Applied problems of nonlinear oscillation and wave theory

Izv. VUZ «AND», vol. 11, № 3, 2003

CHAOS IN THE BRAIN AND IN SENSORY NEURONS

Hans A. Braun, Karlheinz Voigt, and Frank Moss

The brain is a complex organ, possibly among the most complex in the universe. The possibility exists therefore that chaotic dynamics is one of its characteristics. But sensory neurons are also complex and such processes also may be found in them. Here we show some experimental data from electroreceptors of catfish and hypothalamic neurons from the paraventricular nucleus of rat brain slices. The data show the presence of unstable periodic orbits, one of the signatures of low dimensional chaotic dynamics. Professor Vadim S. Anishchenko was a very early pioneer of fundamental studies of chaos and continues to make innovative, inspiring and original contributions to the science of complexity in all fields.

1. Introduction

Studies of chaotic dynamics date to a time just prior to the turn of the last decade with Vadim S. Anishchenko having made early fundamental contributions [1]. Moreover, Anishchenko was an early pioneer in the essentially experimental technique of exploring chaos in electronic circuits specifically designed for that purpose [2,3]. And he continues today actively providing inspiration to young researchers in dynamical systems theory and experiment the world over [4]. On this, the occasion of his sixtieth birthday, it is an honor and pleasure to contribute the following modest paper devoted to experimental searches for chaotic signatures in two biological preparations.

Unstable Periodic Orbits (UPOs) are a characteristic signature of low dimensional dynamical chaos [5,6] and have been experimentally demonstrated and quantitatively measured originally in an electronic circuit [7]. UPOs are the quintessential instability evident in complex systems. A trajectory encounters a saddle-shaped potential, approaches its unstable fixed point along a stable manifold and departs along an unstable manifold. The speeds of approach and departure are governed by the Lyapunov exponents, a positive exponent being the hallmark of chaos. Chaotic systems show spectra of UPOs of various orders. Here we confine our discussions to those of the lowest order, that is period 1.

2. Data analysis: How Unstable Periodic Orbits are detected in neural spike trains

Biology is fraught with instabilities at all levels from single cells to systems of whole organs. Thus we might expect to find UPOs in biological preparations. The information flow in neurons is encoded in the sequences of time intervals between action

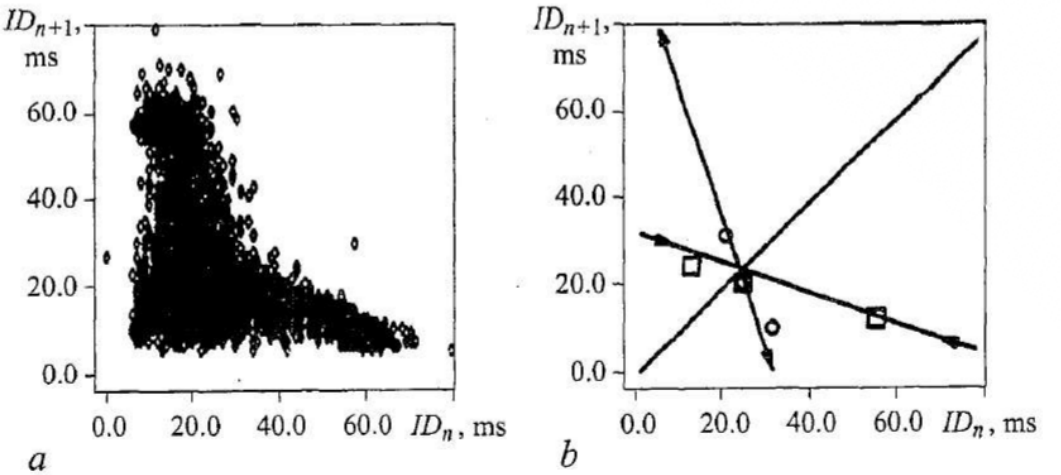

Fig. 1. (*a*) Complete record of time intervals called a scatter plot. (*b*) Single example encounter extracted from the record shown in (*a*). The 45-degree line shows all periodic orbits. The unstable fixed point is the intersection of stable (inward pointing arrows) and unstable (outward pointing arrows) manifolds

potential occurrences, or «spikes». These time series are called «spike trains». So it is in particular patterns of time interval sequences within the trains that we must seek the signatures of UPOs. Indeed, we seek to describe and detect an «encounter» with the unstable fixed point in the aforementioned saddle.

