Department of Mathematics

Breathing with delayed feedback

Natalia Janson

with Christine Parkes and Andrey Pototsky

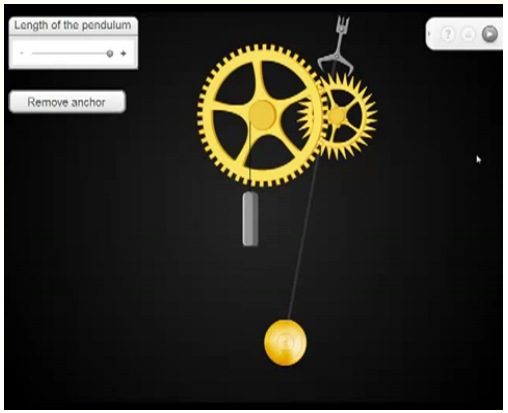
www.lboro.ac.uk/departments/ma

Loughborough University

Processes in cardiovascular system

Heart beats, breathing

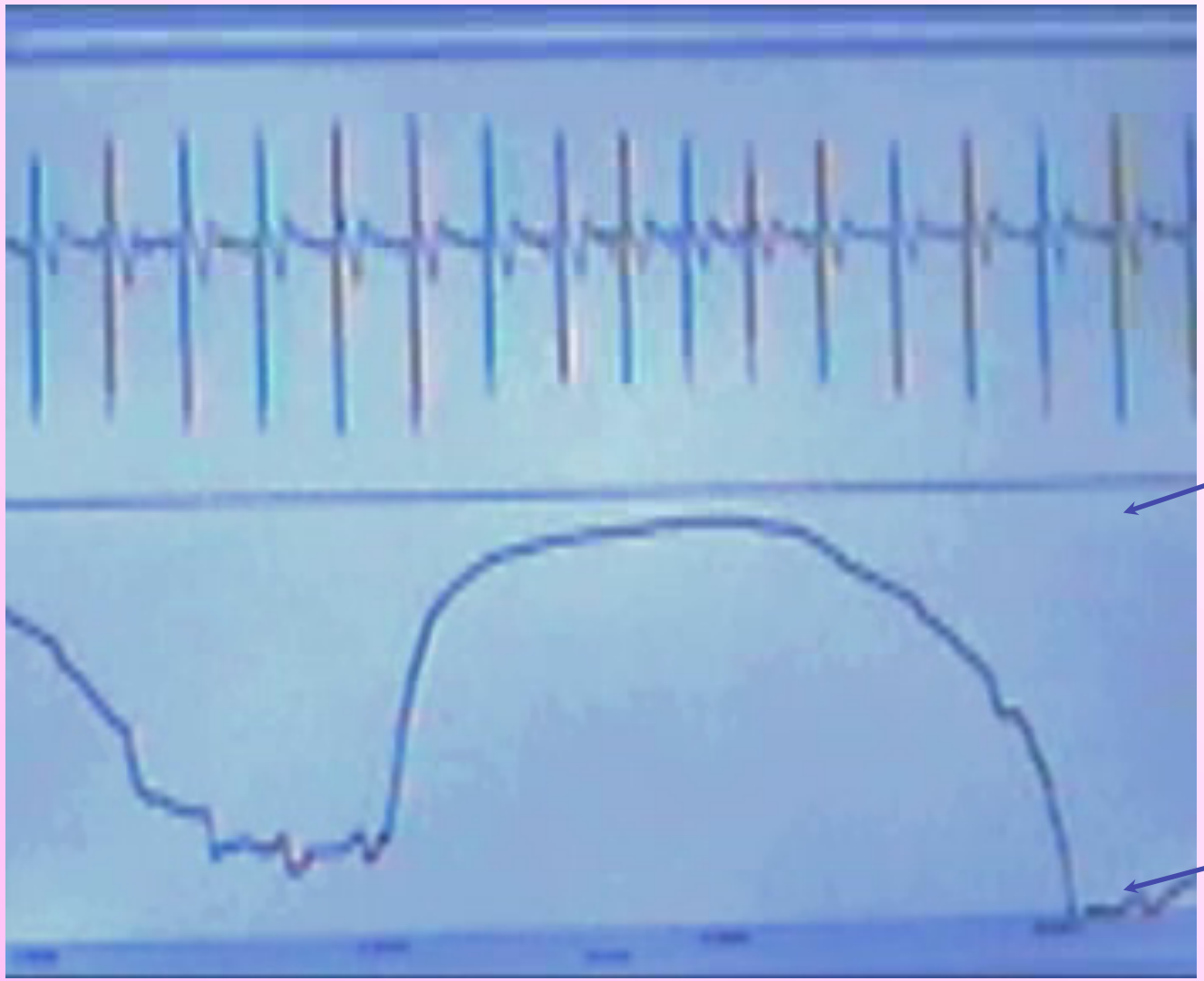
1. Never stop (while the subject lives)
2. Rhythmic, but non-periodic
3. Occurs in a non-linear dissipative system
   - living system



Assume

These processes are self-oscillatory.
Mathematical models: limit cycles, continuously and randomly perturbed

Inter-beat intervals vary, also due to breathing



electrocardiogram

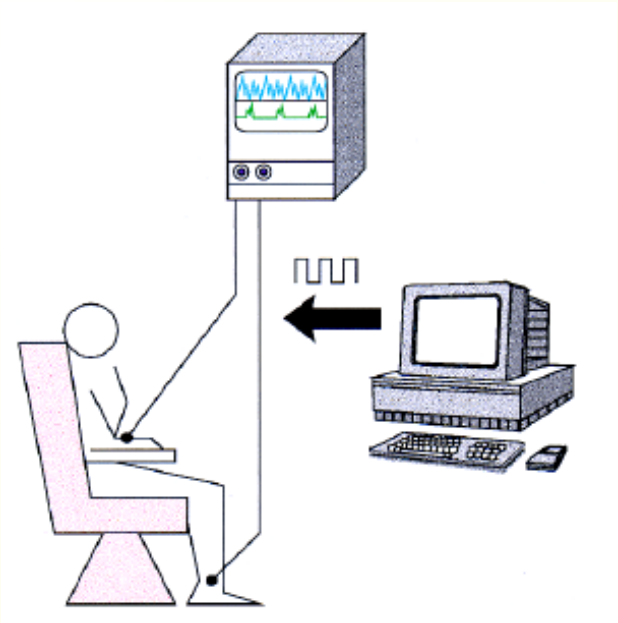
Breathe-in (faster heart-beats)

Breathe-out (slower heart-beats)

Inter-beat intervals vary (sound)

Previous studies with heart beats: 1

Weak visual and auditory rhythmic stimuli can change heart beats in healthy volunteers.



