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Research paper

Using chaotic artificial neural networks to model memory in the brain

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ABSTRACT

In the current study, a novel model for human memory is proposed based on the chaotic dynamics of artificial neural networks. This new model explains a biological fact about memory which is not yet explained by any other model: There are theories that the brain normally works in a chaotic mode, while during attention it shows ordered behavior. This model uses the periodic windows observed in a previously proposed model for the brain to store and then recollect the information.

1. Introduction

Chaos occurs in dynamical systems that are sensitively dependent on initial conditions. Small differences in initial conditions yield widely diverging outcomes. Although such systems are deterministic, long-term predictions cannot be made [1]. There is growing evidence that future research on neural systems and higher brain functions will require a combination of classic neuroscience and the more recent nonlinear dynamics. The neuronal system composed of neurons and gliocytes is often sensitive to external forcing and internal shift in functional parameters, so that the appropriate response can be selected. This characteristic resembles the dynamical properties of chaotic systems [2–4]. It is not necessary for the brain to reach an equilibrium following a transient, but it is constantly shifting between different states. There is some evidence to support the claim that chaos occurs in many biological systems, especially in the human brain [2–25]. For example, it appears that the dynamics in electroencephalogram (EEG) signals are chaotic [8]. The EEG signals may look random to outside observers, but there are hidden patterns in their random-like appearance. The search for chaos in EEG signals started in the early 1980 s. Bressler and Freeman observed that when rabbits inhale an odorant, their EEG signals display oscillations in the high-frequency range of 20–80 Hz [26]. Odor information was then shown to exist as a pattern of neural activity that could be discriminated whenever there was a change in the odor environment. One of these attractors is shown in Fig. 1. This attractor belongs to the EEG of the olfactory bulb in a rat. This attractor seems to be showcasing a periodic attractor

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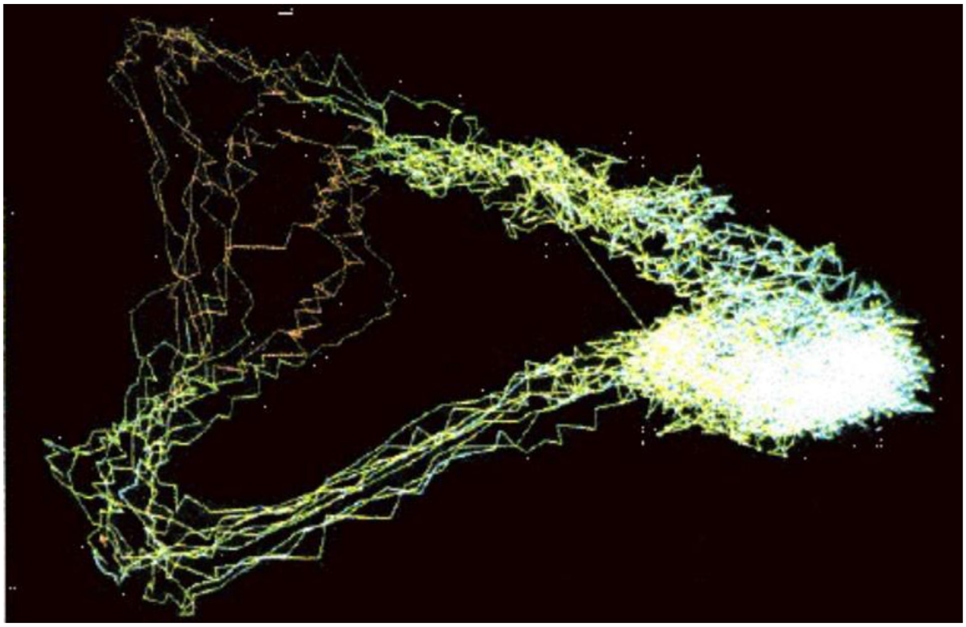

Fig. 1. Strange attractor of the EEG taken from a rat [17].

rather than chaos. Further dissection of the experimental data led to the conclusion that the activity of the olfactory bulb is chaotic and may switch to any desired perceptual state (or attractor) at any time [17]. This change could be from chaos to some kind of oscillations or periodic behavior in the case of inhaling a familiar odor. This periodic behavior seems to be due to the attention and focus regarding the process of saving or retrieving the odor information [27–29]. Some other reasons that might cause the brain to change its behavior is some sort of a malfunction or disease like epileptic seizures [30–34].

Another example of chaos in biological systems is the dynamics at the neuronal level (cellular and subcellular). The transportation and storing of information in the brain is believed to be accomplished by the impulse trains produced by neurons. These trains of impulses or action potentials are often organized as sequences of bursts. The most important information in these sequences involves their temporal patterns, which are also known as interspike intervals (ISIs). The ISIs in a single neuron can show different behaviors including chaos. These impulses are generated by the interaction between the gating of ion channels and the axon's membrane voltage. Hodgkin and Huxley were the pioneers who proposed a dynamical system model of this interaction that predicted realistic action potentials [35]. Their model has been simplified in several forms by some other researchers [6,36].

All of the behaviors that these models exhibit can be found in their bifurcation diagram. A bifurcation is a sudden change in the dynamics when a parameter of the system is incrementally changed [1]. From a dynamical systems point of view, neurons are excitable because they are near a bifurcation where a transition from resting to a sustained spiking activity occurs [37]. All the neurons undergo bifurcation by changing their state. Their new state can be periodic as in tonic spiking (called a limit cycle), or they can be chaotic (called a strange attractor). When a neuron begins to fire in a chaotic manner, its firing is called bursting.

All this evidence led scientists to consider the human brain as a dynamical system that is generally chaotic but can have transitions between different states (or undergo bifurcations) [2–5,8,10–25,38]. For example, when an epileptic patient has a seizure, the EEG is more similar to a periodic signal [39]. Based on properties of chaos and periodic windows and the physiological facts about the human attention system, a hypothesis was proposed that during intense focus the EEG changes from chaotic to a periodic window [27–29].

In psychology, memory is the process by which the information from the outside world is encoded, stored and then accessed by a human being. In the encoding stage, the information is received, analyzed and then translated by the brain into the language in which the data is stored. In the storing stage, the encoded data is stored in the human brain in a permanent way for future access. The third and final stage of memory is the retrieval of the memory which is also referred to as recall or recollection which is calling back the stored information in response to some cue for use in a process or activity. In this stage the stored memory should be located and then accessed by the brain in a state of full attention [40].

It seems that the brain has a chaotic structure in the encoding stage of data storage [41]. This encoding seems to be done by specifying an attractor for the related data and retrieving the attractor whenever that same data is called back [17,18]. Multiple studies have claimed that the attractors associated with remembering or recalling a piece of information (or in general during intense focus) is periodic and ordered [2,16–18,21,28]. This seems logical, since encoding any data to a chaotic attractor will lead to an unpredictable output.