1
The Study of Biological Rhythms

"Dost thou love life? Then do not squander time,
for that's the stuff life is made of."
—Benjamin Franklin (1706–1790)
American Statesman & Philosopher

Introduction

How could you tell if a person is alive or dead? Chances are that your answer will depend upon the presence or absence of a rhythm, the beating of the heart. Biological rhythms are inherent to life itself and can be detected by all the senses. We can see them, hear them, feel them, smell them, and we may even taste evidence of them (Figure 1.1). Perhaps the sense of time itself could be considered a sixth sense. In many ways we can sense how long a time has elapsed since some occurrence was last noted, as well as the time of day, time of month, and time of year from cues all around us (Hering, 1940; Binkley, 1990). Life moves in synchrony to the beat of clocks and calendars, some outside the body and some within the very cells of all living things. Rhythms are among the common strands from which the web of life itself is spun.

By definition, a *rhythm* is a change that is repeated with a similar pattern. Humans, like all other organisms that inhabit this Earth, have a rhythmic order underlying life. Actually, change, not constancy, is the norm for life and the rhythmic timing of change makes predictability a reality. For example, throughout each 24-h day, leaves change their orientation (Figure 1.2), human body temperature rises and falls (Figure 1.3), fungi time their sporulation (Figure 1.4), and activity levels fluctuate (Figure 1.5). These rhythmic changes of life represent only a small segment of an enormous network of biological rhythms, passed on from one generation to the next.

All known variables of life, be they levels of potassium ions in a cell, stages of sleep, or the opening and closing of flowers, have either directly or indirectly been found to display rhythms. Furthermore, adaptations of organisms for survival relative to geophysical cycles, such as the solar day, seasons, and tides, attest to the evolution of the genetic aspects of certain types of rhythmic timing. The objective

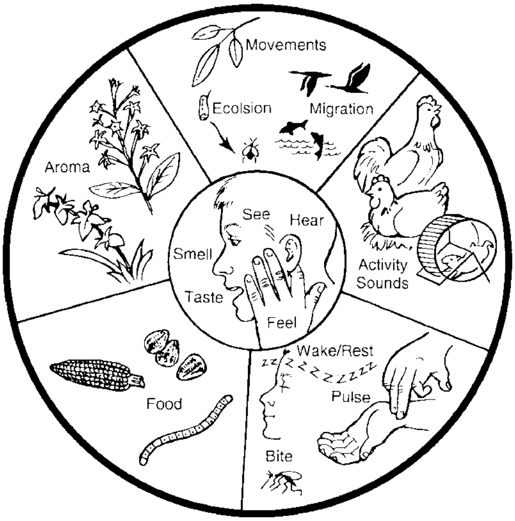


FIGURE 1.1. Rhythms can be detected by the five senses: *sight* (migrations, plant movements, insect emergence); *sound* (roosters crowing or hens clucking, nocturnal activity of rodents, cricket chirping); *touch* (feeling sleepy, taking a pulse or feeling an insect bite at certain times of the day); *smell* (aromas from plants); and *taste* (starch vs. sugar in apple or corn; availability of Palolo worms near Pacific Islands).

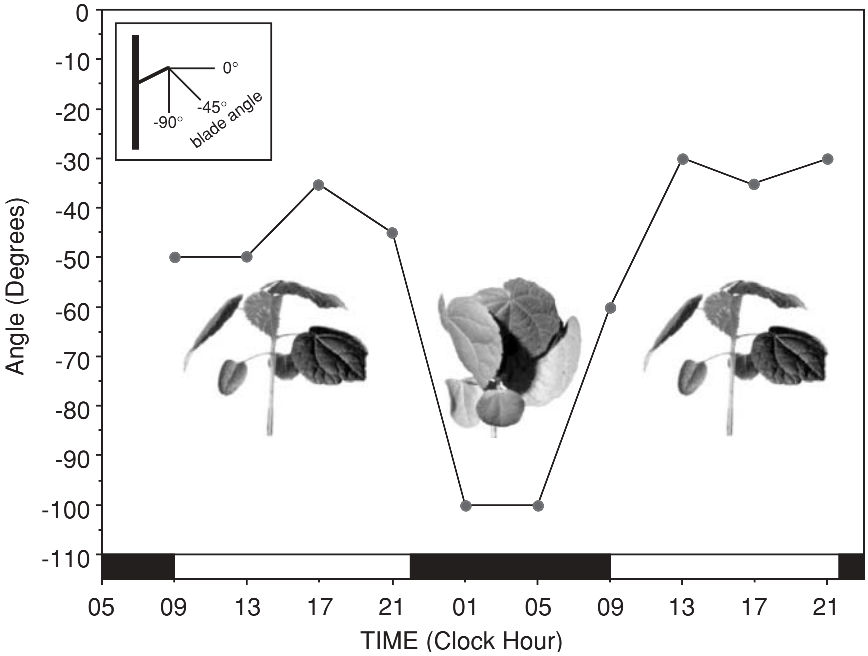
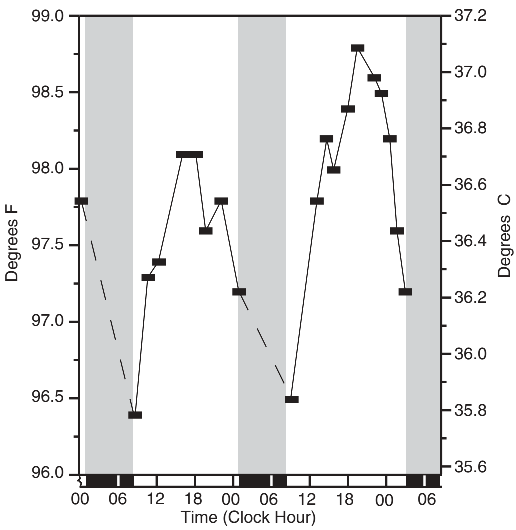


