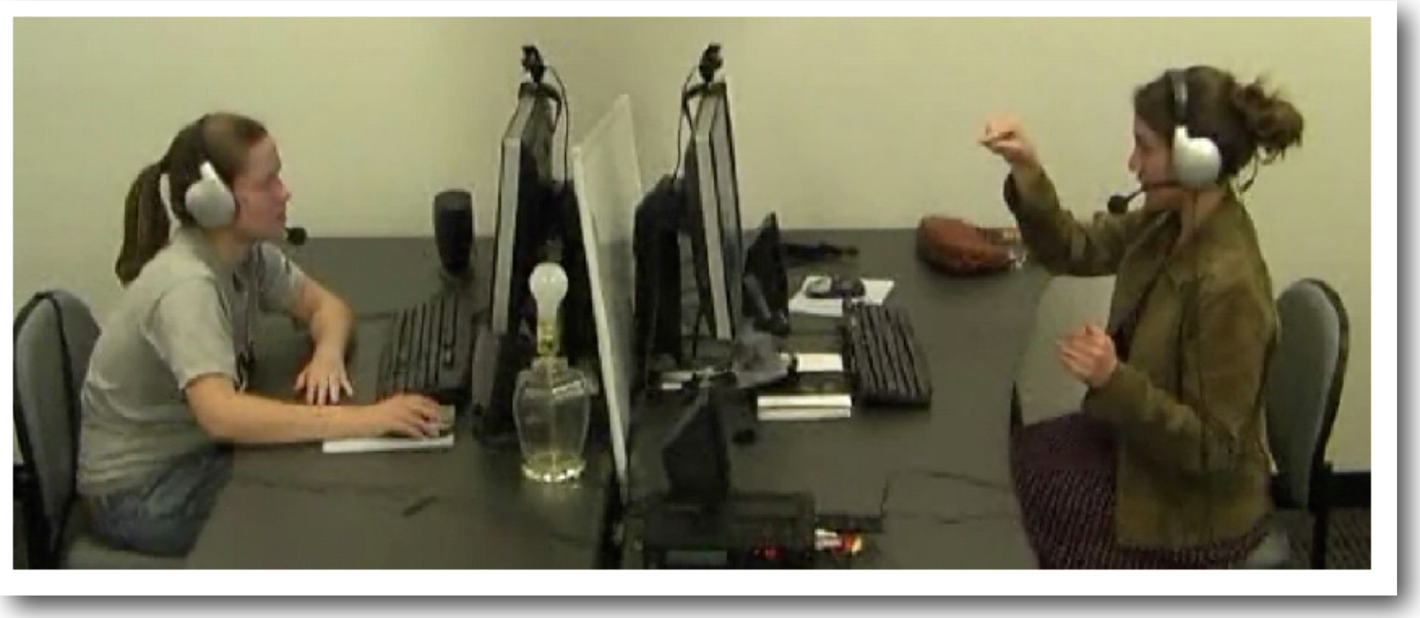
Richardson & Dale, 2005

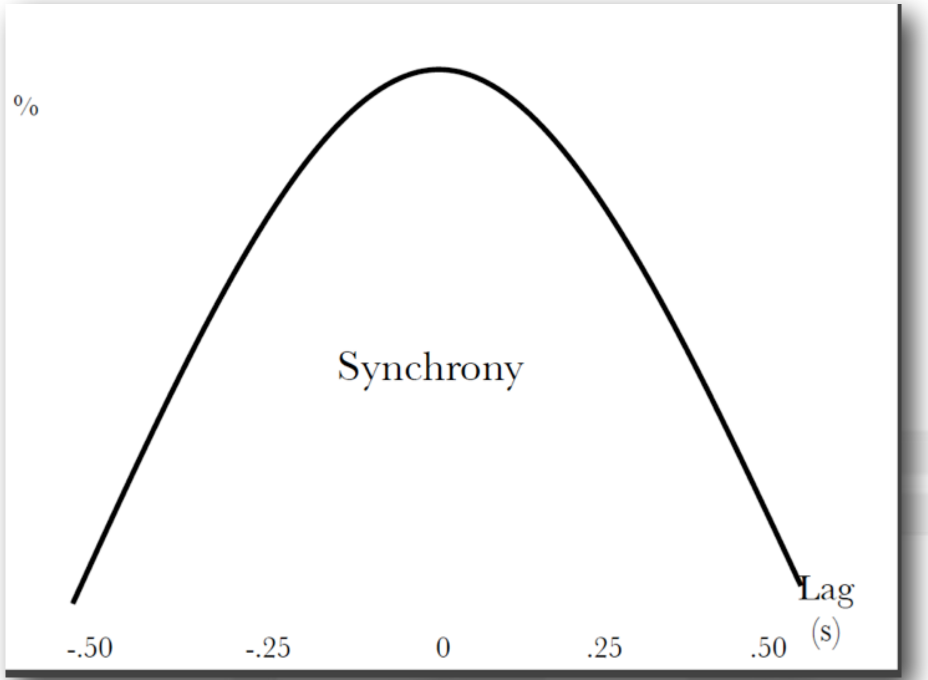
Coupling of eye movements to communication

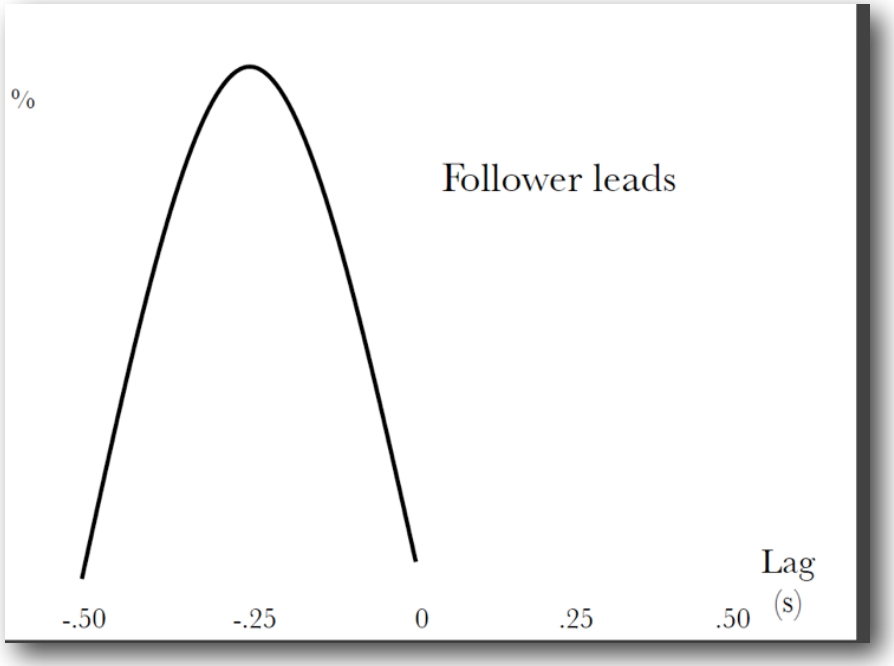
Richardson, D.C., Dale, R., Kirkham, N.Z. (2007). The art of conversation is coordination. *Psychological Science*, *18*, 407-413.

