
Rhythms of the Brain

György Buzsáki

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2006

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Kuala Lumpur Madrid Melbourne Mexico City Nairobi
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Published by Oxford University Press, Inc.
198 Madison Avenue, New York, New York 10016

www.oup.com

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Library of Congress Cataloging-in-Publication Data

Buzsáki, G.
Rhythms of the brain / György Buzsáki.
p. cm.

Includes bibliographical references and index.

ISBN-13 978-0-19-530106-9

ISBN 0-19-530106-4

1. Brain—Physiology. 2. Oscillations. 3. Biological rhythms.

[DNLM: 1. Brain—physiology. 2. Cortical Synchronization.

3. Periodicity. WL 300 B992r 2006] I. Title.

QP376.B88 2006

612.8'2—dc22 2006003082

9 8 7 6 5 4 3 2 1

Printed in the United States of America
on acid-free paper

To my loved ones.

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Prelude

If the brain were simple enough for us to understand it, we would be too simple to understand it.

—Ken Hill

The short punch line of this book is that brains are foretelling devices and their predictive powers emerge from the various rhythms they perpetually generate. At the same time, brain activity can be tuned to become an ideal observer of the environment, due to an organized *system* of rhythms. The specific physiological functions of brain rhythms vary from the obvious to the utterly impenetrable. A simple but persuasive example is walking. Bipedal walking is a periodic series of forward falls interrupted regularly by alternate extensions of each leg. It is almost as natural to us as breathing. This effortless exercise is made possible by the predictive nature of spinal cord oscillators. On smooth terrain, the alternation of leg movements can take us any distance. Perturbation of the clocking, on the other hand, signals a change in the terrain. This general mechanism is the same in all animals, including eight-legged scorpions and centipedes. The notion that oscillators or “central pattern generators”¹ are responsible for the coordination of motor

1. Neural circuits that produce self-sustaining patterns of behavior are called central pattern generators. The most studied central pattern generator is an intraspinal network of neurons responsible for locomotion. Grillner (1985) summarizes the pros and cons of the pacemaker view of central pattern generators in the spinal cord and brain. Stein et al. (1997) and Burke (2001) are nice updates on the topic. Central pattern generators are also responsible for many other types of rhythmic movements, e.g., peristaltic motor patterns of legless animals, rhythmic movement of the wings of crickets during song production, respiration, heart control, movements of the stomach, and other parts of the digestive system. My favorite review on this topic is Marder and Calabrese (1996).

patterns, such as breathing and walking, is old and well accepted in neuroscience. But the tantalizing conjecture that neuronal oscillators can be exploited for a plethora of other brain-generated functions, including cognition, is quite new and controversial. And it is the latter topic, the contribution of oscillations to the invisible, inferred operations of the brain, that this book is mostly about.

Exposing the mechanisms that allow complicated things to happen in a coordinated fashion in the brain has produced some of the most spectacular discoveries of neuroscience. However, I do not want to mislead you from the outset. Clocks are not thinking but ticking devices, no matter how precisely they can predict time. Time needs to be filled with content, provided by the appropriate firing patterns of neurons, whose assembly activity, in turn, is regulated by brain oscillations. Interestingly, the neuronal assemblies that generate the content are often the same as those that give rise to the time metric of oscillations that in turn organize the cell assembly pattern. This peculiar reciprocal causation, brought about by the self-organized features of brain activity, begs for an explanation. A good part of the volume is devoted to discussing experiments that attempt to elucidate these emerging properties of neuronal networks.

At the physiological level, oscillators do a great service for the brain: they coordinate or “synchronize” various operations within and across neuronal networks. *Syn* (meaning same) and *chronos* (meaning time) together make sure that everyone is up to the job and no one is left behind, the way the conductor creates temporal order among the large number of instruments in an orchestra. A close view of Seiji Ozawa at the end of a concert, sweat falling from his face, is proof that conducting an orchestra is a physically and mentally demanding job. In contrast, coupled oscillators perform the job of synchronization virtually effortlessly. This feature is built into their nature. In fact, oscillators do not do much else. They synchronize and predict. Yet, take away these features, and our brains will no longer work. Compromise them, and we will be treated for epilepsy, Parkinson’s disease, sleep disorders, and other rhythm-based cognitive maladies. As I point out repeatedly in Cycles 1–13 of this volume, virtually no nervous function exists without a time metric, be it the simplest motor or the most complex cognitive act. While we know quite a bit about neurons, the building blocks of the brain, and have extensive knowledge about their connectivity, we still know very little how the modules and systems of modules work together. This is where oscillations offer their invaluable services.

