Journal of Integrative Neuroscience

PROLOGUE - THE WORK OF THE LATE PROFESSOR GEN MATSUMOTO

KAZUYUKI AIHARA*, ICHIRO TSUDA†, and HIROSHI FUJII‡

*Institute of Industrial Science, the University of Tokyo, and
ERATO Aihara Complexity Modeling Project, JST
Tokyo 153-8505, Japan
aihara@sat.t.u-tokyo.ac.jp

†Department of Mathematics, Hokkaido University
Sapporo 060-0810, Japan
tsuda@math.sci.hokudai.ac.jp

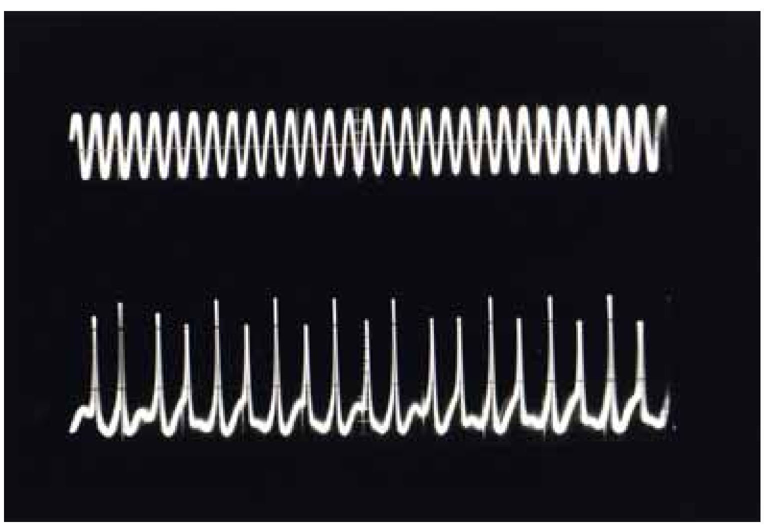
‡Department of Information and Communication Sciences, Kyoto Sangyo University
Kyoto 603-8555, Japan
fujii@bacco.kyoto-su.ac.jp

Received 17 April 2004
Accepted 5 May 2004

Gen Matsumoto had pursued the reality of correspondence between *structure* and *function* in biological systems, based on the facts derived from experiments conducted by himself. His scientific interest was in the genesis of impulses in squid giant axons, the product of 'biocomputers', and possible effects of 'love' on the brain, which were motivated by his own observation of remarkable recovery process in a brain-damaged patient. In all of his studies, he emphasized the biological significance of nonequilibrium systems. He insisted that a neuron can become functional only in far-from-equilibrium states. This means that a neuronal firing is generated by a dissipative structure [6, 12] of membranes. He also emphasized an importance of open systems as the most basic characteristic of dissipative systems, extending the range of energy to the range of information. Thus, his thinking extends to the idea that both humans and animals can receive and send information only provided things which set them at high motivational states are present. He considered 'love' to be the most important factor among such things.

One of the early studies of Gen Matsumoto deserving special mention was the discovery of chaos in squid giant axons, which was done with his student KA, one of the present authors [1, 3]. First of all, it should be noted that he succeeded, first in the world, to maintain squids in a small circular and closed-system aquarium tank for 40-60 days [7]. Using a lot of squid giant axons, he experimentally analyzed excitable dynamics of squid giant axons in details and proposed a hypothesis of the excitation principle as phase transition triggered by externally applied stimulation from the equilibrium structure of the resting state to the dissipative structure of repetitive firing [2, 8]. He also proposed a microscopic model of excitable nerve membranes, paying special attention to axonal undercoat and cytoskeletal structures underneath the axolemma of squid giant axons [9]. Based on these previous studies, Matsumoto, Aihara and their colleagues tried to analyze nonlinear responses of squid giant axons either in the resting or oscillatory state under periodic stimulations, which led to the discovery of deterministic chaos in nerve membranes [1, 10, 11]. Figure 1 shows an example of the chaotic response experimentally observed in squid giant axons. These experimental results clarified the existence of chaos in the level of nerve membranes. In other words, the brain is composed of devices with chaotic dynamics [4, 5]. This was one of the first experimental evidences that chaos could exist and might play a role of functional importance in biological systems.