As we have shown previously for some sensory neurons, these encounters can be detected in 2-dimensional time interval plots, where a time interval between a pair of action potentials is plotted versus the immediately preceding time interval [8-10]. An example is shown in Fig. 1, *a* where a complete neural recording is plotted in this way. In Fig. 1, *b* we show an example encounter extracted by an appropriate algorithm as described below from all the data shown in Fig. 1, *a*. In Fig. 1, *b*, the squares show the approach to the unstable fixed point, marked by the crossing of the two straight lines that indicate the manifolds. Inward-pointing arrows mark the stable and outward-pointing arrows mark the unstable manifolds. As the points converge on the fixed point, they feel the instability and start to diverge along the unstable manifold as shown by the circles. Thus a particular sequence consisting of 3 points approaching followed immediately by 3 points departing identifies an encounter with a period 1 UPO. Of course, such systems often display more complex structures of higher order UPOs than detected here. These have been further investigated in Hodgkin-Huxley-type neuron models [11,12].

Moreover, biological systems are almost always contaminated with high-dimensional random processes, or «noise». Thus we must seek to find (and hopefully to count) the UPOs in the noisy chaotic systems that are usual for biology. In systems contaminated by some high dimensional noise, UPOs spend much of their time in high-dimensional phase space, but occasionally execute trajectories with detectable signatures on 2-dimensional projections. The number, N, of encounters with UPOs in the complete record measures the «strength» of the instability. The problem is that in systems contaminated with noise, there are also «false encounters» that happen just by chance even in completely random data sets. These are taken into account by analyzing «surrogate» data sets for the number N_S of false encounters. These are detected and counted in exactly the same way as for the actual data. In fact, the simplest surrogates are constructed by just randomly scrambling the locations of the time intervals in the actual data set. A statistical measure of the strength of the instability is the following:

$$K = (N\text{-}\langle N_S\rangle)/\sigma.$$

One must repeat the false positive count many times in order to get a good

statistical average $\langle N_S \rangle$, and the standard deviation of the determinations of N_S in the surrogates is σ. Thus in Eq. K has units of standard deviations. For $K \geq 3$, the statistical precision of the determination, that is the presence of UPOs in the data set, is at the 95% confidence level.

3. Results

We will not repeat here the details of the experimental preparations as those have been presented previously [10]. Figure 2 shows results for a catfish electroreceptor