My connection with brain rhythms began in April 1970, during a physiology lecture given by Endre Grastyán in the beautiful town of Pécs, on the sunny slopes of the Mecsek mountains in Hungary. The University of Pécs, or Universitas Quinque Ecclesiensis, as it was called when founded in 1367, has produced a remarkable set of neuroscientists, including János Szentágothai, the legendary neuroanatomist; Béla Flerkó and Béla Halász, pioneers of neuroendocrinology; György Székely, the renowned spinal cord physiologist; and Ferenc Gallyas, the creator of the silver impregnation methods widely used for neuronal labeling.

Like many of us at a young age, in his twenties Grastyán could not quite make up his mind about his future. Finding nothing too interesting or challenging initially,

he decided to train for the priesthood to get some orientation in philosophy. But his mind, far too curious and questioning, prevented him from becoming a preacher. He ended up in medical school during the stormy years after World War II and became the assistant of Professor Kálmán Lissák. Lissák, a student of Otto Loewi in Graz, Austria, and subsequently Walter Cannon's assistant at Harvard, had returned to Hungary to become Chair of Physiology just before the war. Grastyán's pairing with Lissák was fortunate because Lissák, of course, knew quite a bit about rhythms from his years with Loewi, who provided the first evidence that a chemical—a neurotransmitter—is released at the junction (synapse) between the vagus nerve and the heart muscle.² Although Grastyán was perhaps Lissák's closest friend, the two were as different as can be. Lissák was a reserved man, and his lectures were scarcely attended. In contrast, Grastyán was a performing artist whose seminars were carefully composed and choreographed. The huge lecture room in the medical school was always packed, and even students from the neighboring law school came over to listen to his mesmerizing lectures. He generated so much enthusiasm that we students became convinced that the topics he discussed were among the most important in the whole universe.

In that particular lecture of April 1970, he talked about how the brain outputs, such as movement and cognition, control its inputs, rather than the other way around. His key idea was that control in living systems begins with the output. This is the seed for further evolution of the brain. Even in the most complex animals, the goal of cognition is the guidance of action. Indeed, the first simple biological systems did not have any inputs; they did not need them. They simply used an economical motor output, a rhythmic contraction of muscles. This is, of course, is sufficient only when food is abundant in the sea environment. More complex forms of life evolved from this simple solution by modifying the simple rhythmic output. Sensation of direction and distance developed only after the "invention" of movement through space. The idea of output control and feedback is a profound thought even today. Back then, when Pavlovian sensory–sensory association was the dominant ideology in the East and the stimulus–decision–response paradigm dominated Western thinking, Grastyán's teachings were unusual, to say the least.

After his lecture, I rushed home to read the relevant chapters in our official

2. Loewi called the chemical "Vagusstoff," which Henry Hallett Dale from Cambridge, England, identified later as acetylcholine, the first neurotransmitter. They received the Nobel Prize for their discoveries in 1936. I have heard various versions of the story behind the Vagusstoff experiment from Lissák. Here is one from Loewi's own pen:

The night before Easter Sunday of that year I awoke, turned on the light, and jotted down a few notes on a tiny slip of thin paper. Then I felt asleep again. It occurred to me at six o'clock in the morning that I had written down something most important, but I was unable to decipher the scrawl. The next night, at three o'clock, the idea returned. It was the experiment to determine whether or not the hypothesis of chemical transmission that I had thought about years ago was correct. I got up immediately, went to the laboratory, and performed a simple experiment on a frog heart according to the nocturnal design. (Loewi, 1960, 15)

Dale became better known about his "principle": if a chemical is released in one synapse, the same chemical is released in all the other synapses made by the same neuron.