FIGURE 1.2. Change in orientation of velvetleaf (*Abutilon theophrasti*) under a 24-h light–dark (LD) schedule. The relative position of a leaf at different times is shown under a schedule of 13 h of light (09:00–22:00 h) followed by 11 h of darkness (dark bars). Inset illustrates position of the blade in degrees from horizontal (=0°). Data obtained by video monitor in our lab.

FIGURE 1.3. The changes in human body temperature during usual living conditions. Dashed lines (—) indicate time when temperature was not recorded during sleep (shaded area/horizontal dark bars). Subject = healthy man (RBS, age 20 years) (Sothern, unpublished).



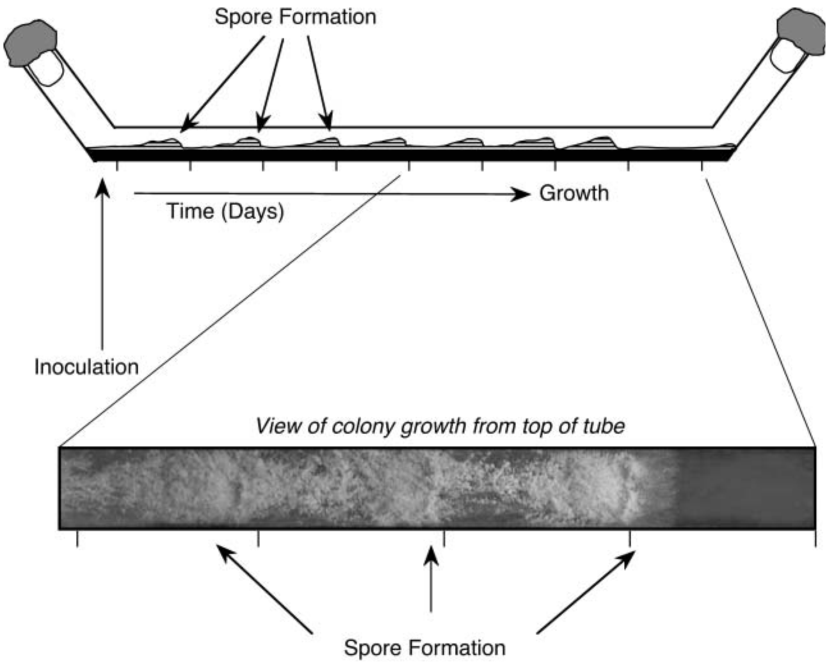


FIGURE 1.4. Fungi *(Neurospora crassa)* growth and spore formation is circadian-rhythmic in constant conditions. Rhythmic spore (conidia) formation in *Neurospora crassa* can be observed when cultured on a nutritive medium in a glass tube. Inoculation was at left end of the tube, with the start of spore formation repeating at 24-h intervals (shown as bumps about every 24 h). Inset photo courtesy of Van D. Gooch, University of Minnesota-Morris.

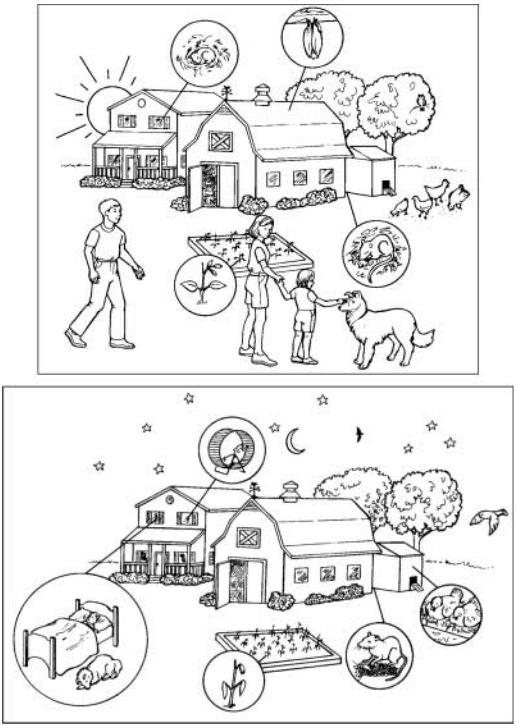


FIGURE 1.5. Comparison of activity in animals and position of leaves in plants over 24 h. Diurnal animals, such as humans and birds, are active during the day, while nocturnal animals, such as hamsters and rodents, are at rest (*top panel*). At night, the reverse happens and while the diurnal animals are at rest, the nocturnal animals, such as the hamster and rat, are active (*bottom panel*). Also, the orientation of leaves changes from the horizontal during the day to the vertical at night.

of this chapter is to briefly introduce the topic of biological rhythms by emphasizing the commonality, presence, and importance of the subject in nearly every facet of life, as well as its status as an integrating discipline of biology.