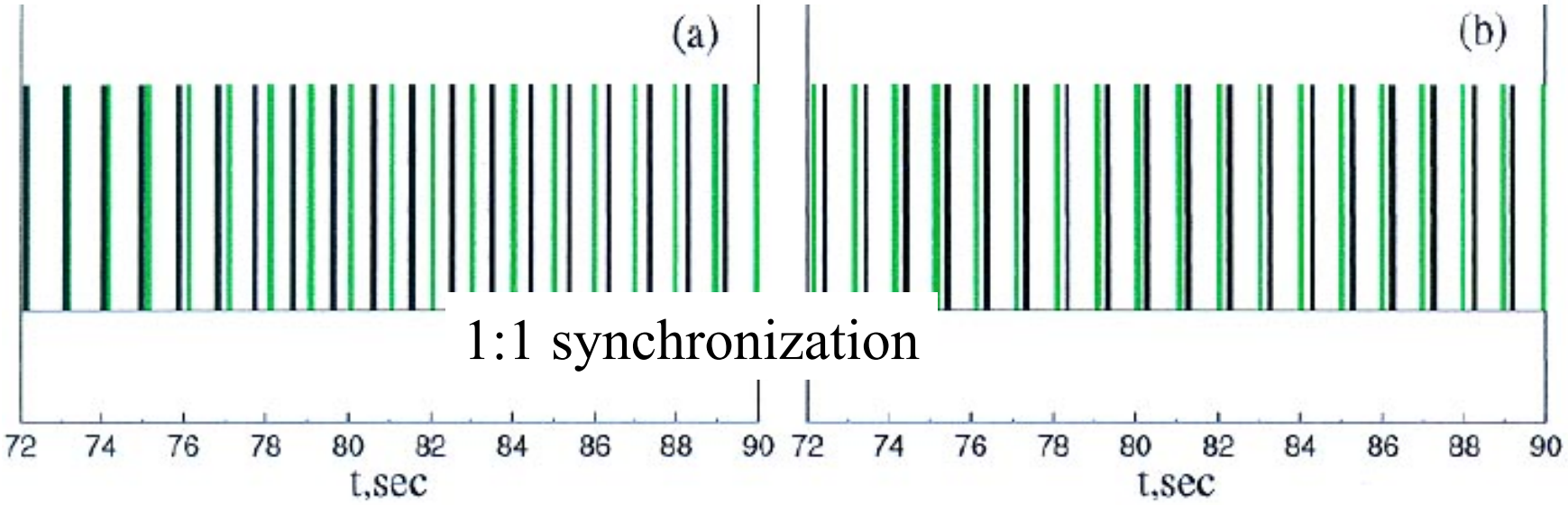
[V.S. Anishchenko, A.G. Balanov, N.B. Janson, N.B. Igosheva, G.V. Bordyugov, Int. Journal of Bifurcation and Chaos 4, 2339 (2000)]
[V.S. Anishchenko, A.G. Balanov, N.B. Janson, N.B. Igosheva, G.V. Bordyugov, Discrete Dynamics in Nature and Society 4, 201 (2000)]