textbook only to realize that there was not a single word there about what I had heard that morning.³ Nevertheless, beginning with Grastyán's introductory lecture on the organization of the brain, my life in medical school acquired new meaning. My original high school plan to become an electrical engineer was vetoed by my parents, who offered me the choice between medical school and law school. While my friends were having fun at the School of Engineering in Budapest, learning exciting stories about radio transmission and electronic oscillators, I spent most of my time studying the unending details of bones and ligaments. But in his physiology lecture, Grastyán was talking about some truly intriguing questions that sparked my interest. I applied to become his apprentice and spent most of my student life in his lab.

The best training in Grastyán's laboratory occurred through my participation in the regular lunch discussions that could go on for several hours, where topics meandered chaotically from homeostatic regulations of the brain to complex philosophical topics. It was during these lunch lessons where I first learned about the hippocampal "theta" rhythm, the oscillation that has become my obsession ever since. My first assignment in the Grastyán school, under the supervision of György Karmos, was to examine the variability of the evoked responses in the hippocampus and auditory cortex in response to sound stimuli as a function of behavior. In a nutshell, our main finding was that the most important factor in predicting the variability of the evoked brain responses was the variability of the background brain activity. This was the first time I faced the fascinating issues of "state," "context," and "spontaneous" activity, problems that remained with me forever.

As I have repeatedly discovered in my career, the informal lunch-seminar approach to science is hard to substitute with formal lectures or the reading of dense scientific papers. Seminars are tailored for an average group of people with the naive assumption that the audience retains all the details and follows and accepts the fundamental logic of the lecturer. In contrast, the essence of lunch conversations is to question the fundamental logic, a quest for clarification and simplification, a search for explanations and answers without a rigid agenda, where the focus is not on covering large chunks of material but on fully understanding even the smallest details. Of course, one can follow up a lecture by finding and reading the relevant published papers on the topic. However, most of the exciting findings in neuroscience are hidden in the small print of specialty journals, often written in a specialized and arcane language comprehensible to, at most, a handful of specialists. Overwhelmed with new and important discoveries in the various sub-specialties, the practicing neuroscientist, such as myself, tends to forget that

3. The idea that the brain's main goal is to control movement has been repeatedly emphasized by several outstanding individuals. Indeed, the brain's only means of interacting with the world is via the motor system, whether foraging for food or communicating by speech, gestures, writing a paper, or sending an e-mail. The outstanding books by Gallistel (1980) and Llinás (2001) discuss this point eloquently. The "primacy" of movement has been emphasized by Hamburger et al. (1966) and Bullock and Horridge (1965). For recent reviews on this topic, I suggest Hall and Oppenheim (1987), Wolpert and Ghahramani (2000), and Robinson and Kleven (2005).

neuroscience is of startling relevance to a contemporary society wrestling with complex issues such as social behavior, depression, and brain aging. It is hard to predict which of the numerous fundamental discoveries could alter the face of such large issues, and unless they are conveyed to others, they might be overlooked without making an impact. This is mainly so because the explanations we provide in papers to the superspecialists may be impenetrable to the uninitiated. Without attempting to place our work into a larger context from time to time, we deprive ourselves of the chance to be able connect to the more macroscopic and microscopic levels of research. Yet, discoveries and insights realize their power only when understood by others. Understanding this important connection is what mostly motivated me to write this volume.

Neuroscience has provided us some astonishing breakthroughs, from noninvasive imaging of the human brain to uncovering the molecular mechanisms of some complex processes and disease states. Nevertheless, what makes the brain so special and fundamentally different from all other living tissue is its organized action in time. This temporal domain is where the importance of research on neuronal oscillators is indispensable, and it is this temporal domain that connects the work discussed in this volume to all other areas of neuroscience.