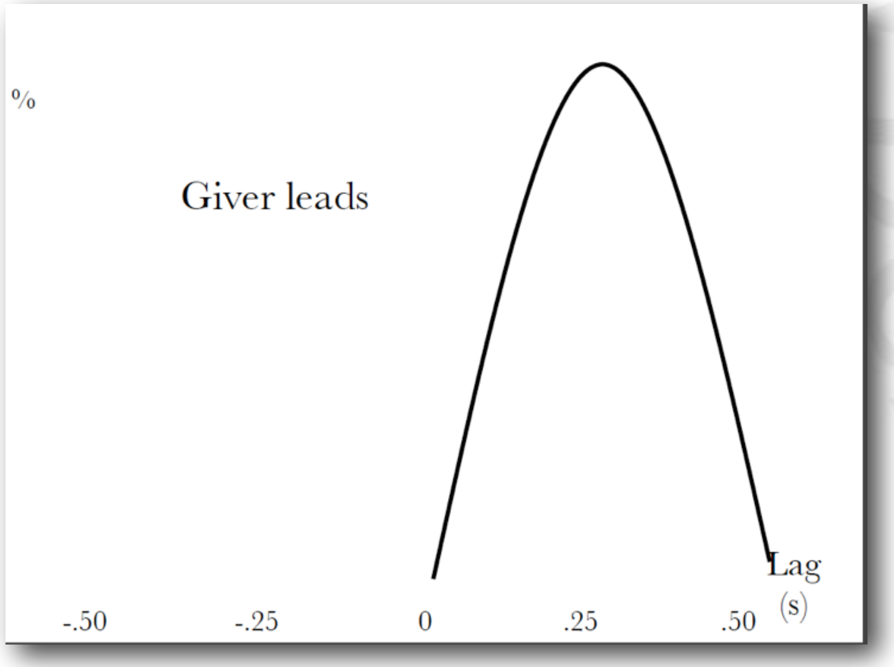
Listeners eye movements are coupled and lagging depending on level of interaction in conversation