Forced synchronisation of heart beats

Periodic beeping
Zero detuning

Black – unforced, Green - forcing

Black – forced, Green - forcing

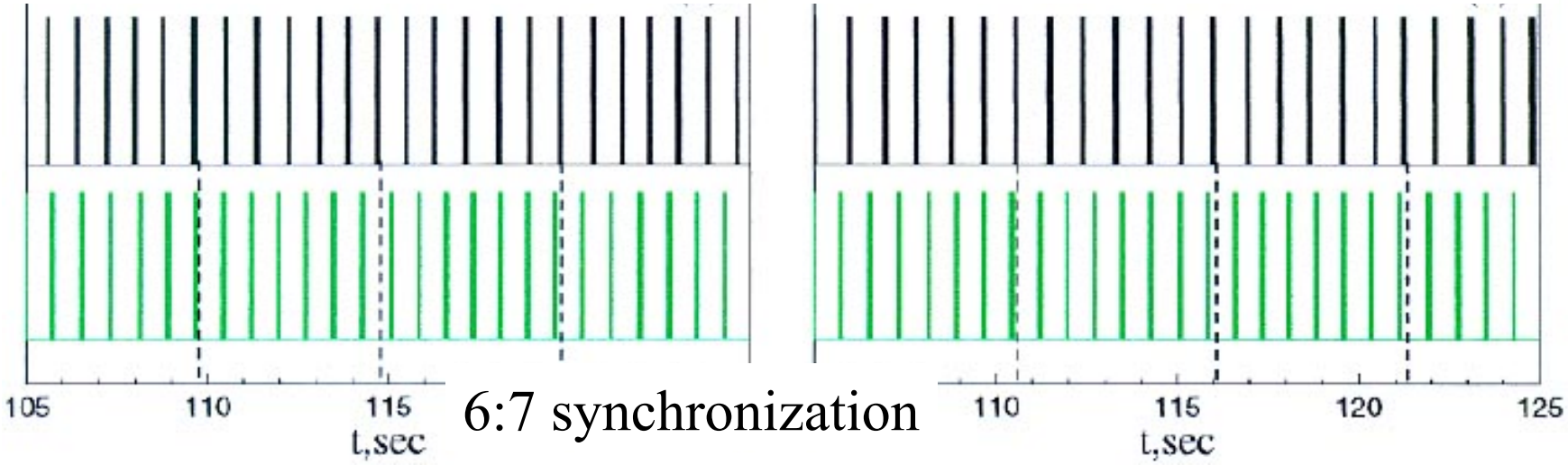


1:1 synchronization

Non-periodic beeping
Large detuning

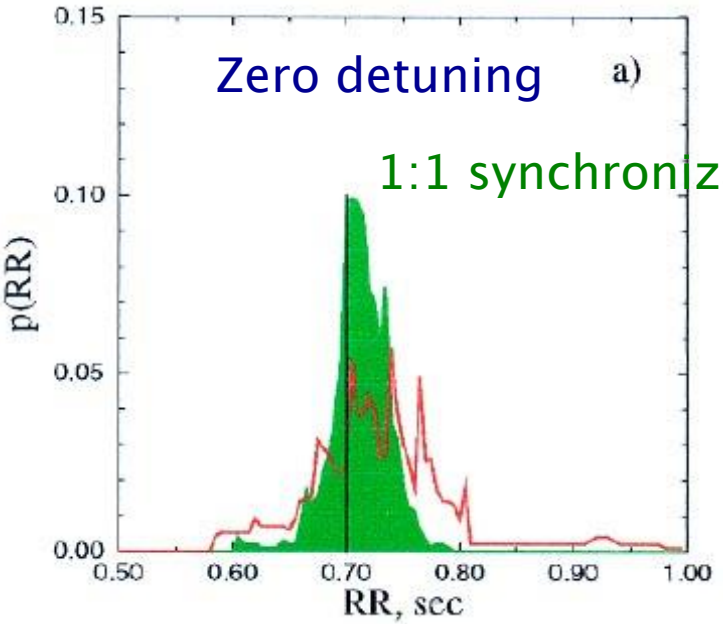
Black – unforced, Green - forcing

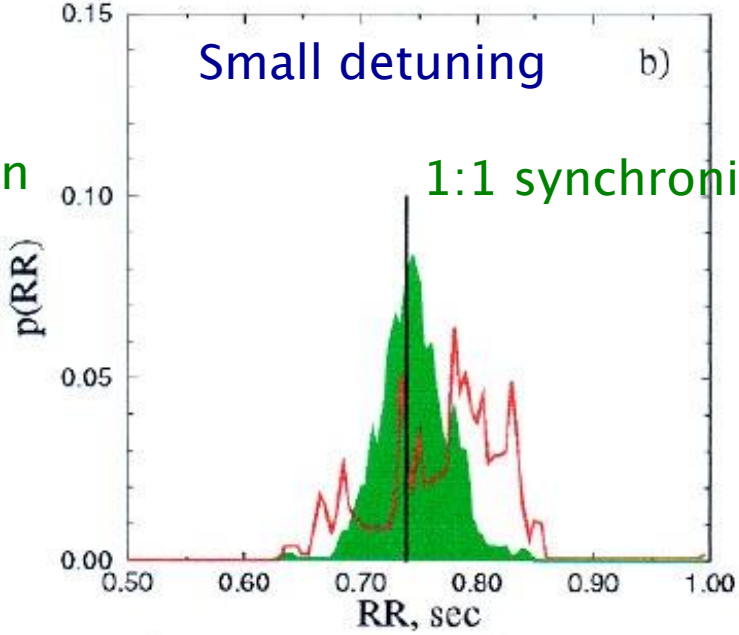
Black – forced, Green - forcing

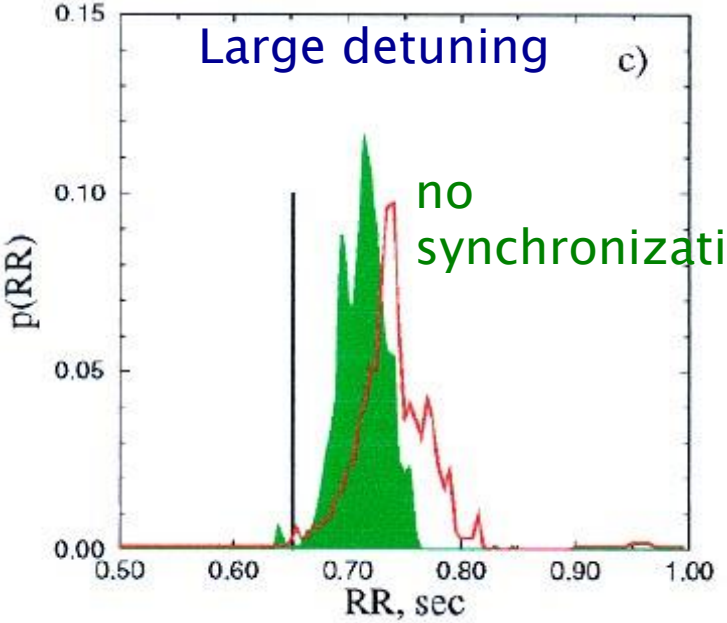


6:7 synchronization

Experimental results – RR distributions







Red – distribution of RR intervals without forcing

Green - distribution of RR intervals with forcing

Black line – frequency of forcing

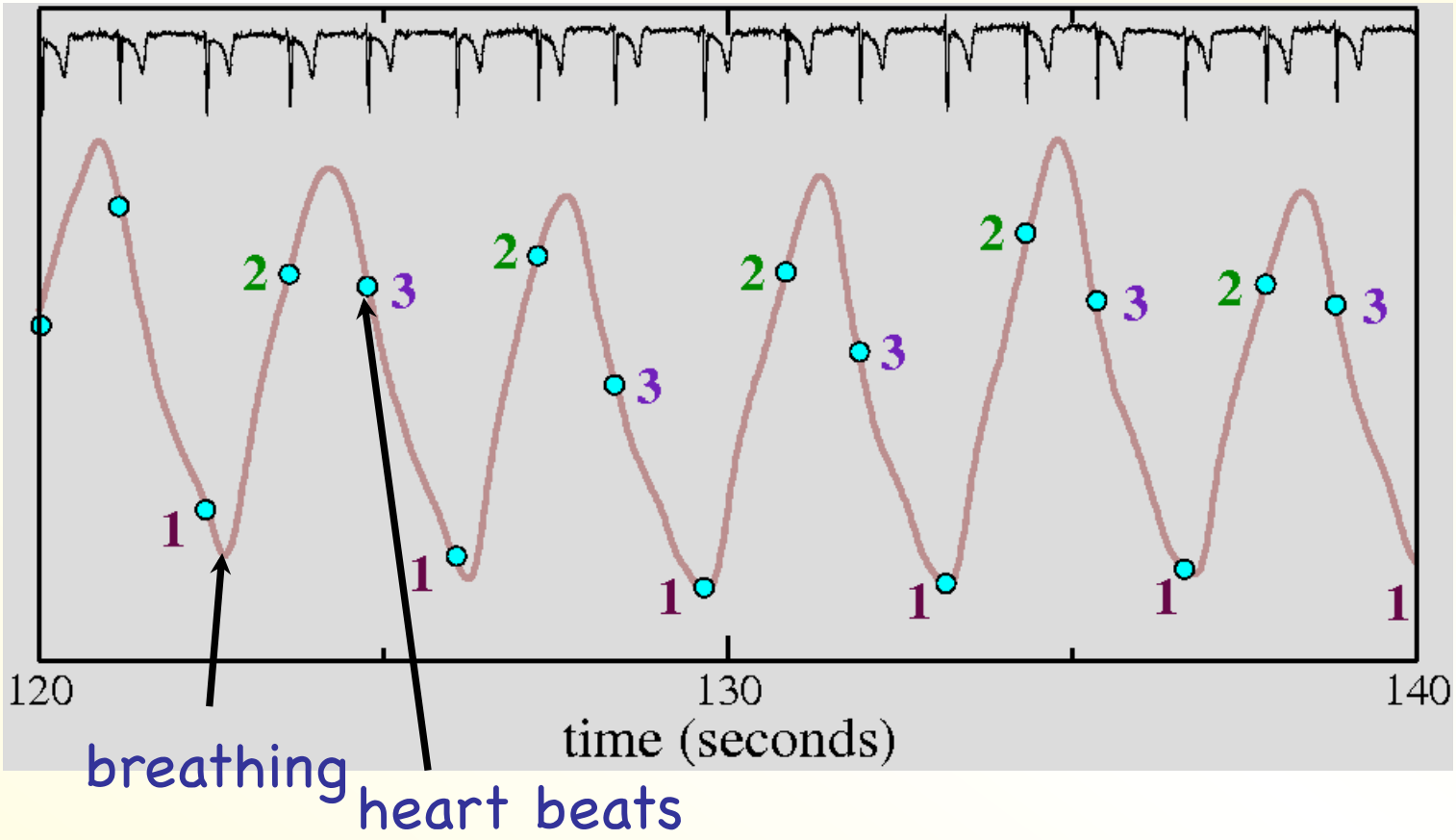
Previous studies with heart beats: 2

Spontaneous breathing can entrain heart beats.