Parallel with the amazing progress in neuroscience, another discipline has emerged: complex systems, a new science that cuts across many fields. During the past decade, I have learned as much about the brain by reading about novel branches of physics, engineering, mathematics, and computer science as I did from studying papers directly dealing with the nervous tissue. Rest assured, the human brain is the most complicated machinery ever created by nature. Nevertheless, it is truly exciting looking for concepts, mechanisms, and explanations that are common among many different systems and cut across the living/nonliving dichotomy. Seemingly unlikely sources such as fractals and Internet communication have provided novel clues for understanding neuronal networks. My goal is to illustrate how this new knowledge is being incorporated into neuroscience at a breathtakingly high speed and to convey fascinating discoveries to neuroscientists, psychiatrists, neurologists, and the growing group of computational scientists, physicists, engineers, and mathematicians interested in complex systems. A covert agenda is that, along the way, describing these new discoveries will encourage outsiders to become brain rhythm enthusiasts.

Deciphering the code of the brain will have a lasting impact on our society. It is not simply an intellectual exercise for a handful of esoteric individuals anymore. It is also more than a “just” a brain-health-related issue, which affects millions in the United States and many more worldwide. As Robert Noyce, the co-inventor of the integrated circuit, once put it: “In order to understand the brain, we have used the computer as a model for it. Perhaps it is time to reverse this reasoning. To understand where we should go with the computer, we should look to the brain for some clues.” Now that our economy, financial institutions, education system, research programs, distribution systems, human interactions, politics, and defense have all become computer and Internet dependent, this quest is more acute than ever. The hope is that the new knowledge about the brain will not only

inspire novel designs for computer architectures and a more efficient and safer electronic communication but also, at the same time, provide a better understanding of ourselves. Books, computers, and Internet communication have *externalized* brain functions and provided virtually unlimited storage space for the accumulated knowledge of humankind. However, this externalized information is only as useful as its accessibility. Currently existing search engines, such as Google and Yahoo, that provide access to this externalized knowledge are very inefficient (even though they are the best available at present) compared to the brain's ability to retrieve episodic information, because neuronal networks utilize fundamentally different strategies for the reconstruction of events and stories from fragments than do search engines. Understanding the brain's search strategies may allow us individuals to have better access to the cumulative knowledge of humankind.

Writing to a general audience interested in neuroscience is a much more arduous exercise than writing scientific papers. Scientists, rather than just the science they have produced, and metaphors that are deliberately absent in specialty journals come to the fore. This process inevitably implies oversimplification from the experts' viewpoint, occasional redundancies, and some rugged transitions for the novice. To alleviate the inevitable, I have written a simplified main story, which I hope to be a relatively easy read in most Cycles. Each Cycle ends with a brief summary, which highlights the primary message of the Cycle. The main story is supplemented by extensive footnotes, which serve partly to define novel terms. In most cases, however, they provide further critical information for the more sophisticated reader, along with links to the appropriate literature. I have deliberately chosen this format because it allowed me to interweave the main story and its more complex ramifications without breaking the flow of thought. The additional comments and citations in the footnotes give rise to an ever-growing tree with intertwined branches of arguments, hypotheses, and discovery.

A couple of years ago, we hosted a painter in our house for the summer. His determined goal was to survey and conquer the New York City art market. Yet, after a month or so, he plainly declared to us that every painting has already been painted and the art dealers are aware of all potential innovators in case the market is in need of such redundancy. He returned to Europe the next day. This is how I felt while writing this book. Clarity, critical details, and giving proper credit compete for space, and achieving the appropriate balance is the most difficult thing in writing a book. The more I explored the mysteries of brain oscillators and neuronal functions, the more I realized that the fundamental ideas (some which I thought were genuinely mine) have already been expressed, often repeatedly. Many times the ideas have come up in studying systems other than the brain, or they were expressed in a different context. But they existed. The deeper I ventured into the problems, the further back in time I had to travel to discover the origin of thoughts.