A Time for Everything

The rhythmic nature of life influences the very existence of organisms, commencing before conception and extending beyond death. Rhythms may be the most ubiquitous, yet overlooked, phenomena of life (Luce, 1970). They are such an integral part of life that the absence or perturbation of specific oscillations (e.g., brain waves and heart beats) in humans and other animals is used in the practice of medicine to distinguish between life and death, as well as between illness and good health (Figures 1.6 and 1.7). How organisms respond to certain chemicals, be they drugs or house dust, insecticides or herbicides, or any of a long list of agents is often time dependent (Table 1.1), with effects more pronounced at certain times than others. In some cases, what may be beneficial at one time may be noneffective or lethal at another. Even the perception of pain, be it disease-related (e.g., from headache, arthritis) or experimentally induced (e.g., by heat or cold or electrical stimuli), often shows a daily rhythm (Labrecque, 1992).

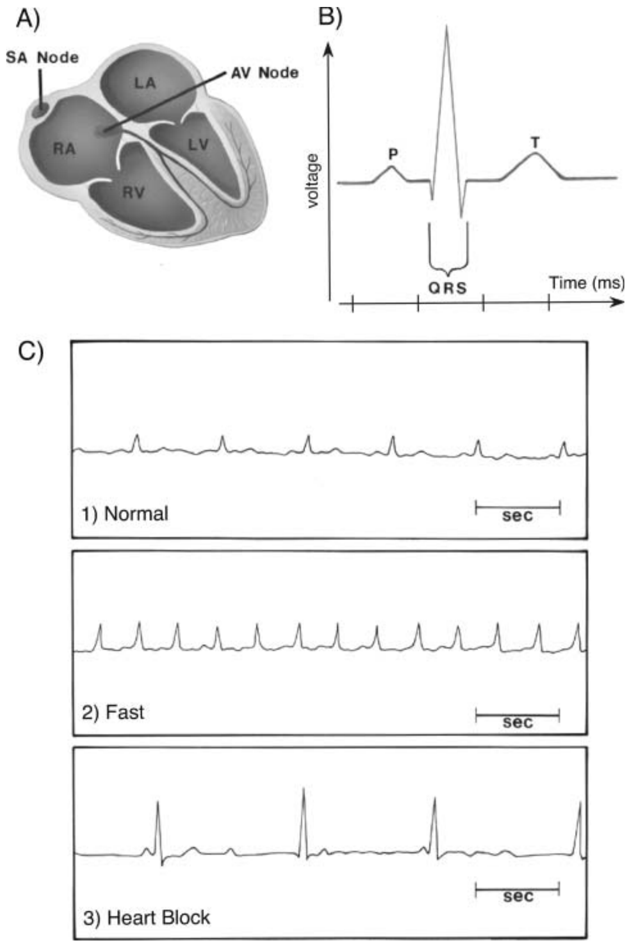


FIGURE 1.6. Diagram illustrating (*A*) the human heart and the specialized cardiac conduction system composed of the sinus node (SA), atrioventricular node (AV), right and left atrial (RA and LA) chambers, and the right and left ventricles (RV and LV). A small electrical current propagates from the sinus node through the atrial muscle to the AV node, which, after a short delay (usually 0.12 s), is transmitted to the ventricles. The electrical events cause both atrial and ventricular contraction. To record the electrical signals from the heart, electrodes are placed on the surface of the body at specific locations (e.g., right arm and left leg). The signals collected in this manner are amplified, and recorded on charts. This recording is called an electrocardiogram (ECG). (*B*) A record of an electrical cycle from a single lead (pair of electrodes). P = atrial electrical activity (depolarization), QRS complex defines the depolarization of ventricles; and T wave signifies repolarization of ventricles. (*C*) Three panels of ECGs (provided by Ann Dunnigan) illustrating their use in the diagnosis of normal as well as abnormal rhythms. *Panel 1*: Normal sinus rhythm rate (rate 75 beats per minute [bpm]); *Panel 2*: abnormally fast regular rhythm at rate of >175 bpm; *Panel 3*: Abnormally slow rhythm where atria do not communicate with ventricles, called complete heart block. In *Panel 3*, sinus node rate ("P") is normal (75 bpm), while ventricular rate is abnormal (40 bpm).