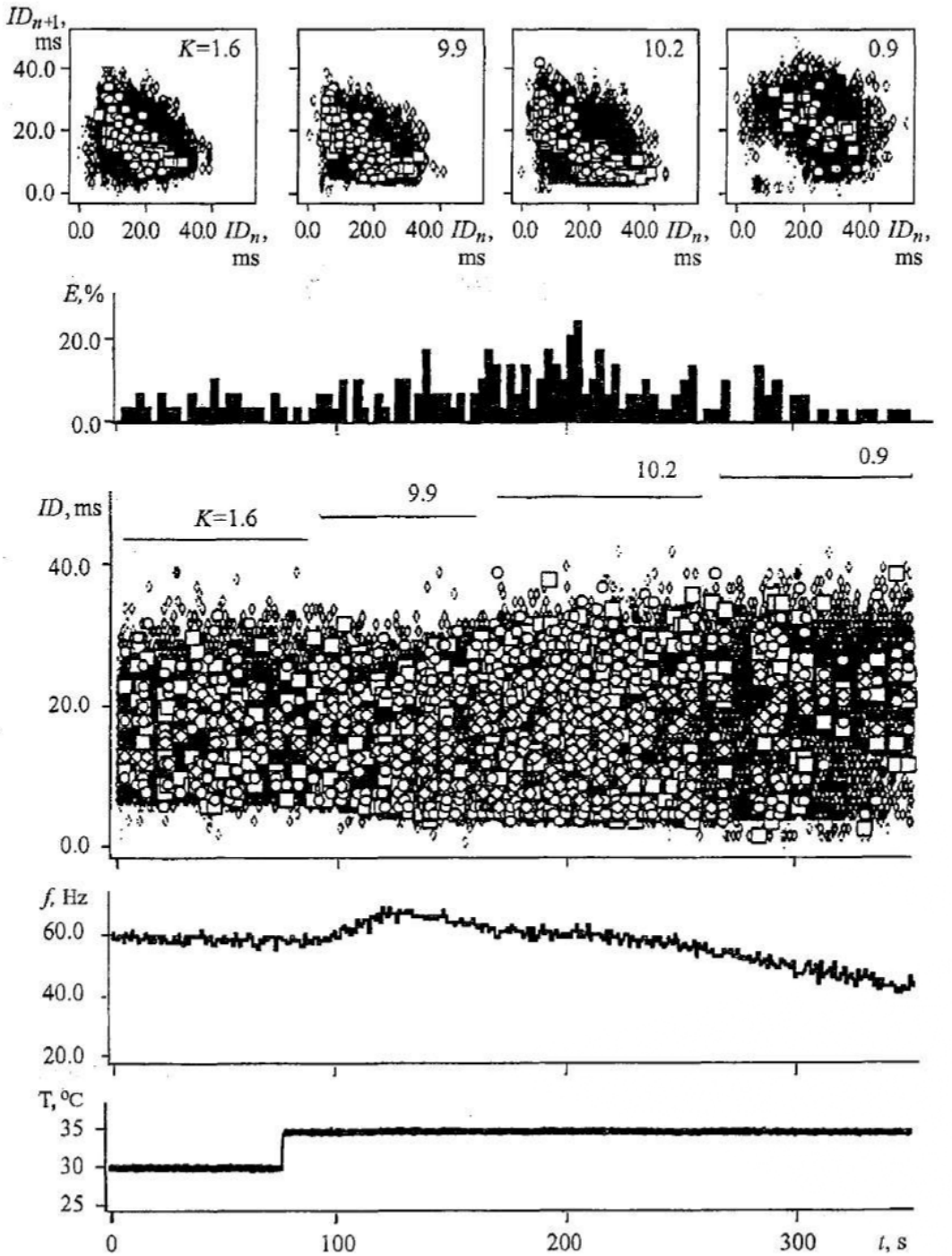

Fig. 2. Scatter plots, histograms of UPO counts, the complete time interval record, mean firing rate and temperature step recorded for the electroreceptor of a catfish

subject to a temperature step at a certain time. The top panel shows 4 scatter plots with the encounters indicated by squares (stable) and circles (unstable) movements along the manifolds. The K-values are shown, the maximum being around 10. The next panel down shows a histogram of the numbers of encounters counted in segments of the data set marked by the solid lines in the panel below. That panel shows the complete record of time intervals plotted against time. The mean firing rate and temperature step are shown in the bottom panels. Note that a bifurcation takes place about 75 s after the temperature step. The transition to period-2 is accompanied by a substantial increase of the UPO count. Note also that the appearance of large numbers of UPOs anticipates the bifurcation as shown by the bar marked with K=9.9 in the middle panel. These occurrences are called «precursors» and have been previously developed as tools for predicting the approach of bifurcations [13].