An oft-heard marketing slogan these days is that we have learned more about the brain during the past decade than during the previous history of humankind. This may be true regarding the volume of factual knowledge. But discoveries are

not (just) facts. They are ideas that simplify large bags of factual knowledge. Such fundamental ideas rarely pop up suddenly. Typically, they slowly emerge after appropriately long incubation periods and are shaped by numerous proponents and critics. Fundamental ideas are rare, and probably as many have been conceived prior to modern neuroscience as in the past few decades. One just has to recognize and adapt the old thoughts to the new lingo and the findings we have recently generated. My dear mentor advised me in my student days, “do not publish when you have only data but when you have a novel idea.” If I followed his advice strictly, I would perhaps still be writing my first paper and this volume would not exist. Although I honestly attempted to reach a balance between summarizing large chunks of work by many, and crediting the deserved ones, I am aware that I did not always succeed. I apologize for those whose works I unintentionally ignored or missed. To claim innocence, I shall simply shift the responsibility onto those who kindly read some parts of the manuscript at various stages and did not complain (enough). These generous colleagues include Kamran Diba, Caroline Geisler, Robert L. Isaacson, Kai Kaila, Christof Koch, Nancy Kopell, Rodolfo Llinás, Stephan Marguet, Edvard Moser, Denis Paré, Marc Raichle, Wolf Singer, Anton Sirota, Paula Tallal, Jim Tepper, and Roger Traub. My dear friend Mircea Steriade took the trouble of reading the entire manuscript and provided invaluable feedback. My special thanks to Mary Lynn Gage for her attempts to transpose my Hungarian-Zombi idioms into comprehensible English. This may not have always succeeded, and I would like to publicly apologize for humiliating Shakespeare’s beautiful language here and there.

At a more general level, I would like to express my gratitude to a number of people whose examples, support, and encouragement sustained me in difficult times and whose collaborations, inspiring discussions, and criticism have served as constant reminders of the wonderful collegiality of our profession—David Amaral, Per Andersen, Albert-László Barabási, Reginald Bickford, Yehezkel Ben-Ari, Anders Björklund, Brian Bland, Alex Borbely, Ted Bullock, Jan Bures, Gábor Czéh, János Czopf, Eduardo Eidelberg, Jerome (Pete) Engel, Steve Fox, Walter Freeman, Fred (Rusty) Gage, Mel Goodale, Charlie Gray, James McGaugh, Michale Fee, Tamás Freund, Helmut Haas, Michael Häusser, Walter Heiligenberg, Bob Isaacson, Michael Kahana, George Karmos, Nancy Kopell, Lóránd Kellényi, Gilles Laurent, Joe LeDoux, Stan Leung, John Lisman, Rodolfo Llinás, Nikos Logothetis, Fernando Lopes da Silva, Jeff Magee, Joe Martinez, Bruce McEwen, Bruce McNaughton, Richard Miles, István Mody, Robert Muller, John O’Keefe, Marc Raichle, Jim Ranck, Menahem Segal, Terry Sejnowski, Larry Squire, Wolf Singer, David Smith, Peter Somogyi, Mircea Steriade, Steve Strogatz, Karel Svoboda, David Tank, Jim Tepper, Alex Thomson, Giulio Tononi, Roger Traub, Cornelius (Case) Vanderwolf, Olga Vinogradova, Ken Wise, Xiao-Jing Wang, and Bob Wong. Over the years, some of these outstanding colleagues—Bob, Bruce, David, Gábor, Helmut, István, Karel, Mircea, Peter, Rodolfo, Roger, Rusty, Ted, Tamás, and Wolf—became my trusted, close friends. Most importantly, I would like to thank my students and post-doctoral fellows without whose dedication and hard work the many experiments discussed in this volume would not exist.

Being a scientist is a dedication. Writing a book is a bit more. Oh yes, it is a lot of fun, but it takes time, precious time that I had to steal from somewhere, mostly from my family. My dear wife, Veronika, and my sweet daughters, Lili and Hanna, forgive me for the many weekends you had to spend without me and for my frequent mental absences at dinners and family events when only my body was present. How fortunate I am to have you as my supporters. Without your understanding and encouragement, this venture would have been worthless.

Dear reader. Do not stop here! The rhythm begins only now.

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Cycle 1

Introduction

There is no good reason to assume that the brain is organized in accordance with the concepts of folk psychology.