[C.Schafer, M.G. Rosenblum, J. Kurths, H.-H. Abel, Nature 392, 239 (1998)]

Previous studies with heart beats: 3

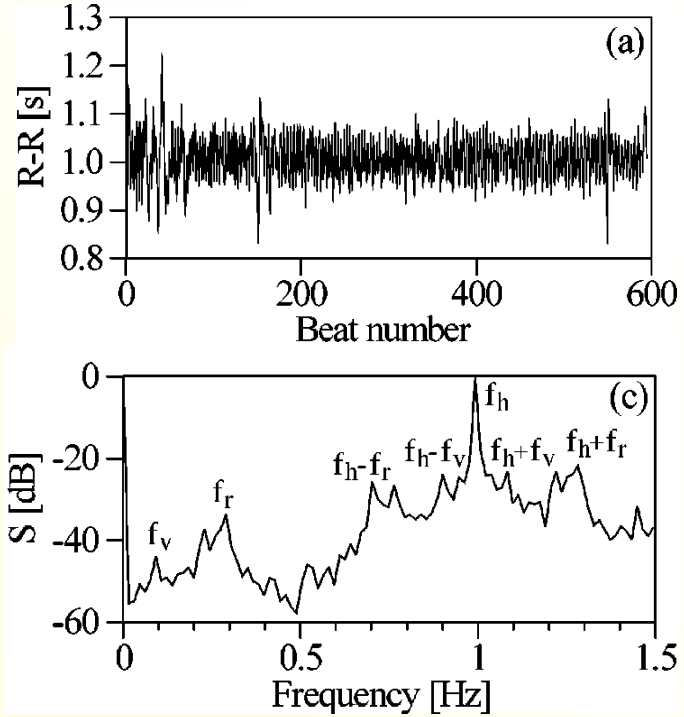
Paced breathing can entrain heart beats.

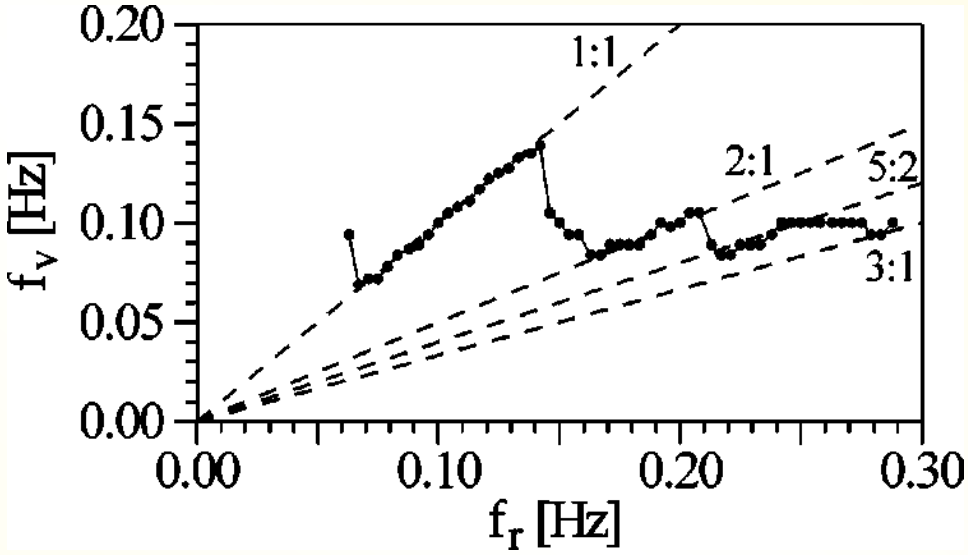


[S. Rzeczinski, A.G. Balanov, N.B. Janson, P.V.E. McClintock, Phys. Rev. E 66, 051909 (2002)]

Previous studies with heart beats: 4

Paced breathing can entrain slow component of heart beats.
Breathing rate is monotonously increased during 30 minutes.
Slow component of heart beats is entrained.





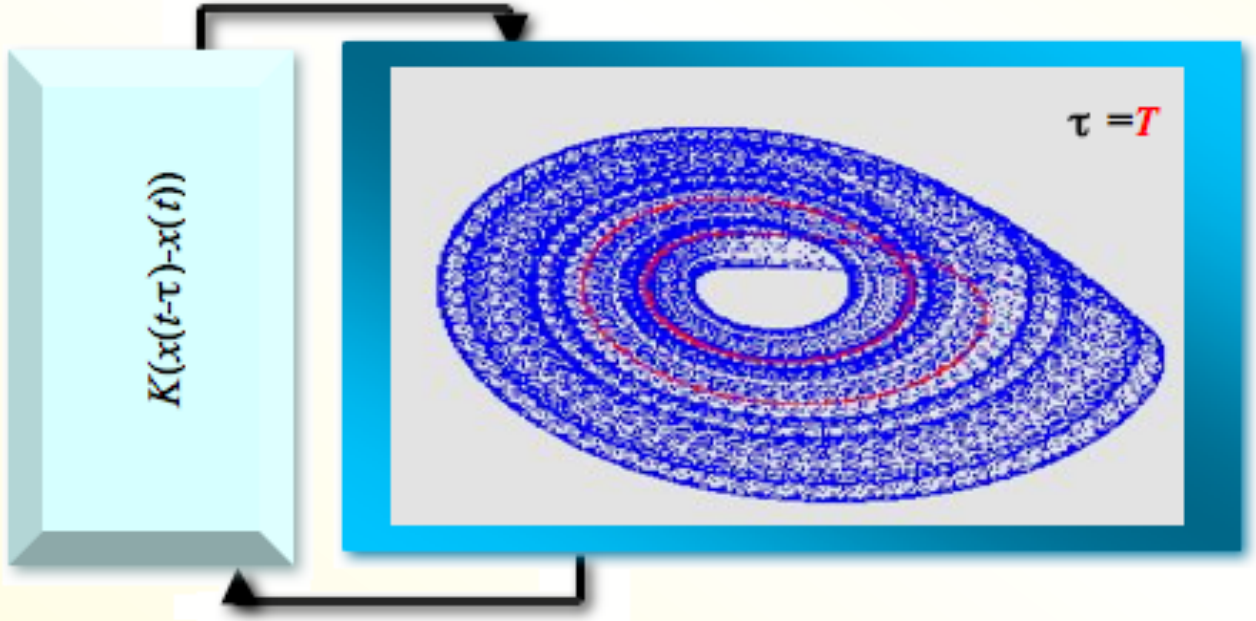
[M.D. Prokhorov, V.I. Ponomarenko, V.I. Gridnev, M.B. Bodrov, A.B. Bespyatov, Phys. Rev. E 68, 041913 (2003)]

What is delayed feedback

$$F(t) = K(s(t-\tau) - s(t))$$

s(t) is some signal measured from the system in real time which can be any, possibly nonlinear, combination of system variables;
K is the strength of the feedback
τ is the amount of the time delay