We turn now to the hypothalamus, a part of the brain involved in temperature regulation of the body. We have found that hypothalamic neurons from the

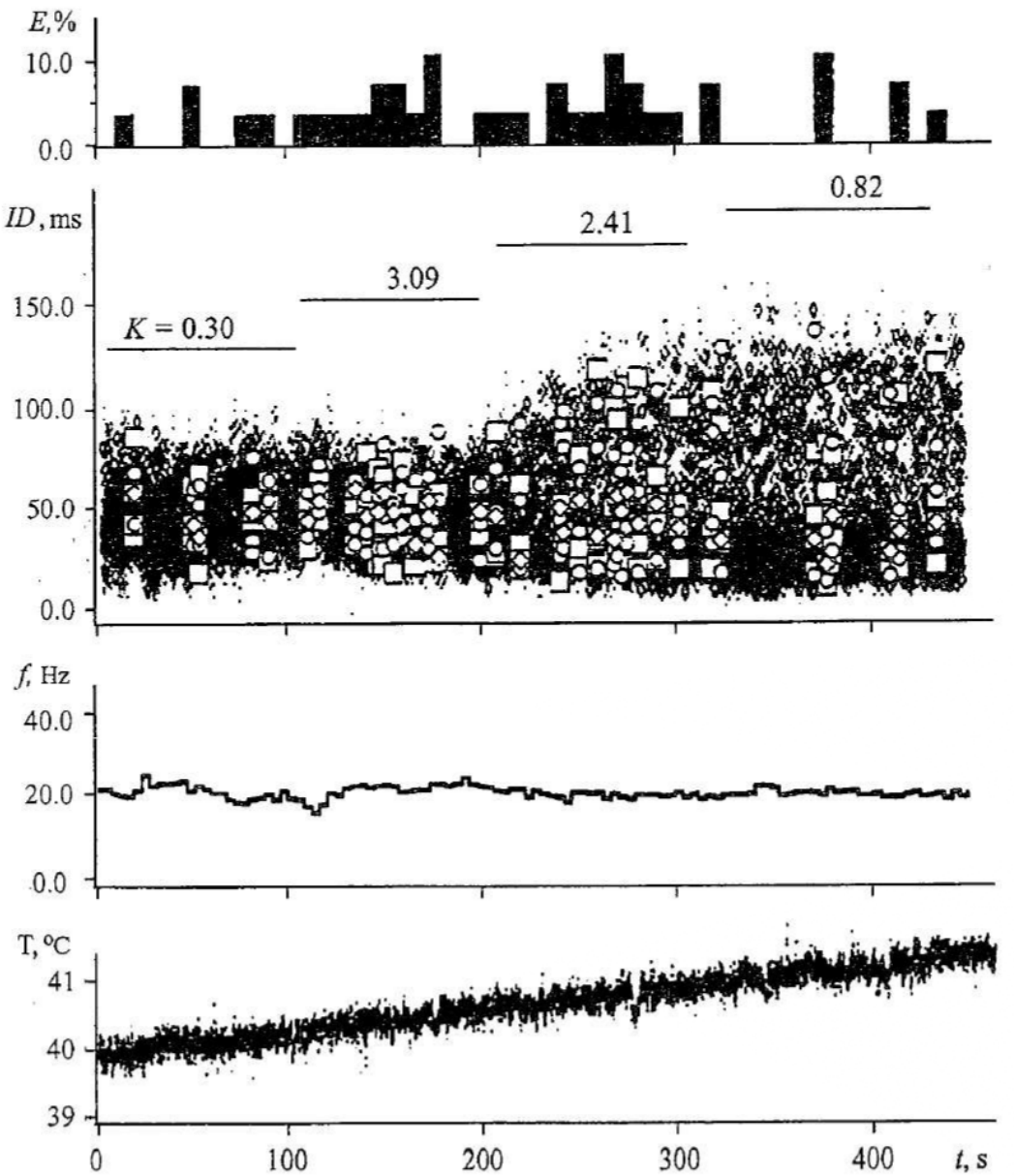

Fig. 3. Histograms of UPOs (top panel), the complete time interval record, mean firing rate and temperature scan (bottom panel) for a hypothalamic neuron in a rat brain slice