—Cornelius H. Vanderwolf

It all began with a dream. A young officer in the Prussian Army received a letter from his sister. In it she wrote about a dream in which her beloved brother fell off his horse and broke his leg. As it happened, the young officer indeed fell off his horse at about the time the letter was sent by his sister. The officer, Herr Doktor Hans Berger, already an established researcher on cerebral blood circulation at the University Clinic for Psychiatry in Jena, Germany, thought that such coincidence could only have happened through some mysterious communication between brains, via telepathy,¹ as such alleged communications between brains are better known.

After returning to Jena from active military duty, Berger was promoted to the Chair of the Department of Psychiatry and Neurology in 1919 and devoted the rest of his career to the study of the brain's electrical activity. Berger reasoned that the electromagnetic forces generated by the human brain could be the carrier waves of telepathy, his true interest. Since even in that day telepathy was regarded as an "occult" subject, his experiments were conducted in utter secrecy in a laboratory located in a small building on the grounds of the clinic. Most of his initial recordings were done on himself, his son Klaus, and patients with skull defects.

1. Telepathy (or the related terms precognition and clairvoyance) is the supposed ability to transfer thoughts, feelings, desires, or images directly from the mind of one person to the mind of another by extrasensory channels and without using known physical means.

He performed numerous experiments and, importantly, eliminated the possibility that the voltage changes measured by his string galvanometer were an artifactual consequence of blood pressure changes; nor did they arise from the scalp skin. After five years of experimentation, he concluded that the most prominent electrical activity could be recorded from the occipital (lower rear) part of the skull when the subject's eyes were closed. In his groundbreaking 1929 paper he wrote, "The electroencephalogram represents a continuous curve with continuous oscillations in which . . . one can distinguish larger first order waves with an average duration of 90 milliseconds and smaller second order waves of an average duration of 35 milliseconds. The larger deflections measure at most 150 to 200 microvolts. . . ."² In other words, the electrical field generated by millions of discharging neurons in the cerebral cortex is 10,000 times smaller than that provided by an AA battery.

Berger called the large-amplitude rhythm (approximately 10 waves per second, or 10 hertz), which was induced by eye closure in the awake, calm subject, the "alpha" rhythm because he observed this rhythm first. He named the faster, smaller amplitude waves, present when the eyes were open, "beta" waves. Paradoxically, Berger's recordings provided firm physical evidence *against* his idea that waves generated by one brain could somehow be detected by another brain. The voltage changes that emerge from the cooperative activity of neurons in the mammalian brain are just too small, and current propagation requires a low-resistance conductor, so it cannot cross air, for example. Although he failed to prove his hypothesis of telepathic communication between brains, his research created a powerful scientific and clinical method for investigating quickly changing brain activity.³

Discovering a dynamic brain phenomenon is one thing. Understanding its meaning and its role in behavior and cognition is quite another. Ever since Berger's

2. Berger (1929). Berger was already familiar with the work of Richard Caton, a Liverpool surgeon who studied the electricity generated by the brains of rabbits and monkeys (Caton, 1875). Berger's international fame was boosted when his work was confirmed and endorsed in by Edgar Douglas Adrian and Bryan Harold Cabot Mathews of the Cambridge Physiological Laboratory. They suggested calling the alpha waves the Berger rhythm, but Hans Berger modestly rejected the offer (Adrian and Mathews, 1934).

3. It is tough to be first in any field of science, and the discovery of the electroencephalogram (EEG) was no different. In addition to Caton's work, Berger also knew about the published works of the physiologists Adolf Beck of Poland and Vladimir Pravdich-Neminski (or W. W. Prawdycz-Neminski in his native Ukrainian) of Russia. Neminski's observations are perhaps most relevant since his "electrocerebrogram" was obtained from the intact surface of dogs' skulls (Neminski 1913). However, he was not the first Russian in this area of research. Vasili Yakovlevich Danilevsky had described observations similar to Caton's in his doctoral thesis, and Nikolai Y. Wedensky had used a telephone circuit to listen to electrical waves in the brains of cats and dogs. Fleischel von Marxow was also among the first discoverers of electrical fields of the brain. However, he placed his results in a sealed letter in 1883 and revealed them only after he learned about Beck's published results. What made Berger's observations stand out from the others were the numerous control experiments he provided along with his observations. Brazier's (1959) chapter is the best summary of the exciting early days in the study of brain electricity and is a source for numerous references. Borck (2005) is another useful source of historical materials.