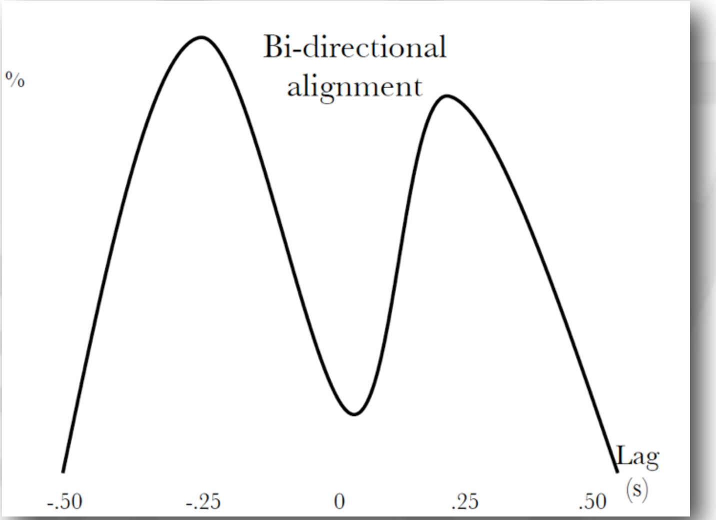




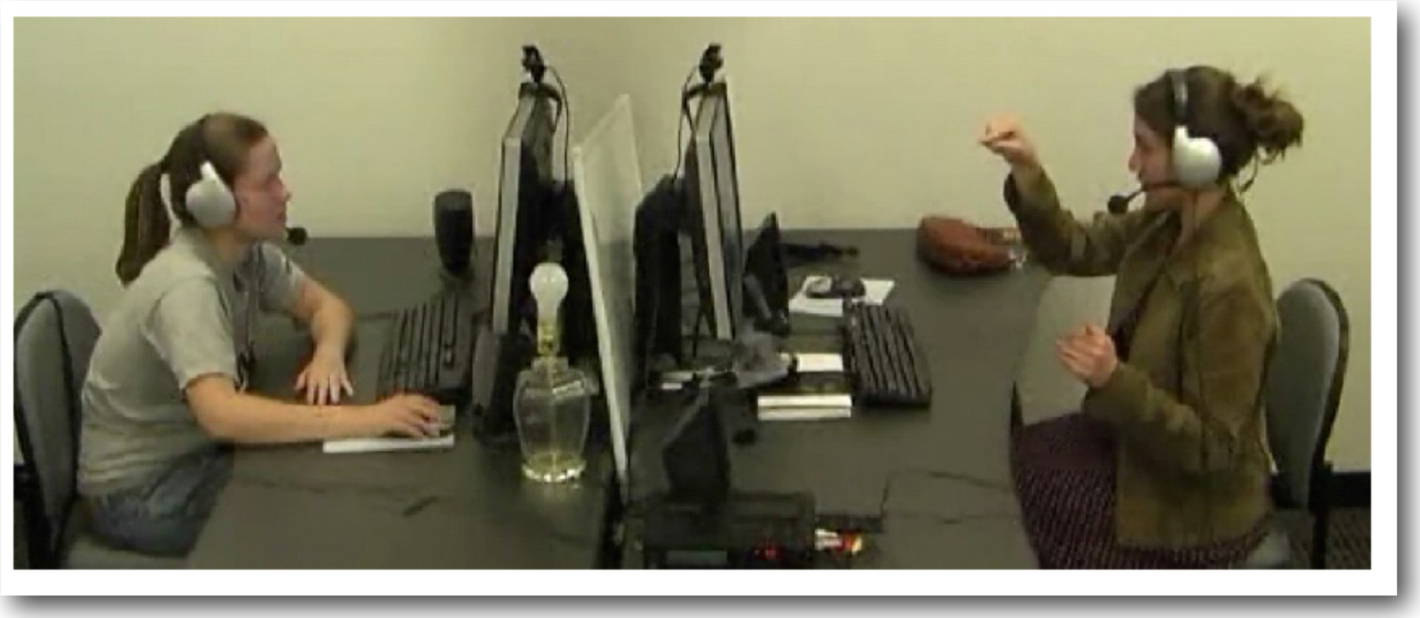


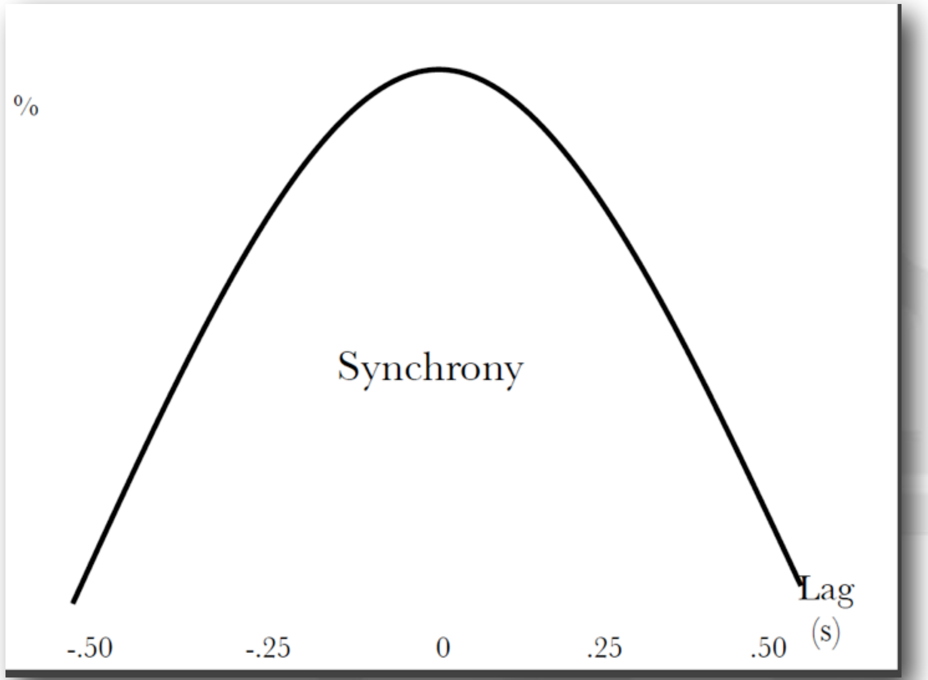


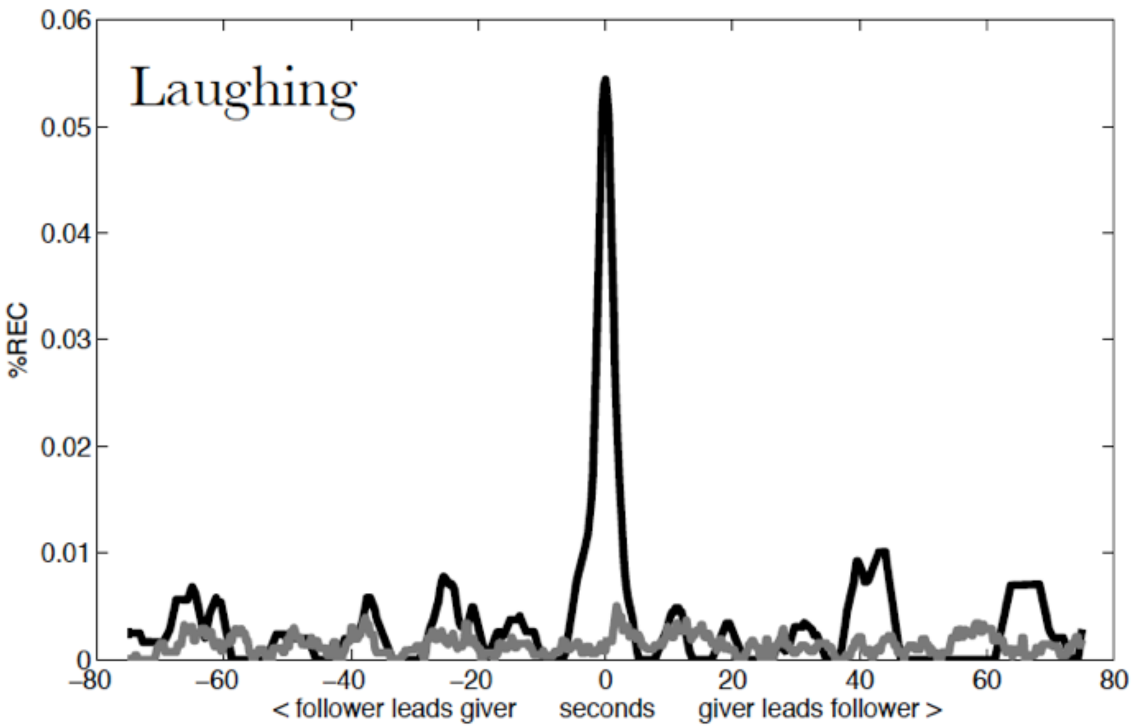




Louwerse, M. M., Dale, R., Bard, E. G., & Jeuniaux, P. (2012). Behavior matching in multimodal communication is synchronized. *Cognitive science*, *36*(8), 1404–26. doi:10.1111/j.1551-6709.2012.01269.x