(a)



(b)

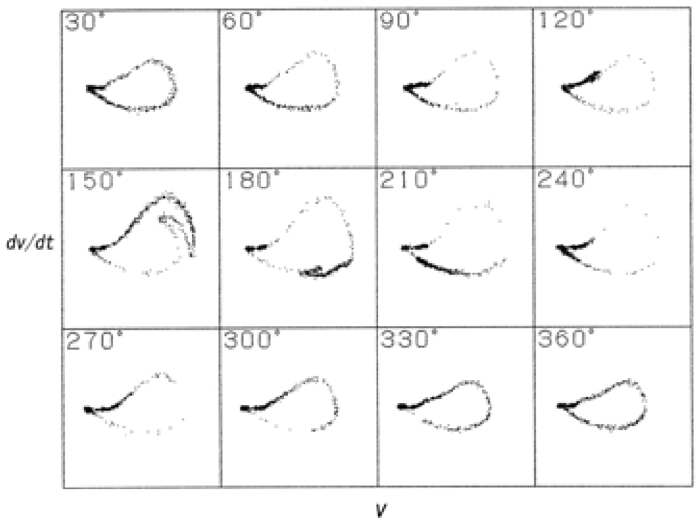


Fig. 1. Nerve chaos experimentally observed in a squid giant axon at a state of self-sustained oscillation with the natural frequency of 183 Hz, which is further periodically forced by sinusoidal current with amplitude 2 A and frequency 297 Hz.
(a) Wave forms (above: the stimulation, below: the membrane potential) and
(b) the stroboscopic plots where the number in each frame is the phase of the sinusoidal currents.

References

[1] Aihara K., Numajiri T., Matsumoto G. and Kotani M., Structures of Attractors in Periodically Forced Neural Oscillators, *Phys. Lett. A* **116**:313-317, 1986.

[2] Aihara K. and Matsumoto G., Temporally Coherent Organization and Instabilities in Squid Giant Axons. *J.Theor. Biol.* **95**:697-720, 1982.

[3] Aihara K. and Matsumoto G., Chaotic Oscillations and Bifurcations in Squid Giant Axons, *Chaos*, ed. by A.V. Holden. (Manchester University Press, Manchester and Princeton University Press, Princeton, 1986), 257-269.

[4] Aihara K., Takabe T. and Toyoda M., Chaotic Neural Networks, *Phys. Lett. A* **144**:333-340, 1990.

[5] Aihara K., Chaos Engineering and its Application to Parallel Distributed Processing with Chaotic Neural Networks, *P. IEEE* **90.5**:919-930, 2002.

[6] Kobatake Y., Transition between two steady states in a porous charged membrane, Physica **48**:301-312, 1970.

[7] Matsumoto G. and Shimada J., Further improvement upon maintenance of adult squid (Doryteuthis bleekeri) in a small circular and closed-system aquarium tank, *Biol. Bull.* **159**:319-324, 1980.

[8] Matsumoto G., Long-range spatial interactions and a dissipative structure in squid giant axons and a proposed physical model of nerve excitation. In *Nerve Mem-*

brane:Biochemistry and Function of Channel Proteins, ed. by Matsumoto G. and Kotani M. (University of Tokyo Press, Tokyo,1981), 203-220.

[9] Matsumoto G., A proposed membrane model for generation of sodium currents in squid giant axons, *J. Theor. Biol.* **107**:649-666, 1984.

[10] Matsumoto G., Aihara K., Ichikawa M. and Tasaki A., Periodic and Nonperiodic Responses of Membrane Potentials in Squid Giant Axons during Sinusoidal Curent Stimulation. *J. Theor. Neurobiol.* **3**:1-14, 1984.

[11] Matsumoto G., Aihara K., Hanyu Y., Takahashi N., Yoshizawa S. and Nagumo N., Chaos and Phase Locking in Normal Squid Axons, *Phys. Lett. A.* **123**:162-166, 1987.

[12] Nicolis G. and Prigogine I., *Self-Organization in Nonequilibrium Systems* (John-Wiley, 1977).