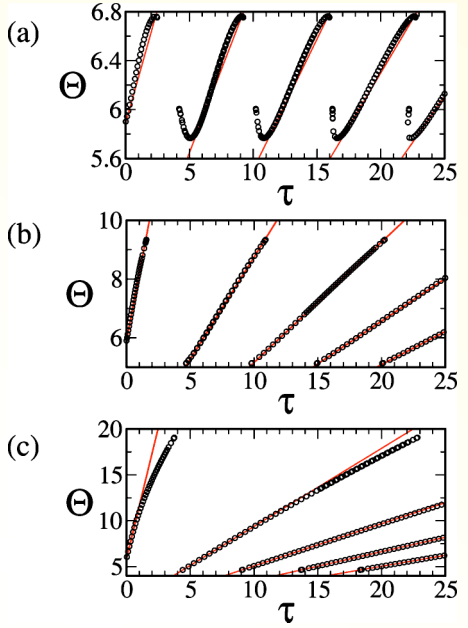
Originally introduced for deterministically chaotic systems and intended to stabilise unstable periodic orbits (UPO).



[K. Pyragas, Phys. Lett. A 170, 421 (1992)]
[K. Pyragas, Phys. Lett. A 206, 323 (1995)]

How can delayed feedback affect self-oscillatory systems?

1. In deterministically chaotic systems:
   Convert chaotic oscillations into periodic.



1. In periodically oscillating systems:

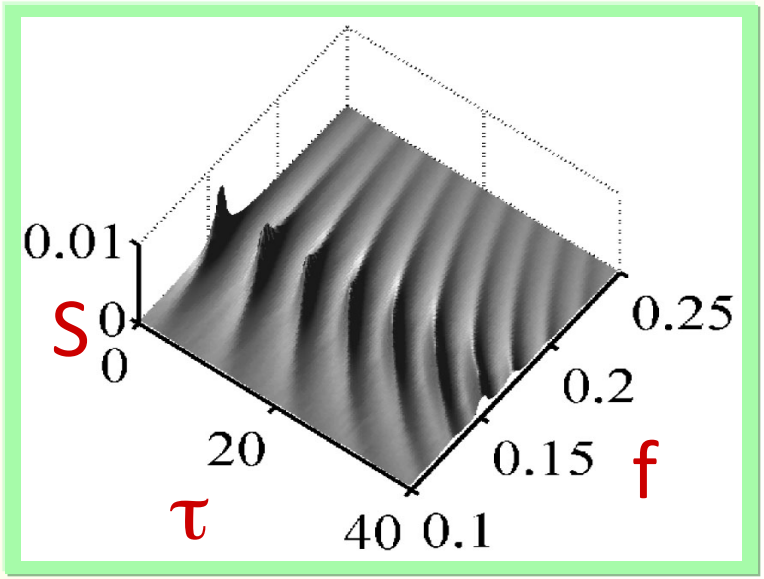
   a) Change period of oscillations

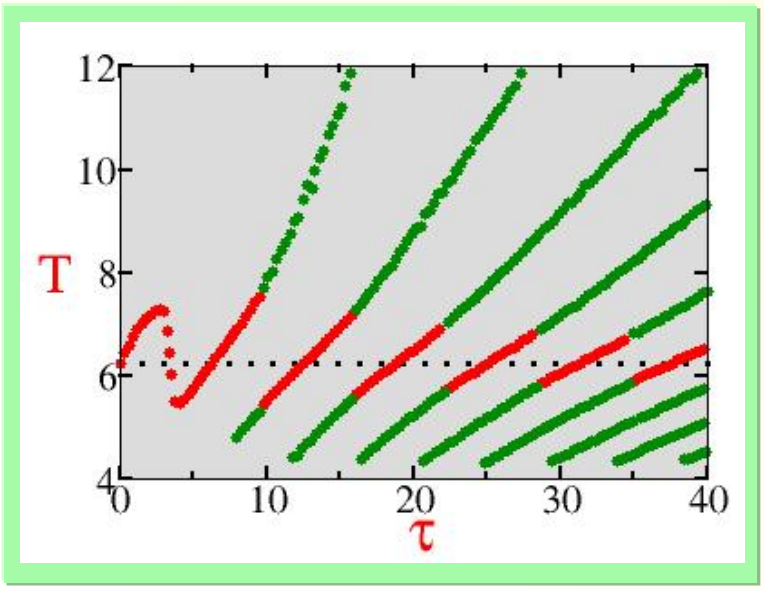
[W. Just et al, Phys. Rev. Lett. 81, 562 (1998)]
[J. Xu and K.W. Chung, Physica D 180, 17 (2003)]
[A.G. Balanov, N.B. Janson, E. Scholl, Phys. Rev. E 71, 016222 (2005)]

   b) Make oscillations chaotic

[J. Weiner, F.W. Schneider, K. Bar-Eli, J. Chem. Phys. 93, 2704 (1989)]

How can delayed feedback affect noise-induced oscillations?





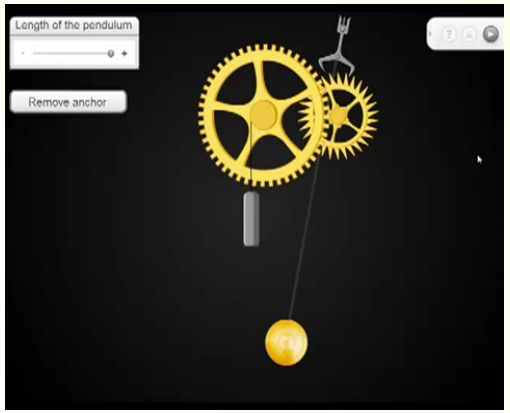
Peak "period": T=1/f

all spectrum peaks
highest peak

[N.B. Janson, A.G. Balanov, E. Scholl, Phys. Rev. Lett. 93, 010601 (2004)]
[A.G. Balanov, N.B. Janson, E. Scholl, Physica D 199, 1 (2004)]
[E. Scholl, A.G. Balanov, N.B. Janson, A. Neiman, Stochastics and Dynamics 5, 281 (2005)]
[N.B. Janson, A.G. Balanov, and E. Scholl, Control of noise-induced dynamics. Handbook of Chaos Control, 2nd Ed, E. Scholl, H.G. Schuster (Eds) 223 2007)]

