Chaos in Neurophysics

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Honor Project for UPII

PHYS 2074H – Lab 005

November 21, 2012

CHAOS IN NEUROPHYSICS

Chaos manifests in various systems in different ways. Mathematicians attempt to quantify chaos, while physicists often try to ignore it. However, many disciplines of science are beginning to recognize the importance of studying chaos. One important study is the behavior of chaos in dynamical system of the brain. Research has provided evidence to support that the brain works most ideally when chaos is present.

To study chaos in the brain, one must first understand what is chaos. It has been quoted that "where chaos begins, classical science stops" (Gleick 1988). Chaos has often been regarded as the century's [1900's] third great revolution in the physical science; relativity challenged Newton's concept of absolute time and space, and quantum theory rejected the Newtonian idea of controllable measurement process (Aubin & Dalmedico 2002). Before the third revolution of chaos, the main principle of mechanics was the Laplacian principle of deterministic predictability (Gleick 1988). If the initial conditions are known for a system, then the behavior can be approximated when the laws of physics are applied properly. Therefore, slight changes in the initial conditions result in only slight alternations of the behavior.

A dynamical system is one that changes continuously over time, such as the motion of planets or chemical reactions (Devaney 1989). The purpose of studying dynamical systems is to determine its outcome, or its behavior. The outcome sought is the final state of being—stability (Gleick 1988). According to the Laplacian principle, the stable behavior in the system does not disappear due to the smallest variations in conditions (Gleick 1988). However, chaos overturns this assumption.

Chaos can be thought of as “a science of process rather than state, of becoming rather than being” (Gleick 1988). It has the ability to show that tiny errors have the ability to propagate, grow, and cause for the predicted behavior of some systems to disappear, replaced by a dramatically altered one (Stewart 2002). Chaos emphasizes the uniqueness of a system. A dynamic system has points of crisis that magnify small changes. The chaos theory reveals there can be instability at any point (Gleick 1988). In other words, the outcome, or behavior, of a dynamical system is highly dependent on the initial conditions.

To understand the essence of chaos is to understand that there is a delicate balance between stability and instability at every scale. Simple, deterministic systems can be complex, and systems exhibiting behaviors too complex for traditional math could obey simple laws. It is important to study chaos because it aids the understanding of dynamical systems and their behavior.

Complex systems, such as the weather, have driving and damping forces. In the case of weather, it is driven by the energy of the Sun, and damped by friction of moving air and water, and by dissipation by water (Gleick 1988). Inside the human body, chaos exists as well, such as the heart and brain.

Before delving into chaos in the brain, it is important to know how the brain works first. The brain is the central processing unit of the body. It is responsible for body movement, thought, behavior, and interpretation of senses. The three basic parts of the brain are the forebrain, the midbrain, and the hindbrain, shown in Fig. 1 (Roberts 1986). Each part of the brain has its own unique properties that work together to function as an effective organ in the body.

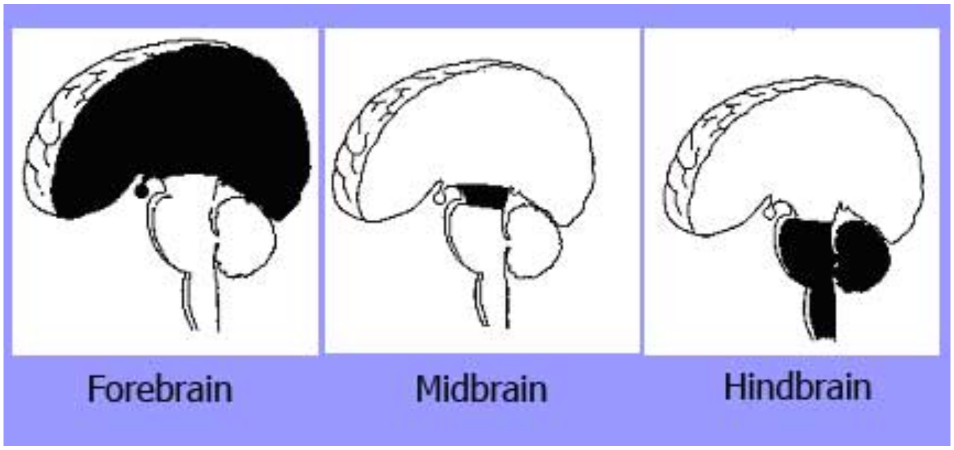

Fig. 1: Three main parts of the brain: the forebrain, midbrain, and hindbrain.

The hindbrain consists of the cerebellum, brain stem, and spinal cord (Altenmüller & Gruhn 2002). It is responsible for sensory and motor functions, such as breathing, equilibrium, and heart rate. The cerebellum is involved in learning motor skills, and process body equilibrium and accurate timing of movements (Altenmüller & Gruhn 2002). Above the hindbrain, the midbrain has two parts: the thalamus and hypothalamus. The thalamus transmits information as part of the course of voluntary movement, and the hypothalamus regulates reflex action (Altenmüller & Gruhn 2002).