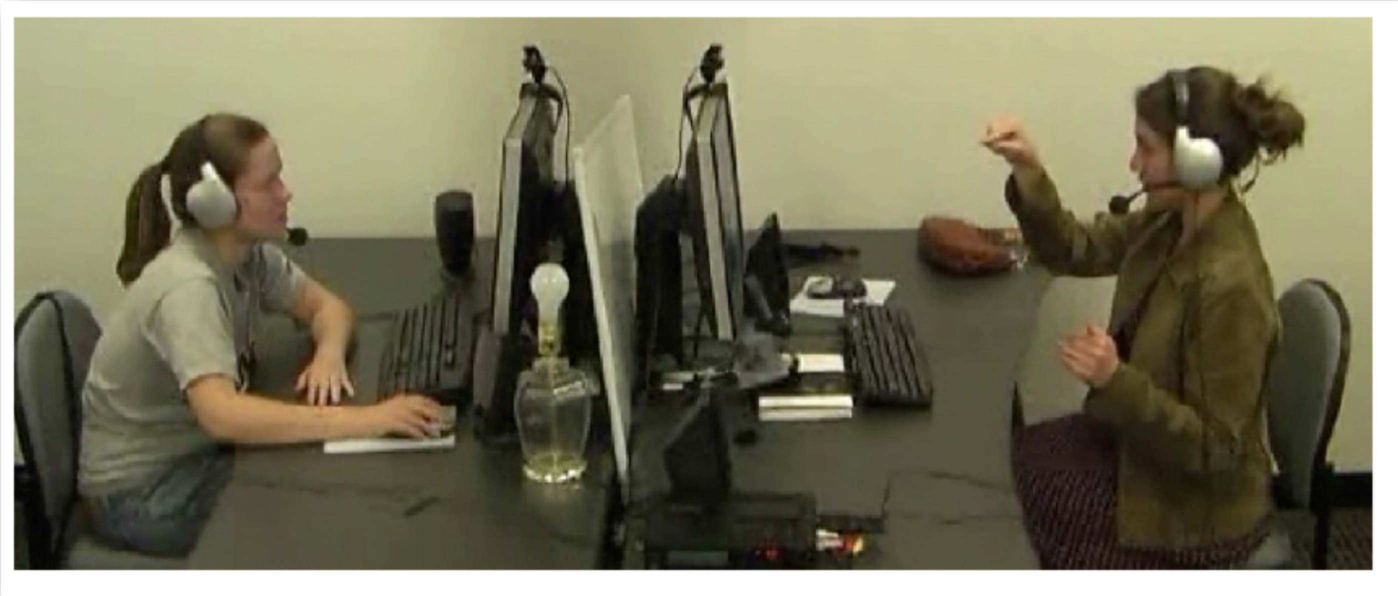


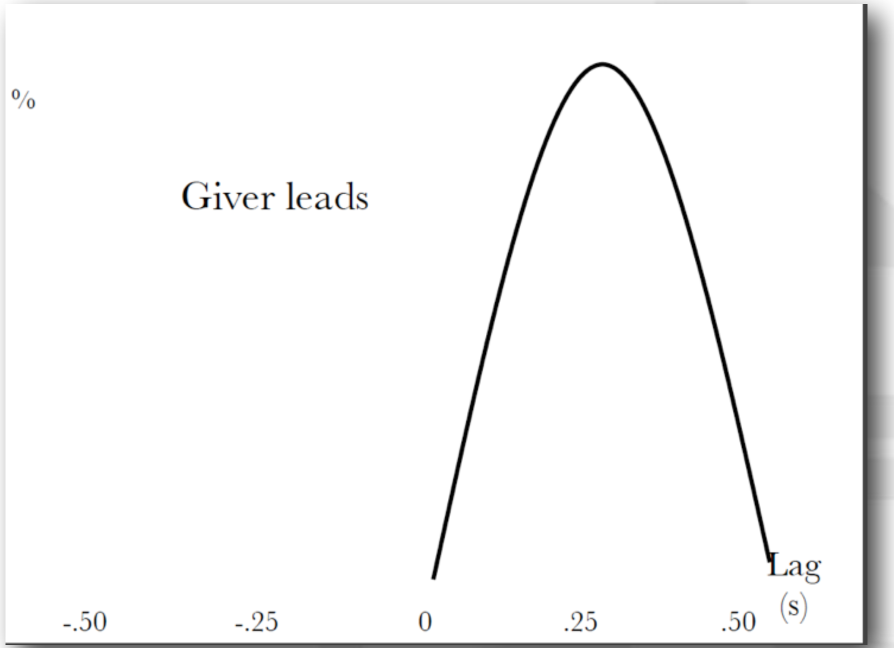


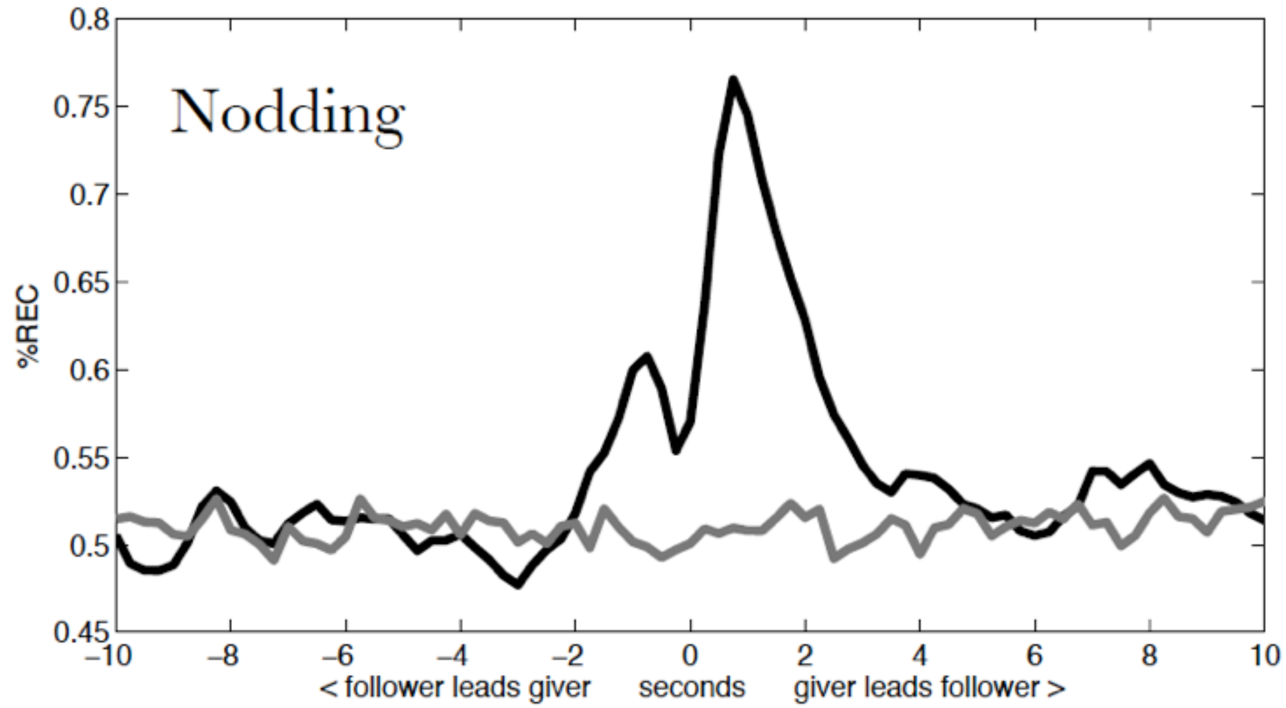


Louwerse, Dale, et al., in prep

Louwerse, M. M., Dale, R., Bard, E. G., & Jeuniaux, P. (2012). Behavior matching in multimodal communication is synchronized. *Cognitive science*, *36*(8), 1404–26. doi:10.1111/j.1551-6709.2012.01269.x