early observations, three questions have haunted neuroscientists: how are EEG patterns generated, why are they oscillatory, and what is their content? Providing answers to these questions is a major goal of this volume. I introduce the topic in Cycles 2 and 3 by discussing the important issue of how the speed of communication in the cerebral cortex can be preserved despite the great size differences of the brains of small and large mammals. Cycle 4 can be skipped by those who have had an introductory class on methods in neurophysiology. It discusses the major methods currently available for investigating brain activity patterns in living tissue and the mechanisms that give rise to the field EEG. Cycles 5 and 6 serve as an introduction to the different types of oscillators and discuss the large family of oscillations in the mammalian cortex. Cycles 7 and 8 are devoted to the “default” states of the brain: sleep and early brain development. Tying the macroscopic features of oscillations to neuronal mechanisms requires large-scale recordings of numerous single neurons. Such techniques allow us to gain some insight into the content of oscillations, which is described in Cycles 9–12. In Cycle 13 I examine the structural and functional requirements of awareness by contrasting brain structures that can and cannot support self-generated patterns and long-range communication through global oscillations.

Periodic Phenomena in Nature

Nature is both periodic and perpetual. One of the most basic laws of the universe is the law of periodicity.⁴ This law governs all manifestations of living and non-living. In its broadest definition, periodicity refers to the quality, state, or fact of being regularly recurrent: a repeating pattern or structure in time or space. What goes up must come down. The sun rises and sets, and the days wax and wane. Without periodicity, there is no time; without time, there is no past, present, or future. In living systems, the periodicity of individual lives gives rise to the continuity of life on Earth. Our existence has meaning only when experienced in time. The essence of music and dancing is rhythm. An important part of human culture is the celebration of the periodicity of life. The Jewish and Muslim religions are attuned to the lunar cycle. Christians adopted a solar calendar. Periodicity can be seen in the monthly windows of opportunity for conception of human life.

Periodicity, oscillation, rhythm (from Latin meaning to flow), and cyclic process are synonyms that refer to the same physical phenomenon. Historically, different academic disciplines have adopted a preferred term to describe these related phenomena. Periodicity is the term of choice in social and earth sciences. Oscillation is the preferred term in physics, and engineers talk about cyclic or period generators. Until recently, neurologists and neuroscientists used the term “brain rhythms” almost exclusively when referring to the various brain patterns.

4. Nature, of course, has no laws, desires, goals, or drives. It simply generates certain regularities that we conveniently assume are governed by some outside forces and use a third-person perspective to refer to these regularities.

Reference to oscillations is quite recent.⁵ The avoidance of the term “oscillator” in brain research for so long perhaps reflected the tacit view that brain rhythms may be qualitatively different from the oscillators discussed in physics textbooks. Assuredly, neuronal oscillators are quite complex. Nevertheless, the principles that govern their operation are not fundamentally different from those of oscillators in other physical systems. Today, it is widely recognized that the brain’s ability to generate and sense temporal information is a prerequisite for both action and cognition. This temporal information is embedded in oscillations that exist at many different time scales. Our creativity, mental experiences and motor performance are modulated periodically both at short and long time scales. But how are oscillatory states brought about, especially if they occur in the absence of external influences? In Cycles 5 and 6 I propose some answers with illustrations from physics and engineering.

Time and Periodicity

Neuroscientists work with time every day but rarely ask what it is. We take for granted that time is “real” and that brains have mechanisms for tracking it. Since time is a major concept in this book, I attempt to provide a working definition without getting lost at the nebulous boundary between physics and philosophy.⁶ Newton held that time flows in absolute intervals, independent of the physical universe. According to Immanuel Kant, space and time are irreducible categories through which reality is perceived by our brains. Albert Einstein combined space and time into “spacetime.” According to him, time is a measure of motion and, as such, is part of the physical universe and thus could be interpreted as its “property”; space and time disappear along with the things. An opposite view is that time is a subjective abstraction and does not exist in any physical substrate and has no more reality than a mathematical axiom. In a broad sense, time is a *measure of change*, a metric of succession, a parameter that distinguishes separate events. One practical definition is that “time is that which is measured by a clock,” a pragmatic description adequate for most branches of physics and neuroscience.⁷

How we approach the problem of time largely determines our view of the outside world around us. First, we need to distinguish two aspects of time. Absolute time is clock time, referring to a particular point in a time series, for example, your birth date. Absolute time is a fundamental element of existence since everything

5. It was the review by Steriade and Deschênes (1984) that popularized the term “neuronal oscillator” in the mammalian nervous system. See also Steriade and Llinás (1988).