The largest and most highly developed part of the brain, the forebrain, is mostly made of cerebrum and the structures beneath it (National Institute of Neurological Disorders and Stroke 2012). The cerebrum is the outermost structure of the brain. It is divided into two parts that control opposite sides of the body; the left side of the brain regulates the right side of the body, and similarly for the other side. The cerebrum is involved with memory storage, motor performance, and coordination of voluntary and involuntary responses (Altenmüller & Gruhn 2002).

The outer covering of gray matter over the cerebrum is the cerebral cortex (Swenson 2006). It is comprised of about 100 billion neurons, interconnected by nerve fibers known as the corpus callosum (Altenmüller & Gruhn 2002). Neurons are the primary functional units that communicate cognitive function across synapses, the space between neurons (National Institute of Neurological Disorders and Stroke 2012). Neurons are made of three parts: the cell body, dendrite, and axon, seen in Fig. 2. The cell body has the nucleus, which manufactures the molecules needed for the neuron to function. Dendrites receive the signals from other nerve cells. The electrical signals may travel from the dendrite and down the axon to other neurons or cells of organs. Axons, which vary in length, are surrounded by a myelin sheath that insulates and aids signals to travel more efficiently. From the neuron, the signal travels across the synapse by prompting the release of neurotransmitters from storage sacs at the end of the axon (National Institute of Neurological Disorders and Stroke 2012).

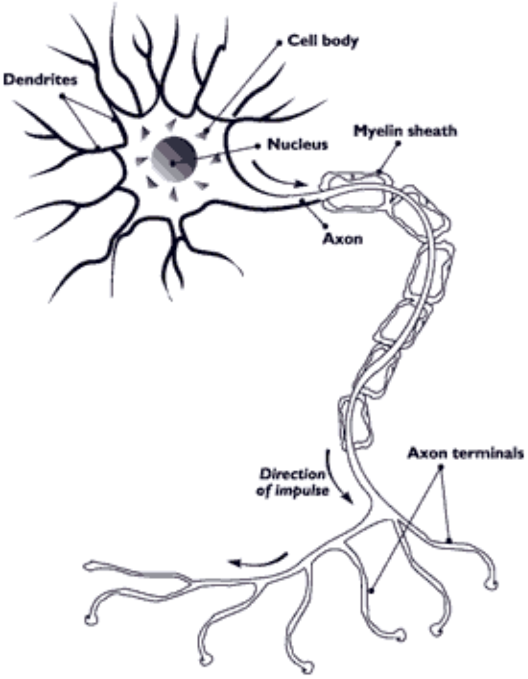

Fig. 2: Labeled parts of a neuron.

The neurons communicate using a combination of both electrical signals by action potentials and synapse potentials, and chemical signals through neurotransmitters (Brown 2001). Electric signal is the brain is generated by charged ions moving across the ionic gradient. Ionic gradients store potential energy across the cell membranes. It is generated by ion carriers, or pumps, to create a high concentration of potassium ions and a low concentration of sodium, calcium and chlorine ions in the cell's interior as compared to its exterior at resting potential (Brown 2001).

The complete process for the electrical signal is illustrated in Fig. 3. At resting potential, the neuron is polarized and the ion channels are closed, minimizing the amount of ions that exchange through the cell membrane (Stufflebeam 2008). The passive diffusion of ions back out of the cell through ion channels creates an electrical gradient. As charged ions move across the gradient, changes are made in the electric potential. The rate of change of the potential produces an electric field: $\vec{E} = -\frac{dV(x)}{dx}\hat{x}$ (Stewart & Stewart 2011). Action potential is the electrical signal generated by full depolarization after a stimulus partially depolarizes to the neuron's threshold (Stufflebeam 2008). The stimulus can either activate or deactivate ion channels. This stimulus can be from neurotransmitters or from previous electric action potentials. Action potential is followed by a phase of repolarization in which the channels close. However, before the neuron can return to resting potential, there is a refractory period, or hyperpolarization, preventing the initiation of another action potential. The process of spreading along the membrane of the axon is called conduction (Stufflebeam 2008). When it reaches the end of the axon terminal, changes in the electric potential of the first neuron trigger chemical

