Tanja Gabriele Baudson, Anna Seemüller and Martin Dresler

# Chronobiology and Chronopsychology: An Introduction

## 1 Time Over Time

*To every thing there is a season,*
*and a time to every purpose under the heaven.*

Ecclesiastes 3:1, *King James Bible*

Herodot relates that the ancient Egyptians kept calendars and observed the stars in order to be prepared for the annual Nile inundation: The silt the water brought was rich in minerals, which served as a natural fertilizer – thus the higher the water, the better the harvest. It was therefore of vital interest to them to find a way to understand the rhythmic "fluctuations" (in the literal sense) governing these forces. Within the flow of time, it was therefore necessary to grasp the "right moment" in order to succeed. The Greek mythology differentiated these two aspects of time even more explicitly and personified them in two different deities: *Chronos*, the god of passing time[1], and *Kairos*, the god of opportunity one has to grab by his hair when he passes by.

Probably from the beginning of humankind on, people have tried to identify patterns in their environments, events that repeat themselves in ever-ongoing cycles, in order to seize the moment. Some of these periodic regularities that can be observed in nature may seem so obvious, so "natural" they may even be hard to notice consciously at first, as we are so used to them: night and day; the change of the seasons; death and childbirth; rain and sunshine. Such recurring events may serve as cues to make life more predictable and thus help people to organize their lives and be ready for what may come.

[1] Even though the name may call up an association to the titan *Kronos*, the two are not related (though a father swallowing his offspring is not too bad an allegory for the cycle of becoming and passing.)

Trying to make inferences and predictions on the basis of what has been observed, that is, to identify the patterns and rules that govern our surroundings, is a crucial element of human intelligence – and maybe even a basic human need.

## 2 Our inner clocks

***Day, n.*** *A period of twenty-four hours, mostly misspent.*

Ambrose Bierce, *The Devil's Dictionary*

Such natural changes and cycles as named above are not only to be found in our external environments, but also within ourselves and other species. *Chronobiology* – as the founding discipline – examines physiological events in living organisms that occur on a periodical basis (so-called *biological rhythms*) and investigates how they are influenced by (and adapt to) external rhythms. *Chronopsychology,* on the other hand, is concerned with psychological rhythms and their influence on cognition and behavior.

External and internal cycles are often related to each other. For instance, our patterns of sleeping and waking influence the production of hormones such as human growth hormone, HGH – which may have a serious impact on children not getting enough sleep (see already Underwood, Azumi, Voina, & Van Wyk, 1971). But external influences are not the only explanation for the fact that we – and many other species – are creatures in and of time. Some periodic cycles within our bodies even occur without any external cues at all (such as daylight), as experimental studies have been able to show, e. g., living in a cave remote from daylight without any natural night-and-day cycles at all (see Zulley, this volume). Such "inner clocks", the existence of which had been doubted by some researchers until the 1980s, have been shown by now to be existing endogenous phenomena that also influence biological organisms in interaction with external synchronizing stimuli, the so-called *zeitgeber*.

# 3 Chronoscience as an Interdisciplinary Science

*When a Tralfamadorian sees a corpse, all he thinks is*
*that the dead person is in bad condition in that particular moment,*
*but that the same person is just fine in plenty of other moments.*

Kurt Vonnegut, *Slaughterhouse-Five*

Biology was one of the earliest sciences to observe and describe phenomena as mentioned above in living organisms – even though the first person to systematically record a circadian plant rhythm was actually an astronomer. As early as in the 18th century, Jean Jacques d'Ortous de Mairan described the leaf movements of mimosas, which he observed to continue even if the plant is kept in complete darkness. There are many more rhythms in nature that occur about once a day (*circadian rhythms*), but there are also higher (*ultradian*) or lower (*infradian*) frequencies. Engelmann (this volume) shows several other examples of such bioclocks and biocalendars in a broad range of species, ranging from unicellular algae to complex mammals.