What do we know about breathing

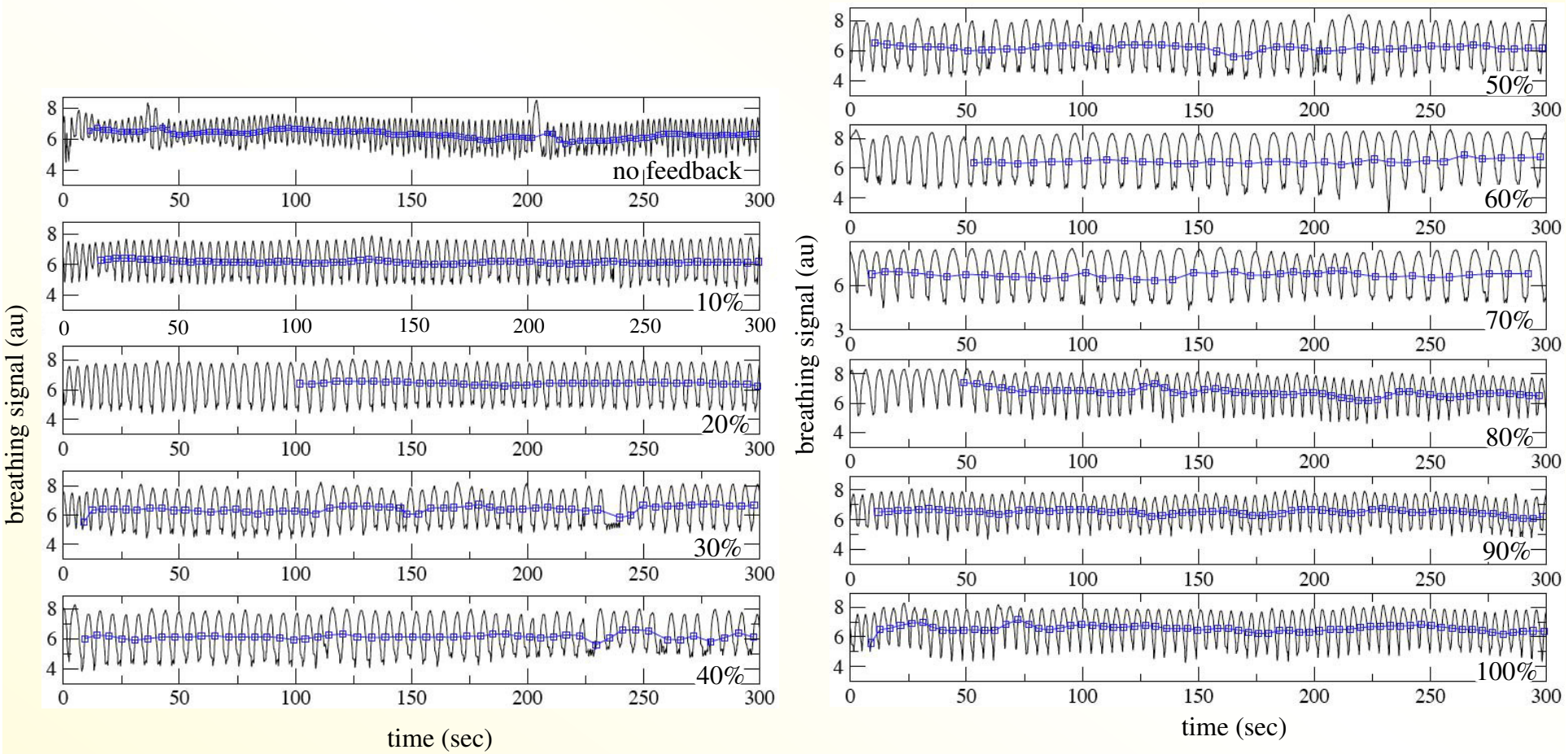
1. Never stops (while the subject lives)
2. Rhythmic, but non-periodic
3. Occurs in a non-linear dissipative system