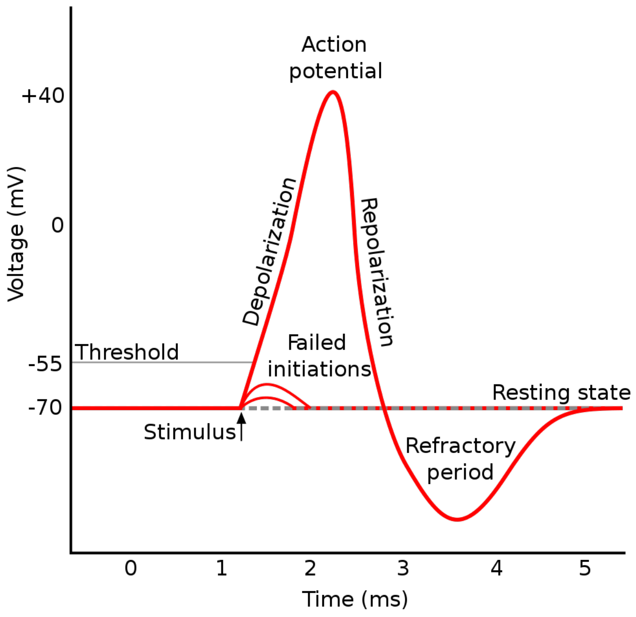

Fig. 3: Membrane potential during signal process

neurotransmission (Halbach & Dermietzel 2006). Presynaptic potential occurs at the end of the axon terminal, while postsynaptic potential occurs after the signal has travelled across the synapse to the dendrites (Clayton, Sager, & Will 2004).

Neurotransmitters are chemicals that travel across the synapse and attach to receptors, which then determines the properties of those neighboring cells. Excitatory neurons are the brain's driving force and inhibitory neurons are the brain's damping force. Acetylcholine is an excitatory neurotransmitter, since it excites cells. It regulates muscle contractions and increases hormone levels. Shortages in acetylcholine can affect memory formation, and is associated with neurological disorders like Alzheimer's disease. Gamma-aminobutyric acid, GABA, is an inhibitory neurotransmitter because it makes cells less excitable. It is an important part of the muscle and visual systems. Increasing GABA levels can increase muscle control, and has been used to treat people with epilepsy and Huntington's disease.

Dopamine is another inhibitory neurotransmitter that controls complex movement and mood. It has been used in practice to treat for both movement disorders, such as Parkinson's disease, and behavior disorders, such as schizophrenia. A fourth neurotransmitter, serotonin, controls blood vessels, induces drowsiness, and influences conditional states, such as behavior, mood, and appetite. Abnormal levels of serotonin are associated with depression, eating disorders, sleeping disorders, and obsessive-compulsive disorders (National Institute of Neurological Disorders and Stroke 2012).

In brain, there exist points of criticality. Parameters are fixed values based on set conditions of which the dynamics of natural processes depend, and vary per instance (Scott 2005). Criticality, or chaos, is reached when the system loses stability by increasing the parameters. It is sufficient to vary one parameter in order to increase nonlinearity (Scott 2005). In other words, the one such parameters of the brain are neurotransmitters. Ironically, through *in vitro* studies and computer models, the brain has been shown to function most ideally when excitatory and inhibitory neuron levels are balanced. As stated earlier, this is an example of the delicate balance between stability and instability in which chaos exists.

Timing, frequency, and intensity need to be interpreted by the brain from the series of electrical signals encoded with information. Different neurons in the brain respond to different portions of the information (Pouille & Scanziani 2004). Specification of neurons to information is determined by varied frequencies. Although each neuron can be receiving multiple electrical signals from multiple sources, its response is limited to those that have the appropriate timing and frequency. Timing is relevant because synchronization is need for efficient interpretation and relaying of information. Intensity is necessary for the brain to decode from the electric signals because it influences what action will be taken (Pouille & Scanziani 2004).

Dynamic range is defined to quantify the range of stimulus intensities giving rise to distinguishable response among the neurons receiving the stimulus. The range is dependent on the inhibitory and excitatory neurons (Pouille et al., 2009; Shew et al., 2009; Larremore et al., 2011). Based on previous findings from computer models and *in vitro* experiments, it is believed that the dynamic range is highest when the excitatory and inhibition levels are properly balanced (Kinouchi & Copelli, 2006; Shew et al., 2009). This implies that if either signal level becomes unbalanced, then the range decreases causing a decreased ability to perceive varying intensities. Therefore, neurotransmitters could influence the dynamic range by altering the intensities at which the neuron can detect stimuli.

The importance of studying chaos in the brain is the same for any dynamical system: to better understand the system. For centuries, the mysteries of the brain have eluded scientists and philosophers. However, technology had not yet caught up to science. Therefore, it was not possible to study the brain in depth, and the brain was regarded as unfathomable.

Over the past several decades though, advancements have been made making it possible to research the inner workings of this neurological system. Although this has allowed us to have better insight on how the brain works, to fully comprehend the brain, live, or *in vivo*, subjects must be researched in order to test the relevance of the *in vitro* studies and computer models. Two methods for studying the brain in live subjects are electrodes and electroencephalography. Each technique has a different approach to incorporating chaos in order to treat neurological disorders.