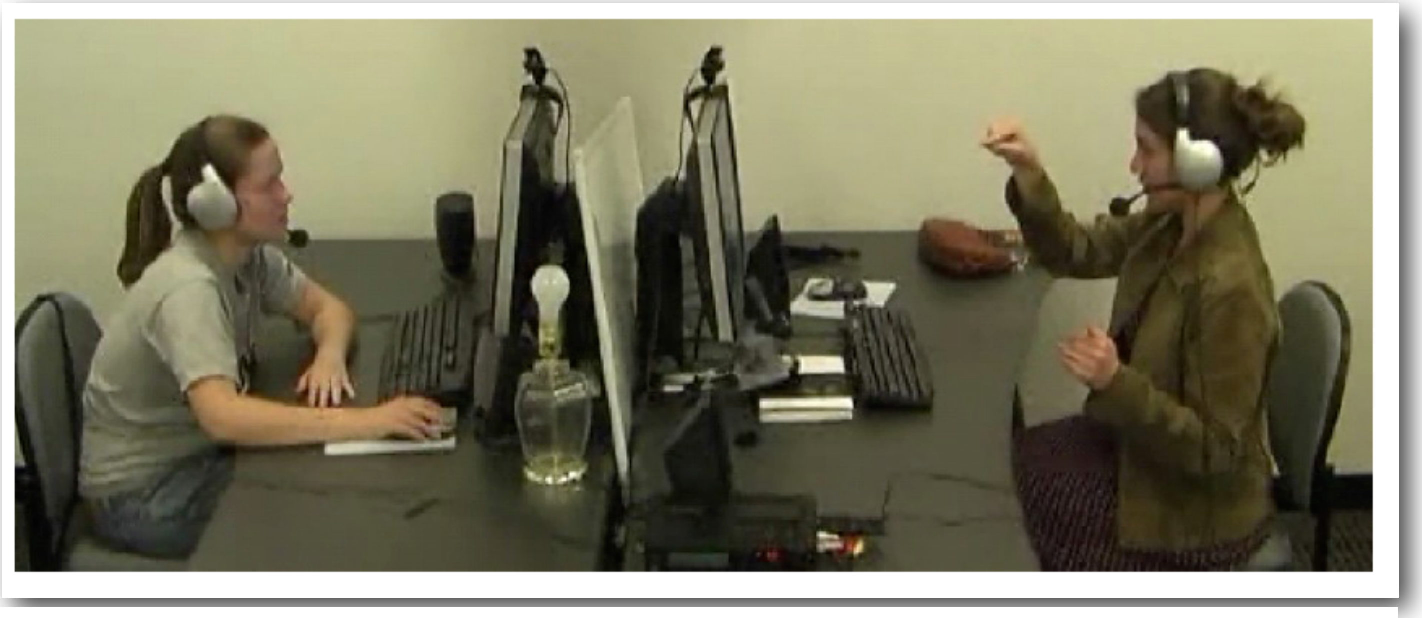


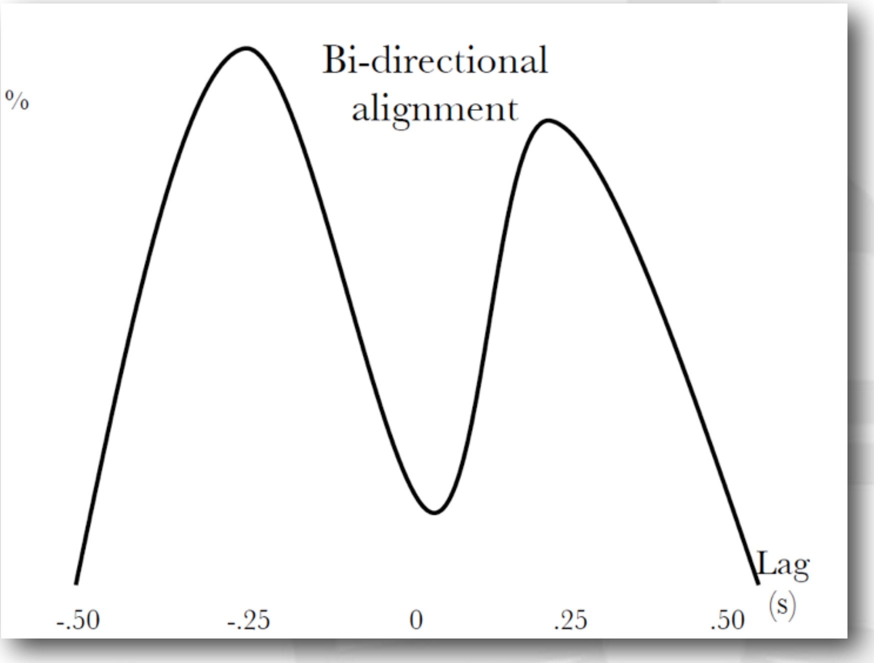


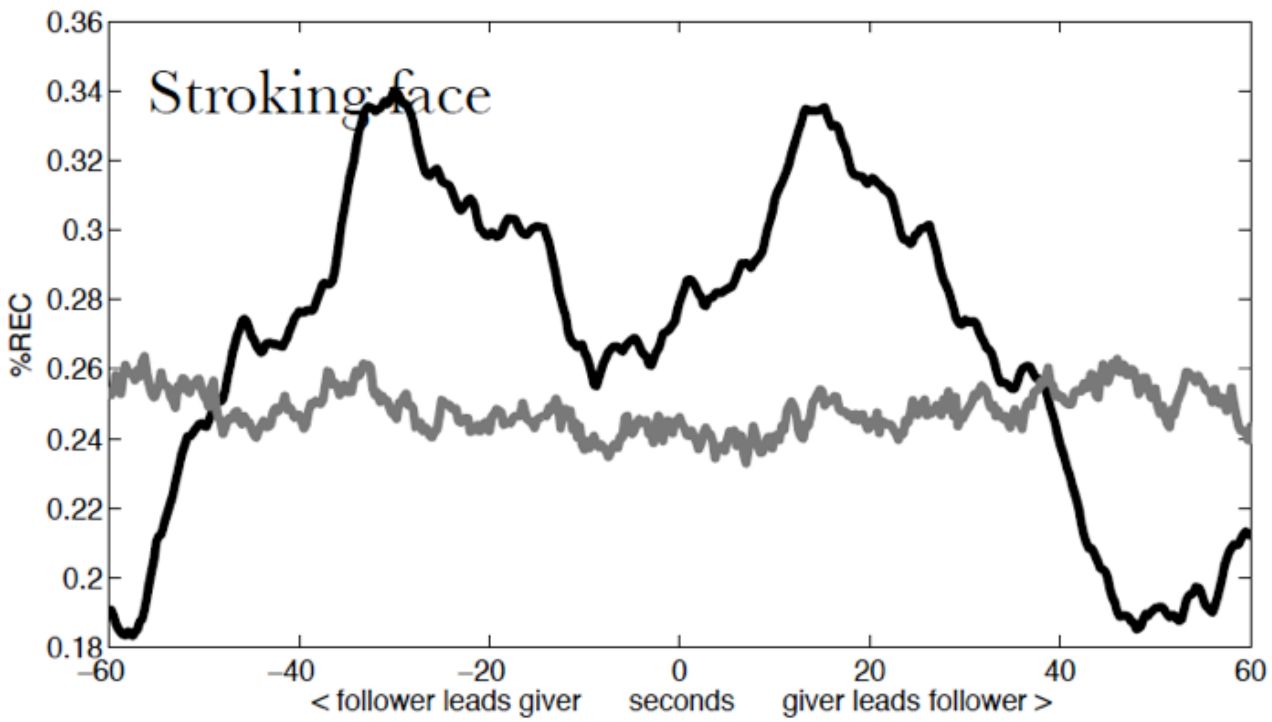


Louwerse, M. M., Dale, R., Bard, E. G., & Jeuniaux, P. (2012). Behavior matching in multimodal communication is synchronized. *Cognitive science*, *36*(8), 1404–26. doi:10.1111/j.1551-6709.2012.01269.x

Louwerse, Dale, et al., in prep







Louwerse, Dale, et al., in prep

Louwerse, M. M., Dale, R., Bard, E. G., & Jeuniaux, P. (2012). Behavior matching in multimodal communication is synchronized. *Cognitive science*, *36*(8), 1404–26. doi:10.1111/j.1551-6709.2012.01269.x

Research question

- **Motor coordination + Cooperation + Learning / Problem solving**

- Does the coordination of postural sway differ between typically developing children and children with a neurodevelopmental disorder, when they perform a cooperative task?

- And if so, how do they differ?