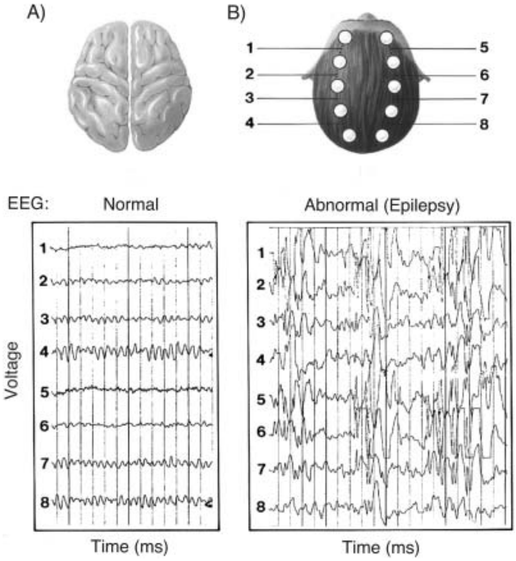


FIGURE 1.7. Diagram illustrating dorsal views of the brain (*A*) and scalp showing the position of electrodes (*B*), and two electroencephalograms (EEG). *Left*: Normal brain EEG measuring electrical potential difference with respect to time shows posterior "alpha rhythm." *Right*: Abnormal EEG in a young patient with epilepsy shows abnormal high amplitude discharges during a seizure. EEG panels provided by Mark Koukkari.

The concept of timing in relation to life and death is not of recent origin, as can be noted in the biblical book of Ecclesiastes 3:2–3:

To everything there is a season and a time to every purpose under heaven: a time to be born and a time to die; a time to plant and a time to pluck up that which is planted; a time to kill and a time to heal; a time to break down and a time to build up … .

The rhythmic nature of birth[1] (Figure 1.8), morbidity (presence of disease), and mortality[2] are widely documented in the scientific literature. While these are but a few of the many examples of daily changes, there are seasonal differences as well, which show an annual rhythm in these same events (Figure 1.9). Even the common things that we are aware of, such as the migration of birds (Gwinner, 1977, 2003), or the less common events, such as the germination of seeds in certain species, display an annual rhythm (Bünning & Mussle, 1951).

Three Rhythm Domains

Much of the early work on biological rhythms focused on cycles in which the *period* was 24 h. These rhythms are referred to as *circadian rhythms* because they reoccur with a period of 24 h during usual light–dark conditions, and can

[1] Results from a classic study which summarized rhythms in human natality based upon the hourly incidence of 207,918 spontaneous labors and 2,082,453 natural births (Smolensky et al., 1972) showed that the onset of labor and birth under usual circumstances was most frequent between midnight and 06:00 h.

[2] Sudden cardiac death (Willich et al., 1987) and cerebral infarction (stroke) or hemorrhage (Marshall, 1977) are more prevalent between midnight and 06:00 h.

TABLE 1.1. Examples of time-dependent responses of organisms to various chemicals.

Chemical	Organism	Comments	Reference
Ethanol	Human	Blood levels greater at 07:00 h; poorer performance after 19:00 and 23:00 h	Reinberg et al., 1975
Histamine	Human	Greater reaction of lungs or skin near midnight	Reinberg et al., 1969
House dust	Human	Bronchial hyperreactivity greater during nighttime than daytime	Gervais et al., 1977
Lidocaine (anesthetic)	Human	Duration of anesthesia in teeth and skin longer in mid-afternoon	Reinberg & Reinberg, 1977
Theophylline (asthmatic drug)	Human	Sustained-release dose at 20:00 h better than 08:00 h in controlling nocturnal dip in lung function	Reinberg et al., 1987
Corticosteroids	Human	Once-daily dosing of inhaled steroid between 15:00 and 17:30 h optimal for asthma control	Pincus et al., 1997
Pentobarbital (anesthetic)	Rat	Duration of anesthesia longer in early dark (activity)	Scheving et al., 1968
Pentobarbital (anesthetic)	Mouse	Maximal mortality in early dark (activity)	Bruguerolle et al., 1988
Arabinosyl cytosine (anticancer drug)	Mouse	Increased tolerance in mid-light (resting)	Haus et al., 1972
Dichlorvos (insecticide)	Cockroach	Greatest toxicity in early dark	Eesa et al., 1987
Bentazon (herbicide)	Velvetleaf	Less injury near middle of the light span	Koukkari & Johnson, 1979
Glyphosate and glufosinate (herbicides)	Weeds	Maximum control at midday	Martinson et al., 2002

continue with a period close to 24.0 h when the organism is isolated from external cues. Thus, periods of about (*circa*) a day (*dies*) are present when organisms are isolated from environmental 24-h cycles, such as the alternating light and darkness of the solar day, and/or changes in temperature. This “free-running” period is an important characteristic of a circadian rhythm. In addition, the period is relatively consistent over a range of temperatures (temperature compensation). These and other characteristics are discussed more extensively in Chapter 2 on General Features of Rhythms.

While the circadian rhythms represent the dominant cycle that has been studied relative to the activities of humans and other organisms, cycles having periods shorter or longer than circadian, such as 90-min or seasonal cycles, are also important. Biological cycles that have periods less than 20 h are called *ultradian rhythms*, while cycles with periods longer than 28 h are called *infradian rhythms*. Depending upon the variable, infradian periods can be measured in weeks, months, years (circannual), and longer. Collectively, these three rhythmic domains comprise a network or web of rhythmic oscillations that in many ways can be likened to the various chemical pathways that perform different functions, but occur simultaneously within the same organelle or cell.