The question where the generators of these rhythms, the so-called *oscillators*, are located has been an important research issue in genetics – for if rhythms are not exogenous, they should most probably have a genetical basis. In the 1990s, researchers were able to identify gene mutations that either extend or shorten the breeding cycle of *Drosophila melanogaster*. The PER genes (PER standing for "period") exist in different variations: PERLONG, which leads to longer cycles, PERSHORT, which shortens them, and PER– (arrhythmic, i. e., no observable rhythm at all). All of these mutations can be found at the same gene locus (see Kandel, Schwartz, & Jessell, 1996, for an overview). Brukamp (this volume) also reports on other "clock genes" that have been identified by now in mammals as well.

As can be seen from the different contributions to this volume, chronobiology is no longer the only science interested in what kinds of biological rhythms exist and how they work. Another focus of chronoscience – a collective denominator for all sciences interested in biological rhythms and its consequences – has been the latter, i. e., the impact these rhythms have on our well-being and on our lives in general.

This issue has gained importance with changes in society that made it possible – or even necessary – for people to live "against" their biological rhythms. Shiftwork has been a topic of particular interest from early on, as shiftworkers have been observed to report more health issues than people working at times congruent with their natural rhythms (e. g., Salvendy, 1997). In a similar fashion, this is also true for people who have to get up earlier than they naturally would if not forced to live against their so-called *chronotype*. For instance, this is the case for school children who belong to the “owl” rather than the “lark” chronotype – sometimes with far-reaching consequences (Hahn, this volume).

But education and applied psychology are not the only areas to make use of such fundamental discoveries. Medicine and associated fields also profit from chronoscientific findings, as biological rhythms are important for the understanding of disorders and health issues. The impact is particularly impressive in pharmacology: So-called *cytostatica*, medications which stop cell proliferation (e. g., in malignous tumors), have been found to show differential efficiency depending on the time of day (e. g., Harris, Song, Soong, & Diario, 1990). Observing these rhythms has thus made it possible to use less medication to achieve the same results with far less side effects.

## 4 Beyond Rhythm

*I’ve been on a calendar, but I’ve never been on time.*

Marilyn Monroe

It is not always trivial to identify rhythmic patterns – the smaller the oscillations, the harder it is to observe them. However, even small differences may have a big impact on observable characteristics. The hypothesis that mental speed is related to cognitive ability had already been proposed when empirical psychology was still in its infancy (Galton, 1883) and has recently received a substantial boost again (Jensen, 2006). With their “Temporal Resolution Power Hypothesis,” Troche and Rammsayer (this volume) provide empirical evidence that temporal acuity is related to both psychometric intelligence and scholastic achievement.

What we learn and achieve also depends crucially on what we are able to remember. Therefore, we do not only remember events from our lives, but also their temporal context. How this time information is stored in memory, and why we forget over time is discussed by Seemüller (this volume).

But memory also helps us transcend the boundaries of the here and now of our existence. The fact that our brain is able to construct events based on past experiences enables us to develop completely novel scenarios. It can therefore be said that we are, in a way, able to travel through time, either by reveling in memories or by imagining our future. A link between memory and future thinking is not only conceivable, but has also been shown in neuroscientific studies (see Weiler, this volume).

The ability to anticipate events is of crucial importance with respect to decision-making as well. How explicitly we imagine and set our goals has an influence on the probability of achieving them (e. g., Locke, Shaw, Saari, & Latham, 1981). The value of a reward is discounted the further away it is; therefore, delaying immediate gratification and controlling behavioral impulses is a necessary ability for reaching goals that are still remote. To impulsive persons (and also pigeons; see Ohmann, this volume), the time until a reward is given seems far longer than to more patient people; for the former, the tradeoff between size of reward and temporal distance to it thus less advantageous than a more immediate, yet smaller reward.

How long we experience time to be therefore plays an important role – unfortunately, we are not only unable to hold fleeting moments of beauty, but also seem to have a strong tendency to overestimate the length of unpleasant events, which appear much longer to us than the pleasant ones. Hinz (this volume), based on a number of empirical studies, presents evidence that this "antihedonistic tendency" is not a purely subjective experience, but can be shown using various other methods, too. But maybe this is also what makes the beautiful moments so much more precious . . .