- And… why?

Participants

Typically developing children

- 183 dyads
  - M_{age} = 10;8 years
  - *SD* = 1;00
  - range: 8-13
  - 95 boys and 88 girls
- Dyad composition
- Recruitment of participants

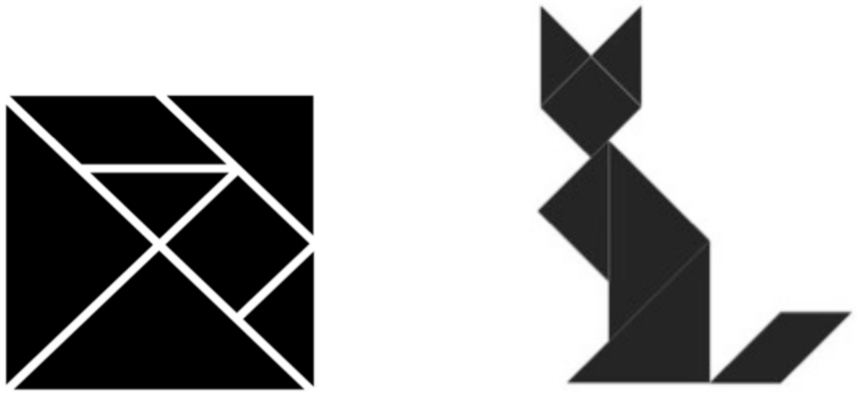
Children with a neurodevelopmental disorder

- 106 dyads
  - M_{age} = 10;10
  - *SD* = 1;3
  - range: 8 – 13
  - 74 boys and 32 girls.

Materials and Procedure

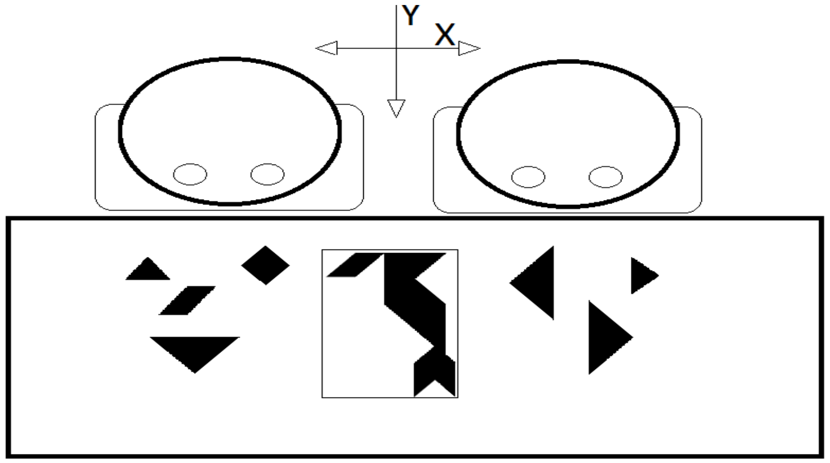
Tangram task

- Three sets of 18 puzzles
- Printed on A4 paper
- Pretest, coop, posttest



Two Nintendo Wii Balance Boards

- Simultaneously recorded postural sway
- Sampling rate 100Hz
- Records x- and y-coordinates



Data Preparation

- Data reduction
  - 100Hz → 5Hz
  - Time series of approximately 3,000 data points per dyad

- Displacement scores
  - $\mathrm{Displ}_t = \sqrt{(X_{(t+1)} - X_t)^2 + (Y_{t+1} - Y_t)^2}$