The range of periods for biological rhythms is broad, extending from cycles that are measured in milliseconds to cycles that are over 100 years in length. Some

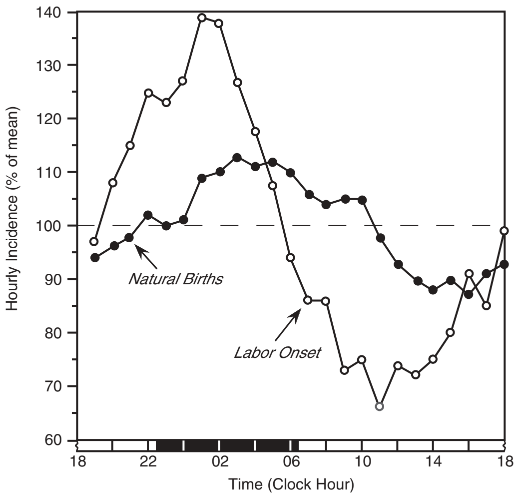


FIGURE 1.8. Comparison of the circadian (*circa* = about, *dies* = day) waveform for the onset of labor and birth in humans, illustrating a natural sequence of events beginning with a peak in the onset of labor early in the night (dark bar) followed by a peak in natural births early in the morning. Hourly incidence of onset of >200,000 spontaneous labors and >2,000,000 natural births (redrawn from Smolensky et al., 1972).

examples illustrating the diversity in periods and types of variables are presented in Table 1.2 (ultradian and circadian domains) and Table 1.3 (infradian domain). Multiyear cycles, such as the emergence of the periodical cicada (*Magicicada* spp.) every 13 years in the south and midwestern USA or every 17 years in the northeastern USA, the 8- to 10-year population cycles of the ruffed grouse (*Bonasa umbellus*) in Minnesota, and the 15- to 120-year cycles in flowering of various species of bamboo, are among the spectacular rhythmic events found in nature that are little understood.

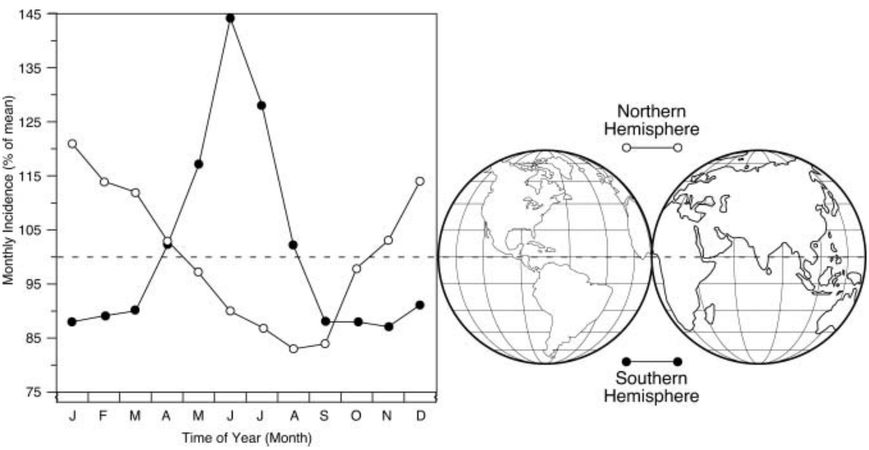


FIGURE 1.9. Monthly cardiac mortality shows circannual rhythm in the northern and southern hemispheres. A greater proportion of overall annual deaths from heart disease occurs in the winter for each hemisphere (redrawn from Smolensky et al., 1972).

TABLE 1.2. Examples of variables illustrating a range of rhythmic periods in the ultradian and circadian domains.

Time	Period	Variable	Organism	Reference
Seconds	<1 s	EEG activity (delta frequency)	Human (*Homo sapiens*)	Krippke, 1972
	<1 s	ECG (depolarization of heart ventricles)	Human (*Homo sapiens*)	see Figure 1.5
	30–45 s	NADH levels	Yeast (*Saccharomyces carlsbergensis*)	Chance et al., 1964
Minutes	1 min	Courtship song (male)	Fruit fly (*Drosophila melanogaster*)	Kyriacou & Hall, 1980
	2–4 min	Leaflet movements	Telegraph plant (*Desmodium gyrans*)	Koukkari et al., 1985
	4–15 min	Reaction time	Human (*Homo sapiens*)	Lovett-Douse et al., 1978
	15 min	Cortisol secretion	Horse (mares) (*Equus caballus*)	Drake & Evans, 1978
	30 min	Transpiration	Oat (*Avena sativa*)	Johnsson, 1973
	45–62 min	Leaflet movements	Soybean (*Glycine max*)	Guillaume & Koukkari, 1987
	76 min	Cellular protein content	*Acanthamoeba castellanii*	Lloyd et al., 1982
	75–100 min	Pupillary motility	Human (*Homo sapiens*)	Lavie, 1979
	85–90 min	Cortisol secretion	Monkey (*Macaque mulatta*)	Holaday et al., 1977
	90 min	Deep body and udder temperatures	Holstein cow (*Bos taurus*)	Bitman et al., 1984
	90–100 min	REM-NREM sleep	Human (*Homo sapiens*)	Aserinsky & Kleitman, 1953
	100 min	Shoot movements (circumnutation)	Pole bean (*Phaseolus vulgaris*)	Millet et al., 1984
Hour	4 h	Enzyme activity	Euglena (*Euglena gracilis*)	Balzer et al., 1989
	12 h	Amylase activity	Alfalfa (*Medicago sativa*)	Henson et al., 1986
Day	24 h	Body temperature	Human (*Homo sapiens*)	Aschoff et al., 1972
	24 h	Sleep–wakefulness	Human (*Homo sapiens*)	Kleitman, 1963
	24 h	Leaf movements	Albizzia (*Albizzia julibrissin*)	Koukkari, 1974
	24 h	Activity	Flying squirrel (*Galucomys volans*)	DeCoursey, 1960

TABLE 1.3. Examples of variables illustrating a range of rhythmic periods in the infradian domain.