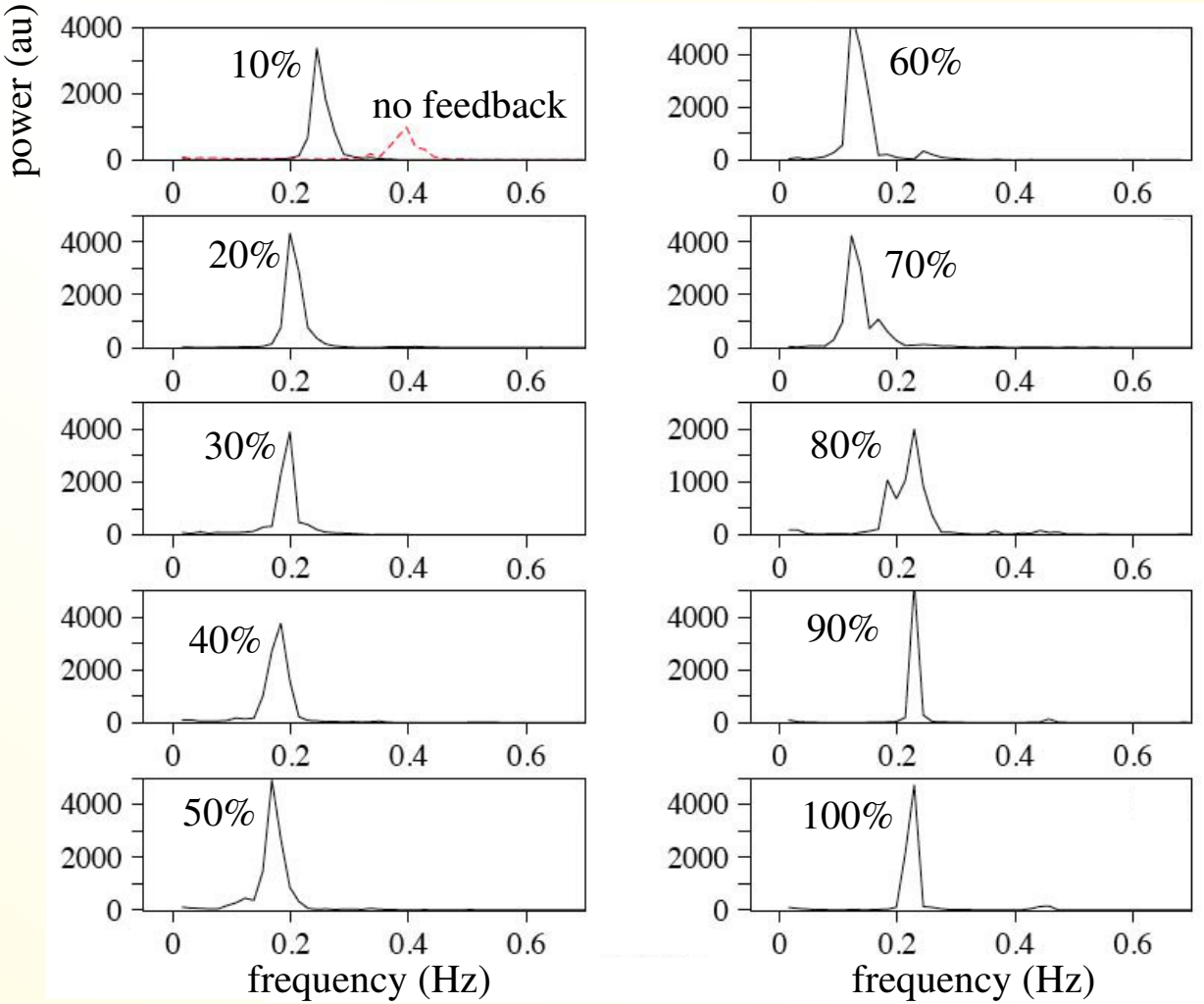
Assume

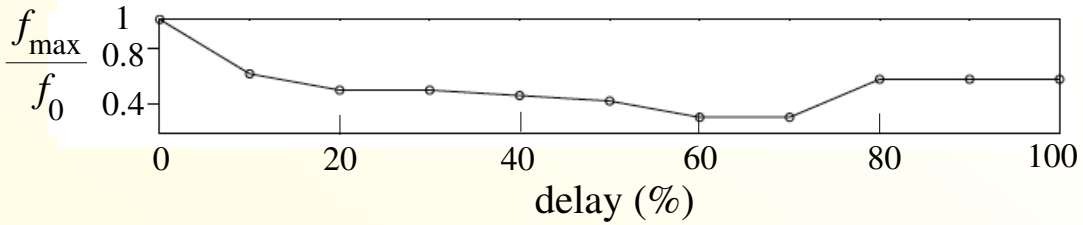
- Breathing is a self-oscillating process.
- Just like heart beats, but can be consciously controlled.
- Mathematical model: randomly perturbed limit cycle?