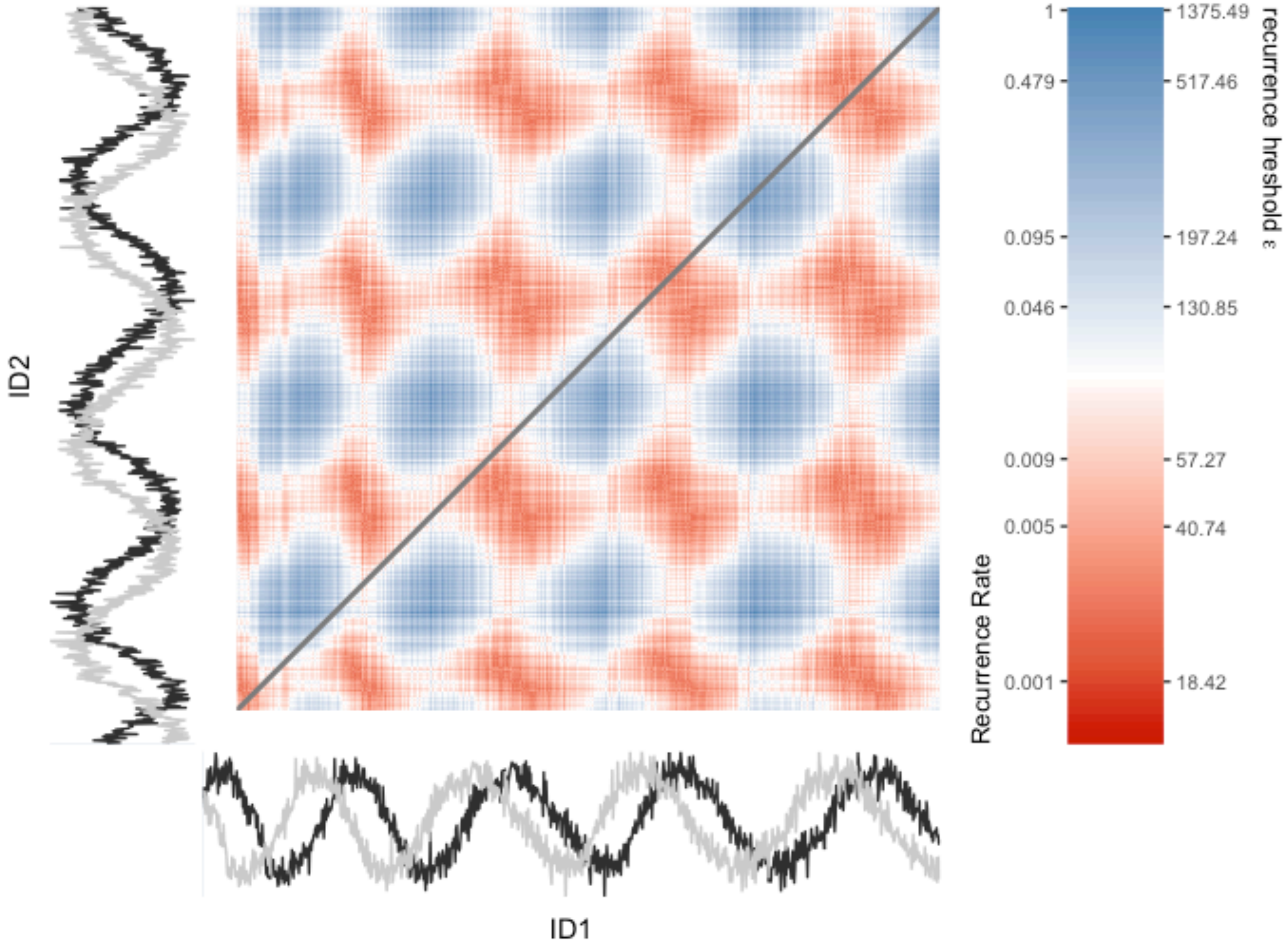
- In a previous study we showed that measures obtained from surrogate and randomized timeseries differ significantly from the observed timeseries (Vink, Wijnants, Cillessen, & Bosman, 2017).

Cross Recurrence Quantification Analysis

dyad 1001 ?

- Can detect and quantify occurrences of synchronization i bivariate time series in reconstructed phase space (Shockley, 2005).

- Parameters used:
  - Time lag = 5 data points
  - Embedding dimension = 7
  - Recurrence rate = 5%
  - Thus, radius could vary