Time	Period	Variable	Organism	Reference
Week	7 days	Oviposition (egg laying)	Spring Tail (*Folsomia candida*)	Chiba et al., 1973
	7 days	Organ transplant rejection	Human (*Homo sapiens*)	DeVecchi et al., 1981
	7 days	Imbibition of seeds	Bean (*Phaseolus vulgaris*)	Spruyt et al., 1987
Month	27–34 days	Menstrual cycle	Woman (*Homo sapiens*)	Presser, 1974
	6 months	Ulcer perforation	Human (*Homo sapiens*)	Svanes et al., 1998
Year	1 year	Seed germination	*Digitalis lutea, Chrysanthemum corymbosum, and Gratiola officinalis*	Bünning & Müssle, 1951
			Wild potato (*Solanum acaule*)	Ludwig et al., 1982
			Pole bean (*Phaseolus vulgaris)*	Spruyt et al., 1988
	1 year	Antler replacement	Sika deer (*Cervus nippon*)	Goss, 1969
	1 year	Migration	Willow warbler (and others) (*Phylloscopus trochilus*)	Gwinner, 1977
	1 year	Hibernation	Golden-mantled ground squirrel (*Citellus lateralis*)	Pengelley & Fisher, 1977
	1 year	Ovarian weight	Yamuna River catfish (*Heteropneustes fossilis*)	Sundararaj et al., 1982
	1 year and 7 years	Gonadal weight	Purple sea urchin (*Strongylocentrotus purpuratus*)	Halberg et al., 1987
	8 years	Alpha-amylase activity	Wheat (*Triticum* spp.)	Kettlewell et al., 1999
	8–10 years	Population	Ruffed Grouse (*Bonasa umbellus*)	Gullion, 1982, 1985
	13 or 17 years	Emergence	Periodical Cicada (*Magicicada* spp.)	Hoppensteadt & Keller, 1976
	100–120 years	Flowering	Chinese bamboo[a] (*Phyllostachys bamusoides*)	Janzen, 1976

[a]While the range between successive synchronized reproductions by seed is from 3 to 120 years, most bamboo species have shorter, yet still very long times between seeding (15–60 years).

Implications of Body Clocks

We have become a "clock driven" society, one that arranges time according to the demands of a commercial or industrial complex often fostered by profit and/or leisure, rather than arranging time so that our internal body clocks are in synchrony with the natural environment of this "clockwork Earth." Accidents, catastrophes, and illnesses are inevitable when the time cycle of society does not heed the biological rules that underlie the rhythms of humans or other organisms.[3] For example, the reason that many traffic accidents occur during night and early morning hours is not only due to the difficulty in seeing in reduced light, but also to a decline in the alertness of the driver who is trying to overcome the physiological urge to sleep. Alertness is but one of the many performance variables that are under rhythmic control (Figure 1.10). It may be no coincidence that some of the major industrial catastrophes of our time were not related to weather, but were associated with erratic work–rest schedules and fatigue (see Essay 1.1).

Essay 1.1** (by RBS)**: Accidents and Catastrophes

Four major industrial accidents that gained worldwide attention were each attributed to human error due to shift-work and its accompanying fatigue. The methyl isocyanate chemical accident in Bhopal, India, nuclear accidents at 3-Mile Island in the USA and in Chernobyl in the Ukraine, and the oil spill from the tanker Exxon Valdez in Alaska, all occurred at night (Reinberg & Smolensky, 1985; Moore-Ede, 1993). The nuclear accidents resulting in the release of radioactive gases occurred at 3-Mile Island at 04:00 h on March 28, 1979 and at 01:23 h in Chernobyl on April 26, 1986. The Exxon Valdez accident resulting in an environmentally catastrophic oil spill, occurred at 00:04 h on March 24, 1989, while the gas leak in Bhopal occurred at 00:56 h on December 3, 1984. All of these accidents occurred after midnight and were determined to be the result of operator error due to poor work–rest schedules, monotony, and fatigue. Interestingly, while hundreds of villagers and thousands of cattle in Bhopal died as they slept when the gas cloud swept over them, night-shift workers in the chemical plant, and nocturnally active rats observed scurrying around dead bodies all survived with little, if any, ill-effects from the toxic gas. Presumably, due to internal circadian time (stage) and not the external clock time, they were less susceptible to the toxic effects of the gas during the activity portion of their circadian sleep–wake cycle: rats are naturally active during the night, while the workers were in the active portion of their shifted circadian cycle.