paraventricular nucleus in rat brain slices are indeed temperature sensitive, and that UPOs can track and anticipate the onset of bifurcations. Well-characterized rats were executed humanely, their brains extracted and slice preparations obtained following previously detailed procedures [10]. The neurons were then identified and extracellular recordings of their firings made while the temperature of the bath was slowly swept upward. The results are shown in Fig. 3. The upper panel shows histograms of the encounters for the recording segments shown by the solid bars below. The K-values are marked on the bars. The complete record of time intervals is shown in the second panel down. The mean firing rate and temperature sweep are shown in the bottom two panels. Encounters are again identified by squares (stable) and circles (unstable) in the complete record. The first part of the record (time <100 s) shows stable period-1 activity with no significant numbers of UPOs. Later, at around 150 s, we can easily see the precursors marked by K=3.09 just prior to the period doubling bifurcation. Just after the bifurcation at the beginning of the period-2 regime, large numbers of UPOs again occur with K=2.41. Note that in the fully developed period-2 regime after about 300 s, the neuron again becomes stable with K=0.82 indicating no detectable UPOs. Thus we can track the transitions from stable period-1 to unstable period-2 and back to stable period-2 again using our technique for detecting and counting UPOs.

All animals used in this study were treated humanely and in strict accordance with the appropriate German Federal Requirements in effect at the time of the experiments.

4. Summary

We have shown how UPOs can be detected and counted in biological preparations of sensory neurons. The two preparations used were electroreceptor neurons in the catfish and hypothalamic neurons in the paraventricular nucleus of a rat brain. In all cases the neurons sense temperature changes by first anticipating then executing period doubling bifurcations. The sudden increase of the density of UPOs can be used to anticipate these bifurcations. We have here addressed the general topic of instability and stability in biological electrosensory neurons and in the thalamus of the rat brain.

This work was supported by the INTAS grant 01-2061 and by the US Office of Naval Research. F.M. is grateful to the Alexander von Humboldt Foundation for continuing support.

References

1. *Anishchenko V.S.* Dynamical Chaos - Basic Concepts. Teubner-Texte zur Physik, Leipzig, 1987.

2. *Anishchenko V.S.* Dynamical Chaos in Physical Systems: Experimental Investigation of Self-Oscillating Circuits. Teubner-Texte zur Physik, Leipzig, 1989.

3. *Anishchenko V.S.* Dynamical Chaos - Models and Experiments. World Scientific, Singapore, 1995.

4. *Anishchenko V.S., Astakhov V.V., Neiman A.B., Vadivasova T.E., and Schimansky-Geier L.* Nonlinear Dynamics of Chaotic and Stochastic Systems. Springer Verlag, Berlin, 2002.

5. *Artuso R., Aurell E., and Cvitanovic P.* Recycling of strange sets I: cycle expansions // Nonlinearity. 1990. Vol. 3. Pp. 325-338.

6. *Artuso R., Aurell E., and Cvitanovic P.* Recycling of strange sets II: applications // Nonlinearity.1990. Vol. 3. Pp. 361-375.

7. *Pierson D. and Moss F.* Detecting periodic unstable points in noisy chaotic and

limit cycle attractors with applications to biology // Phys. Rev. Lett. 1995. Vol. 75. Pp. 2124-2127.

8. *Braun H.A., Schfer K., Voigt K., Peters R., Bretschneider F., Pei X., Wilkens L. and Moss F.* Low-dimensional dynamics in sensory biology 1: thermally sensitive electroreceptors of the catfish // J. Comp. Neurosci. 1997. Vol. 4. Pp. 335-347.

9. *Braun H.A., Dewald M., Schfer K., Voigt K., Pei X., Dolan K., and Moss F.* Low-dimensional dynamics in sensory biology 2: facial cold receptors of the rat // J. Comp. Neurosci.1999. Vol. 7. Pp. 17-32.

10. *Braun H.A., Dewald M., Voigt K., Huber M., Pei X., and Moss F.* Finding unstable periodic orbits in electroreceptors, cold receptors and hypothalamic neurons // Neurocomputing. 1999. Vol. 26-27. Pp. 79-86.