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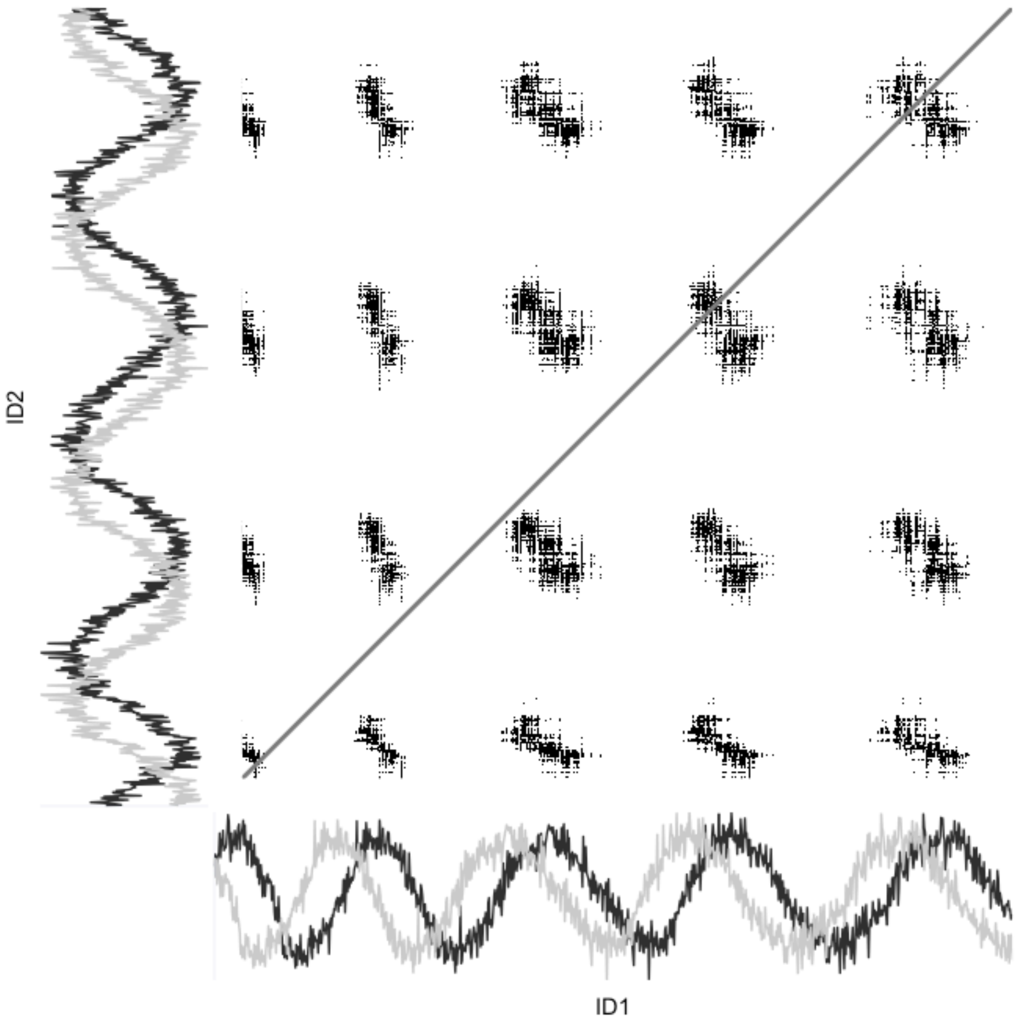
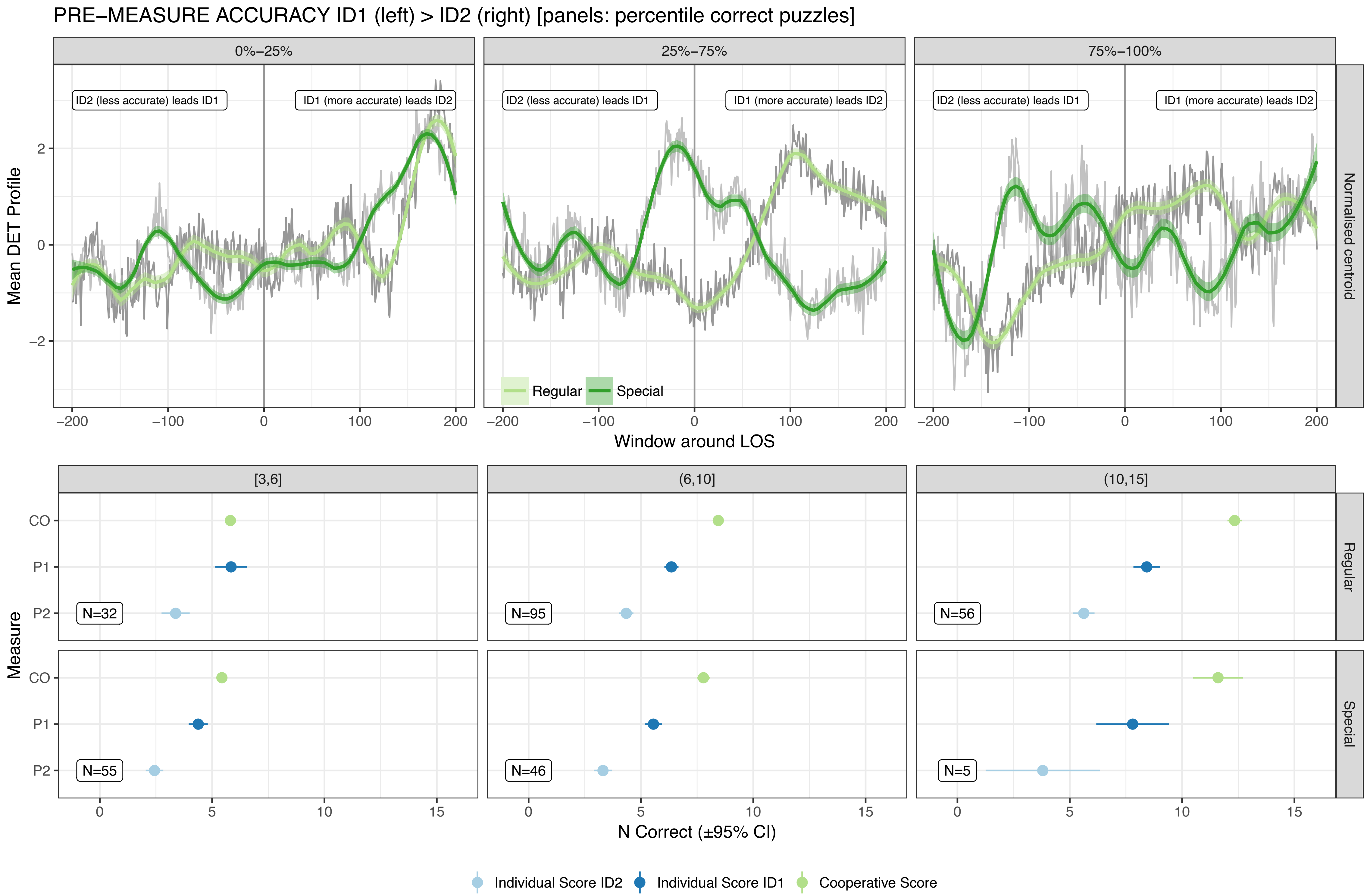
- 


PRE−MEASURE ACCURACY ID1 (left) > ID2 (right) [panels: percentile correct puzzles]
0%–25%
25%–75%
75%–100%
ID2 (less accurate) leads ID1
ID1 (more accurate) leads ID2
Mean DET Profile
Normalised centroid
Regular
Special
Window around LOS
[3,6]
(6,10]
(10,15]
CO
P1
P2
N=32
N=95
N=56
N=55
N=46
N=5
Measure
N Correct (±95% CI)
Individual Score ID2
Individual Score ID1
Cooperative Score

To summarize

- Children with a neurodevelopmental disorder and potentially comorbid postural sway disturbances performed less than their typically developing peers.
- However, their movement process (i.e., interpersonal synchronization/ coordination) was similar.
- In addition, less disorder in synchrony predicted better task performance
  - This supports the view that in less restricted tasks where there is multifinality (i.e., more than one way of solving the problem):

    "diversification of action is likely to occur, and complementary forms of interaction will in many cases supersede synchronous kinds of interaction" (Wallot, Mitkidis, McGraw, & Roepstroff, 2016, p. 3).