Another less well-known, but major disaster occurred in western Canada on February 8, 1986 at 08:41 h, when a freight train going 94 km/h collided head-on with a passenger train going 78 km/h, killing 23 people and causing over $30 million in damages (Smiley, 1990). Weather was not a factor, nor was there any hardware error; a red light was ignored by the engineer of the freight train and no brake application was made. The night before the accident, the freight engineer slept only 3.5 h, while the brakeman slept only 5 h before their train departed at 06:25 AM. Both had worked irregular schedules during

[3] This statement does not refer to the popular pseudoscience notion that good days and bad are based upon birth date (see discussion on Biorhythm Theory in Chapter 10).

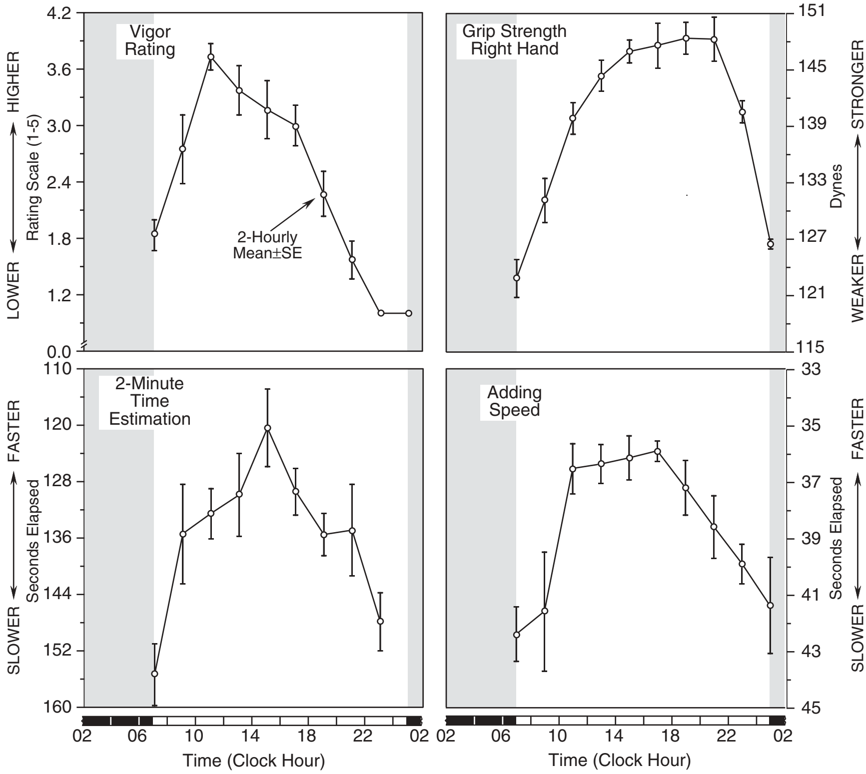


FIGURE 1.10. Circadian patterns in some performance tests by a young man (RBS, 23 years of age) doing self-measurements every 2–4 h during waking-only for 2 weeks reveal that mental and physical performance were at their best in the middle of the daily activity span. Two-hour averages computed from a total of 90 measurements. Dark bar and shaded area indicate times of sleep when no data were obtained.

> the previous month, with the engineer finishing a 6-h run at 23:30 h the night before. It was concluded that the number one factor underlying this catastrophe was human error brought on by the interaction between 24-h biologic rhythms and lengthy, irregular work–rest schedules, and consequent negative effects on alertness and performance of the freight crew.

The broad and interesting topic of the applications and implications of rhythms in society as concerns both humans and organisms in their environment will be discussed in Chapter 10 on Society.

Chronobiology: An Integrating Discipline

The study of *biological rhythms*, known as *chronobiology*, is an integrating discipline that has been ranked parallel with the more classical disciplines of

TABLE 1.4. A comparison among the four disciplines of biology relative to duration and episodic designation (cf. Ehret, 1980).

Discipline	Period or duration	Episodic designation
Biological rhythms	Less than a second to years	Existence
Development	Seconds to years	Life span
Genetics	Minutes to years	Dynasty
Evolution	Hours to years	Age

development, *genetics*, and *evolution* (Ehret, 1980). All four of these disciplines span the structural levels of organization from molecules to ecosystems. A comparison among the four disciplines in regard to duration and episodic designation is presented in Table 1.4. The inclusion of chronobiology in formulating questions and hypotheses that lend themselves to experimentation now provides a broad unifying approach that extends from single-celled organisms to higher plants and animals. This can be seen by the continuing annual increase in the number of published scientific papers, which are accruing in the thousands per year since the late 1960s, and can be found in an online literature search[4] that uses circadian and other rhythm domain terms as key words (Figure 1.11).

Historically, the interdisciplinary nature of chronobiology was evident even in the composition of the small group of seven individuals who met in August 1937 in Sweden to create the first international organization focusing on the study of biological rhythms.[5] Of the three review papers presented at this conference that were of a more theoretical nature, one was based upon plant rhythms (by Anthonia Kleinhoonte from Holland), the second focused on animal rhythms (by Hans Kalmus from England), and the third dealt with human rhythms (by Arthur Jores from Germany) (Jores, 1938, 1975) (cf. Kalmus, 1974).[6]

[4] The online search engine PubMed (http://www.ncbi.nlm.nih.gov/PubMed/) was used for this literature search of articles indexed at the National Center for Biotechnology Information of the National Library of Medicine. There are hundreds of additional papers on rhythms in books, meeting proceedings, and journals, some of which can be found with other online search engines (e.g., Medline, BIOSIS, AGRICOLA).