6. Hawking (1992) is an excellent introduction to this difficult topic. Hall (1983) is another easy read. A radically different definition of time is proposed by Leyton (1999). Leyton derives time from spatial symmetry and its broken version: time is essentially symmetry breaking (e.g., asymmetric representation of plane symmetry by oscillatory phase; see Cycle 11).

7. In physics, standard time interval (a second) is defined by an oscillator: 9,192,631,770 hyperfine transitions in the ¹³³Cs atom.

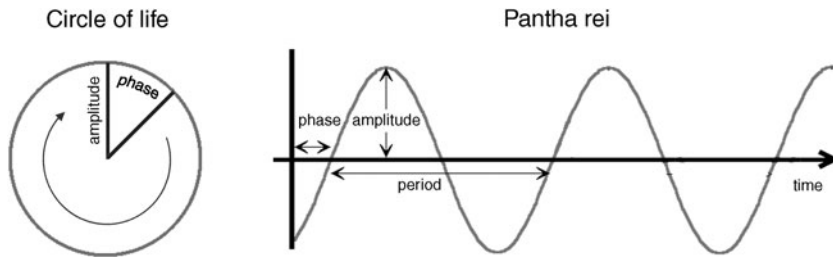


Figure 1.1. Oscillations illustrate the orthogonal relationship between frequency and time and space and time. An event can repeat over and over, giving the impression of no change (e.g., circle of life). Alternatively, the event evolves over time (*pantha rei*). The forward order of succession is a main argument for causality. One period (right) corresponds to the perimeter of the circle (left).

exists in time. Duration refers to the change of time, the interval between two points in time. Elapsed time is therefore relative, and it has an interval span (e.g., hour), whereas absolute time does not have a span (e.g., date). We make a similar absolute versus relative distinction in space as well, when we talk about position and distance. However, while distance can refer to many directions (vector) in space, time has only one direction (scalar).

The intimate relationship between space and time is packaged into the concept of “spacetime” (x, y, z, t dimensions). Oscillations can be conceived of and displayed in terms of either space or time. The phase-plane of a sinusoid harmonic oscillator⁸ is a circle. We can walk the perimeter of the circle once, twice, or billion of times and yet we always get back to our starting point. “What has been is what will be, and what has been done is what will be done; and there is nothing new under the sun”⁹ This is the “circle of life,” and our walk on its perimeter is measured as dislocation (figure 1.1, left).

An alternative to the periodicity view of the universe is to display periodicity as a series of sine waves. Now we can walk along the troughs and peaks of the line without ever returning to the starting point (figure 1.1, right). Time here is a continuum with the cycle as its metric. The cycles are identical in shape, and the start and end points of the cycles form an infinite path into the seemingly endless universe. This meandering line illustrates the basis of our time concept: *linear*

8. The different types of oscillators are defined and discussed in Cycle 6.

9. The quote is from the book of Ecclesiastes (chapter 1, verse 9, Revised Standard Version). The concept of recurrence is prominent in Hinduism and Buddhism, among others. The spoked wheel of life (*dharma*) is an endless cycle of birth, life, and death. The concept of recurrence is also prominent in Friedrich Nietzsche’s philosophy (best expressed in *Also Sprach Zarathustra. Ein Buch für Alle und Keinen*). A picture of nature as being in “balance” often prevails in both biological and religious discussions. Although a general equilibrium theory has never been explicitly formulated, environmentalists and conservationists tacitly assume that nature is in an eternally stable equilibrium; therefore, we should keep it that way. However, if this were the case, how did we get here in the first place?

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