Breathing slowed down: signals

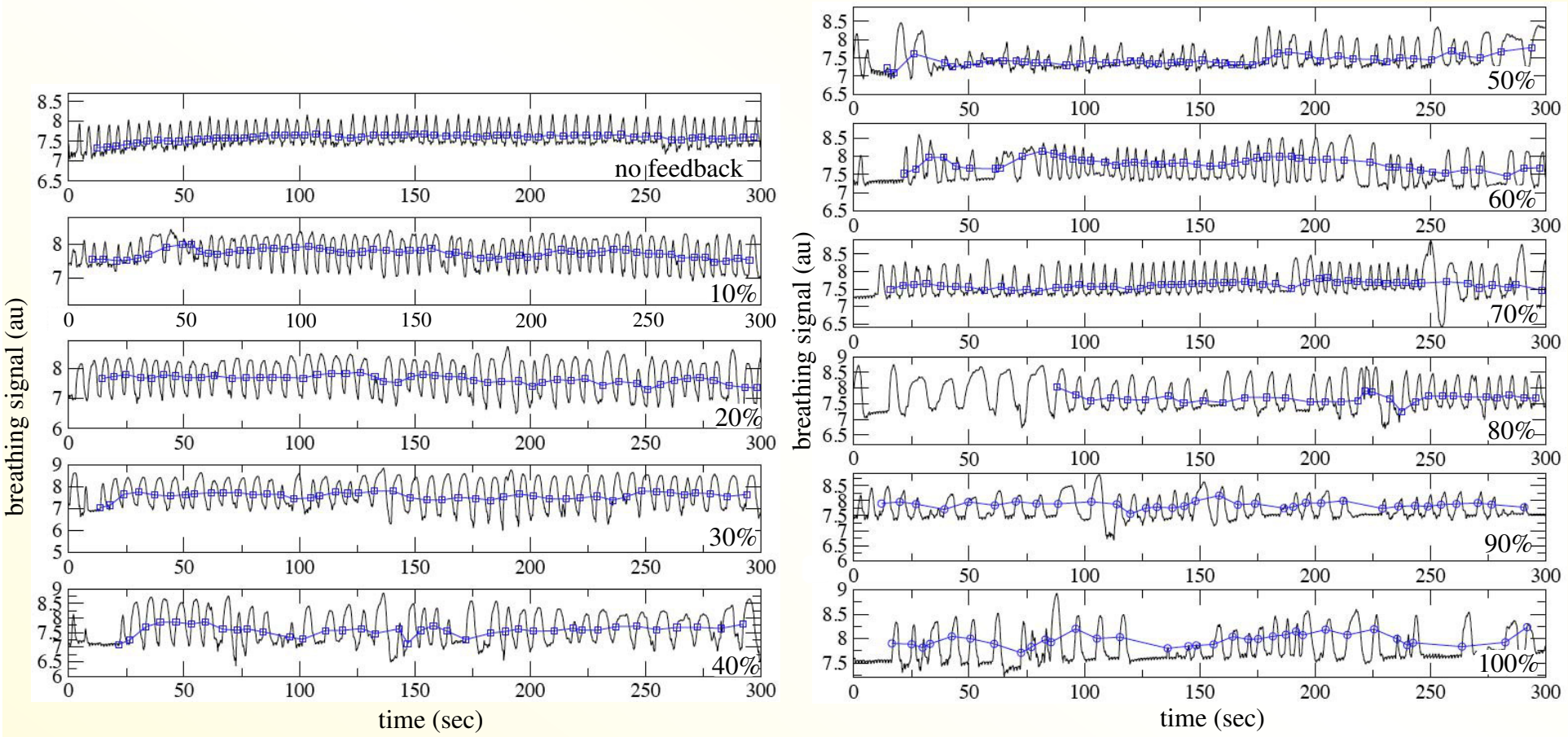


Breathing slowed down: parameters

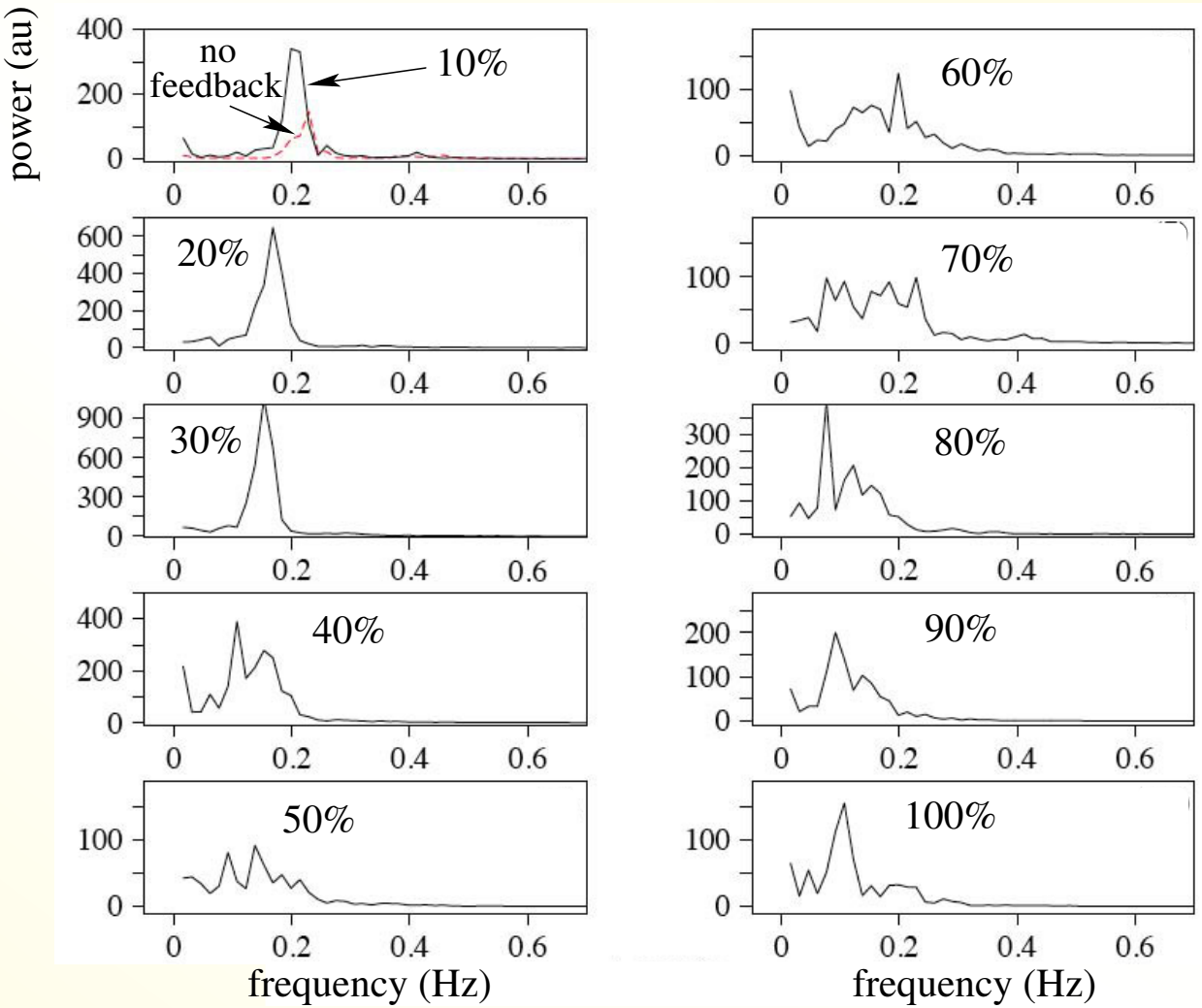


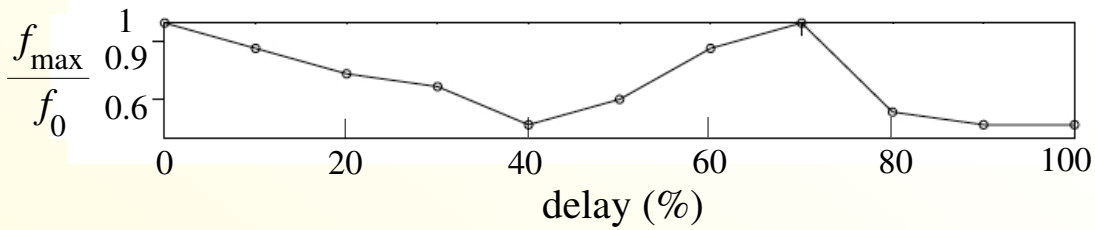


Chaotisation of breathing: signals



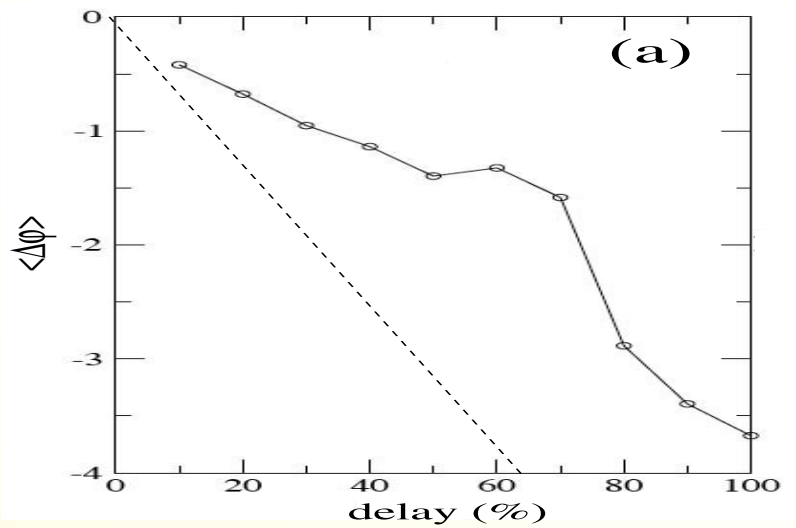
Chaotisation of breathing: parameters

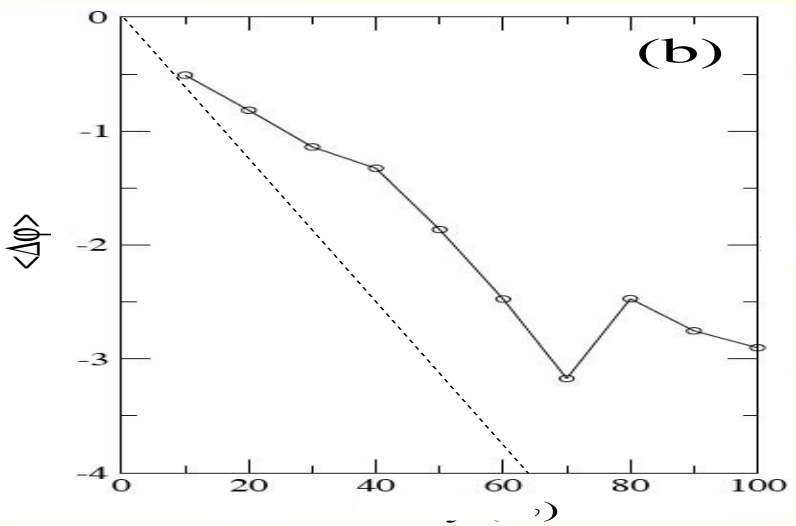




Average phase difference with delayed feedback

Phase of breathing $$\phi(t) = 2\pi(i-1) + 2\pi\frac{t-t_i}{t_{i+1}-t_i}, \quad i = 1, 2, \ldots$$





Dashed straight lines – if feedback had no effect on the breathing.

(a) Breathing slows down between 10% and 70%, while staying regular for all delays.

(b) Breathing slows down while staying regular for delays 10% to 30%, and becomes irregular at 40% and more.

Summary

Out of 24 volunteers:

1. in 11 people breathing was slowed down as the percentage delay grew.

   Within this group
   a) in 6 humans breathing stayed quite regular
   b) In 5 volunteers transition from periodic to irregular breathing pattern

2. In 3 volunteers breathing became faster with delay.
   In this group,
   a) in 2 humans breathing remained regular
   b) in 1 human it became very irregular.

3. In 1 volunteer breathing became more regular with delayed feedback than without, but retained its average period.

4. 9 volunteers showed no apparent response to the delayed feedback.

[N.B. Janson, A. Pototsky, C. Parkes, Delayed feedback applied to breathing in humans, European Physical Journal 222(10) pp 2623-2631 (2013).]

Discussion

1. Slowing down for moderate values of delay is known to be typical - consistent.
2. Chaotisation by delay is typical -- consistent
3. Due to noise and non-stationarity, it is difficult to detect effects in living systems - only very robust effects are detectable

Acknowledgements

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Thanks to EPSRC for support.