[5] The next meeting of the International Society for the Study of Biological Rhythms was held with 12 participants in Holland just before World War II. The third meeting took place in Hamburg, Germany in 1949, with 50 participants. This organization changed its name to the International Society for Chronobiology at its first meeting in the USA in 1971 and included several hundred participants. There are now numerous societies studying rhythmic phenomena, including the American Association of Medical Chronobiology and Chronotherapeutics; the European Pineal Society; the European Society for Chronobiology; Groupe d'Etude des Rhythmes Biologiques; Societa Italiana di Cronobiologia; the Japanese Society for Chronobiology, the Society for Light Treatment and Biological Rhythms; the Society for Research on Biological Rhythms; the Mediterranean Society for Chronobiology; among others.

[6] For historical notes see *Bulletin du Groupe d'Etude des Rythmes Biologiques* (1989) 21(1) (1er trimestre); and Cambrosio A, Keating P. (1983) *Social Studies of Science* 13: 323–353.

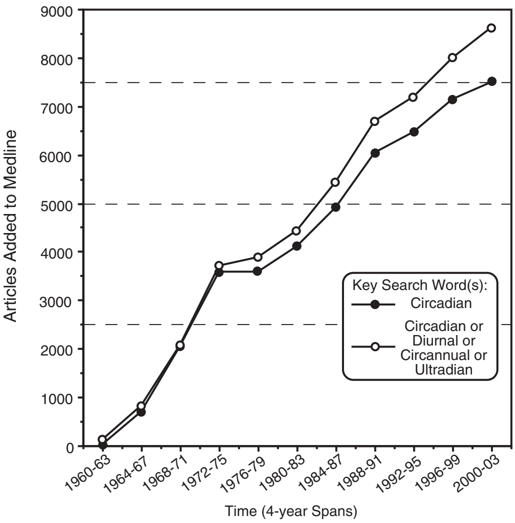


FIGURE 1.11. The number of articles on biological rhythms found by an online search engine (PubMed) using the key words circadian, diurnal, circannual, and ultradian, now number in the thousands over spans of 4 years. There are hundreds of additional papers on rhythms in books, meeting proceedings, and journals, some of which can be found with other online search engines (e.g., Medline, BIOSIS, AGRICOLA, etc.).

Chapters in This Book

In this book, chapters have been prepared around main topics on biological rhythms. However, in some cases there is considerable overlap of material among chapters, which is unavoidable due to the ubiquity of the topic. Biological rhythms have a number of unique characteristics and terms that will be introduced in a separate chapter, and referred to throughout the book. Some of these characteristics, such as the stability of the period of circadian rhythms and how their phase[7] can be shifted, have been incorporated into models to better understand the mechanisms of timing (see Chapter 5 on Models) and how they contribute to the temporal organization of life. Clocks, calendars, and units of time that arose from cycles in the natural environment are described and compared with internal biological clocks in Chapter 3 on Time.

The rhythmic interactions between living things and the things that make them live are complex. Some are easily observed and/or measured, whereas others can be examined only indirectly by specific assays, images, or mathematical interpretations. How the rhythmic nature of life is best observed and monitored, as well as how data can be analyzed for rhythm characteristics, represent chapter topics (autorhythmometry, analyzing data) that help provide a basic understanding of biological rhythms. Because there is often a direct relationship between the internal rhythms of an organism and the external rhythms of the environment, the topic of photoperiodism, which focuses upon the response of

[7] Any point on a rhythmic pattern relative to a fixed reference point can be a phase. The time of a peak or trough relative to local midnight are two commonly used phases. In many laboratory studies, the zero point coincides with the start of the light span (e.g., circadian time), rather than midnight.

organisms (be they plant or animal) to given durations and times of light and darkness over the seasons, is included as a chapter. Chapters that deal with tidal and lunar rhythms, sexuality and reproduction, natural resources and agriculture, society, and clinical and veterinary medicine, describe from a practical perspective how knowledge of biological rhythms applies to, or affects, nearly all aspects of life.

Take-Home Message

Biological rhythms are common phenomena of life and are found in all major groups of organisms, but are often overlooked. The length of time required to repeat a rhythmic cycle is called the period, a characteristic that has been used to categorize rhythms into three major groups: circadian (20–28 h), ultradian (<20 h), and infradian (>28 h). Circadian rhythms are usually synchronized by cyclic changes in light and darkness and/or temperature. When isolated from such environmental cues, the rhythm continues (free-runs), but usually with a period slightly longer or shorter than precisely 24.0 h. Some typical examples of biological variables for rhythms include (a) *circadian*: body temperature in humans and leaf movements of plants; (b) *ultradian*: brain waves of humans and twining of movements of bean shoots; and (c) *infradian*: the menstrual cycle of human females and the annual germination of certain seeds.

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