Electrodes are conducting probes specially designed to measure the voltage for a solution concentration. Using to obtain chemical information is called potentiometry (Harris 2010). For the brain, the solution being measured is the cerebrospinal fluid, which fills the spaces the brain's cortex (Agamanolis 2012). Electrodes are inserted into the brain, and it measures the potential difference via voltage difference in ion distribution. This can be used to observe brain activity. The electrode is able to detect the movement of electrical signals as it alters the concentration gradients.

Electrodes can be efficiently used to monitor the effect of drugs on the brain. Introducing more neurotransmitters to the area the electrodes have been inserted can pharmaceutically alter the levels of inhibition and excitation. The drugs affect the ion channels, therein, changing the potential difference to be measured by the electrodes. This allows for researchers to observe the effect increasing certain parameters has on the behavior of the system, the brain. For example, in the case of sensory neurons, there is a correlation between inhibition levels and the dynamic range (Pouille et al., 2009; Shew et al., 2009). The dynamic range is highest when the inhibitory and excitatory neurons are properly balance compared to those with a disrupted one. The dynamic range decreases when the inhibition has been increased, and it decreases more, comparatively when inhibition has been decreased.

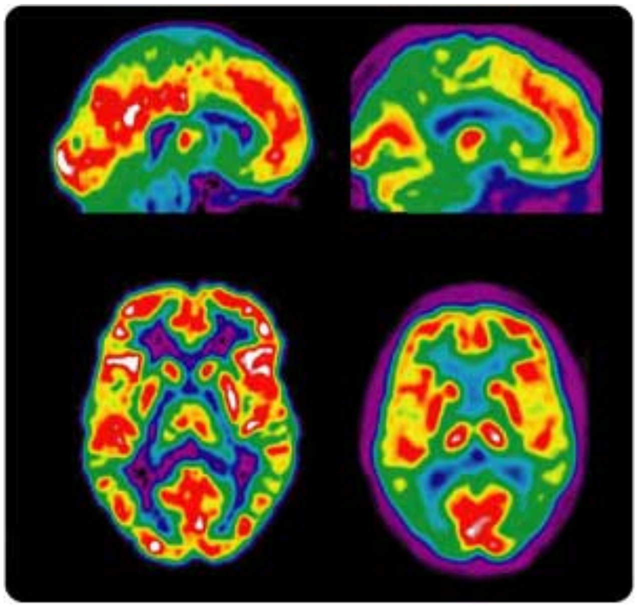

Fig. 4: Electroencephalogram of healthy brain (left) and Alzheimer's brain (right)

Electroencephalography was developed by Hans Berger in the late 1920s as a technique to record electrical activity of the human brain (Clayton, Sager, & Will 2004). Berger discovered there were four fundamental frequency ranges: delta from one to four Hertz (Hz), theta from four to eight Hertz, alpha from eight to twelve Hertz, and beta from 14 to 30Hz. It was observed that these frequencies were related to certain mental states: high-amplitude alpha waves dominated a relaxed, inattentive state, while low-amplitude beta waves were associated with busy and alert states. The electrical signal recorded in electroencephalograms is attributed to postsynaptic potentials (Clayton, Sager, & Will

2004). An example of an electroencephalogram is shown in Fig. 4. The left side depicts a healthy brain, while the right side represents a brain with Alzheimer's disease, which appears to be subdued in color compared to the other, suggesting less neuron electrical activity.

Aside from pharmaceutical medication, other methods have been researched to treat neurological disorders. One such method uses a driving force of frequency to synchronize brainwaves. Brainwave entrainment is a device used to change brain state by altering its frequency. This is achieved through entrainment, a process in which two or more independent rhythmic behaviors synchronize to produce one period (Clayton, Sager, & Will 2004). The brainwave entrainment introduces a rhythmic stimulus to the visual and auditory senses. This influences the frequency of the brain, and therein, influencing the interpretation of electrical signals sent to neurons. The effects of brainwave entrainment have been studied for pain, headaches, migraines, anxiety, stress, attention deficit hyperactivity disorder, learning disabilities, and behavior problems (Huang & Charyton 2008).

Chaos is an important aspect key to understanding the brain and other complex systems in our universe. As it has been seen in various other disciplines, neurophysics has begun acknowledging that chaos was relevant. In doing so, researchers have been able to observe patterns in previously unexplained phenomena, such as the brain's points of criticality. They also developed techniques to incorporate chaos into neurological studies, such as brainwave entrainment and pharmacologically altering the levels of inhibitory or excitatory neurons. In the future, with a better understanding of chaos, the mysteries of the brain can be linked both within and out of the system.

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