11. *Braun H.A., Huber M.T., Dewald M., Schfer K., Voigt K.* Computer simulations of neuronal signal transduction: The role of nonlinear dynamics and noise // Int. J. Bifurc. and Chaos. 1998. Vol. 8. Pp. 881-889.

12. *Braun W., Eckhardt B., Braun H.A., Huber M.* Phase space structure of a thermoreceptor // Phys. Rev. E. 2000. Vol. 62. Pp. 6352-6360.

13. *Omberg L., Dolan K., Neiman A., and Moss F.* Detecting the onset of bifurcations and their precursors from noisy data // Phys. Rev. E. 2000. Vol. 61. Pp. 4848-4853.

Institute of Physiology, University of Marburg, Germany
Center for Neurodynamics, University of Missouri at St. Louis, USA

Recieved 28.08.2003

УДК 577.359

ХАОС В МОЗГЕ И В СЕНСОРНЫХ НЕЙРОНАХ

H.A. Braun, K. Voigt, F. Moss

Мозг является сложным органом, относится к числу наиболее сложных объектов мироздания. Поэтому существует вероятность, что одной из его характеристик является хаотическая динамика. Однако сенсорные нейроны также являются сложными, и в них также могут быть найдены хаотические процессы. В данной работе мы демонстрируем некоторые экспериментальные данные, записанные с электрорецепторов полосатой зубатки и гипоталамических нейронов из паравентрикулярных ядер срезов мозга крысы. Данные демонстри-руют наличие неустойчивых периодических орбит - одной из характерных черт маломерной хаотической динамики. Профессор В.С. Анищенко был среди самых первых инициаторов фундаментальных исследований хаоса и продолжает осуществлять новаторский, вдохновляющий и оригинальный вклад в науку сложности во всех ее областях.

Frank Moss holds degrees in both Physics (PhD) and Engineering (BS and MS) from the University of Virginia. He studied macroscopic quantum fluids at the University of Rome in Italy on a Postdoctoral Fellowship awarded by the National Science Foundation. Moss' early research centered on turbulence in superfluid liquid helium, for which he was later awarded Fellowship in the American Physical Society. Later he studied random fluctuations and noise in nonlinear physical systems, and in the early 90's broadened these studies to include applications in sensory biology. In 1995, he established the Center for Neurodynamics and continues as its Director. Research of the Center has attracted editorial commentary in numerous science journals, for example, Nature, Science and Science News as well as the popular press including The Economist and The Financial Times (London). Moss is the author of over 215 scientific publications including the editorship of several books and special issues of journals. He has given over 260 lectures at national and international conferences and institutes. He was awarded senior fellowships by the British government and by NATO and is a winner of the prestigious Humboldt Research Prize in Germany as well as numerous other awards for notable research. He currently serves on the editorial boards of two international journals and is a consulting editor for numerous others. He is a past chairperson of the Division of Biological Physics of the American Physical Society. He is currently Curators' Professor at the University of Missouri at St. Louis, USA. E-mail: mossf@umsl.edu

Hans Albert Braun is head of the Neurodynamics Group at the Institute of Physiology at the University of Marburg in Germany. He has been trained as electronic engineer at the Technical University in Karlsruhe where he obtained a degree in «Electrobiology». In course of a supplementary study of «Human Biology» he obtained his PhD at the Medical Faculty of the University of Marburg.

His research involves experiments and models of neuronal encoding and neuromodulatory processes in peripheral sensory receptors (thermo- and electroreceptors) and hypothalamic neurones (neuroendocrine functions) including computer modelling studies of affective disorders. The aim is the understanding of neuronal systems dynamics at different levels and to elucidate their functional principles.

Hans A. Braun is member of several scientific societies and has been honored with the fellowship of the Biophysics Division of the American Physical Society. E-mail: braun@mailer.uni-marburg.de

Karlheinz Voigh - Institute of Physiology, University of Marburg, 35037 Marburg, Germany.