## 5 Outlook

*We are not capable of producing a concept of time*
*that is at once cosmological, biological, historical and individual.*

Paul Ricœur

The ten articles compiled in this volume cover a broad range of different aspects of chronoscience and, more generally, of how time influences the lives of all beings, from simple unicellular to humans. Each of the diverse disciplines concerned with these issues provides an additional perspective and offers valuable insights. Sometimes, it is surprising how similar the ideas are, even when generated by two disciplines that, apparently, do not seem to have much in common. Kupke and Vogeley (this volume), for instance, show an astonishing correspondence between the conception of time proposed by neuroscience and phenomenology.

As editors, we first wish to thank the authors for their contributions and the numerous intriguing insights therein our readers will hopefully enjoy as much as we do. We are also indebted to Wolfgang Pabst, Armin Vahrenhorst, and Erika Wiedenmann from Pabst Science Publishers for their kind and valuable help (and for their patience). Finally, we thank Michael Engler for his assistance with the proofreading of the final chapters. We hope this volume will encourage researchers from many fields to overcome the centripetal forces of their disciplines, to think beyond their own noses, and last not least to enjoy the enriching collaboration with each other on the investigation of the many still unsolved problems.

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Jürgen Zulley

# Human Chronobiology

In Search of Biological Time

## 1 Introduction

Chronobiology is the science and research of the rhythmic development of biological processes over time, from monocellular protozoa to pigeons and people. It looks at how time on earth directly influences biological functions, how humankind as a biological entity has adapted to its time on earth, and whether timescales are built into the intrinsic development plans of humans. It also examines whether we are at the mercy and subjugation of our time on earth or whether we are practically part-autonomous: Do we have an “internal clock” (i. e., do we possess intrinsic control over our own organism in temporal terms), or do our biological timescales depend wholly on extrinsic factors to make do with the time spent on earth?

Many facets of human life are a direct function of the time of day, the most obvious examples being sleep and wakefulness. However, the neurophysiologist Karl-Friedrich Burdach, in his book *Dietetics for the Healthy* published in 1811, searched for links between the time of day and bodily functions, above all, the sleeping and waking states. For example, he describes “slow and strong heartbeat and breathing” in the early hours of the day when “powers of judgement and reason predominate over other powers.” He writes as well of “almost fever-pitch pulse rates in the evenings, dedicated to convivial pleasures and the jovial games of fantasy.” Burdach also observed mood swings during the course of the day: “People are different, depending on the time of day . . . and in the same way that botanist Linné ascertains the time of day by examining the condition of plants to create the ‘plant-clock’, we could also make ourselves a ‘human-clock’ and predict how individuals we know well will be affected by the particular condition of the morning or evening.”

Burdach was convinced that these phenomena were causally linked to the time of day, recognizing that twilight in particular made people sleepy, a view widely shared by many of his medical contemporaries. This was despite knowing that people living north of the Arctic Circle generally tended to sleep "once a day" – just like us – even during times of continuous darkness or light such as polar-nights or midnight sun. It is a fact, too, that the sleeping patterns of people living between the Pole and the Polar Circle vary more over the year than those of people living closer to the equator.

There was also the more traditional hypothesis that people have a kind of "internal clock" which tells them what to do and when. In 1793, the German physicist and author Georg Christoph Lichtenberg from Göttingen arrived at the same hypothesis, stating that "so-called people of the clock normally live to be old", and concluding that there must be such a thing as an internal clock: "Behaving by the clock is however dictated by an intrinsic clock-following predisposition." Shortly afterwards, the Tübingen physician Johann Heinrich Ferdinand Autenrieth wrote in his 1801 *Manual of empirical human physiology*: "Even in a constitution of good health, and oft-times with more intensity despite diminished vitality, the whole body does therefore seem to undergo lively oscillation, independent of circulation."

## 2 Clinical Rhythm Research

With these counter-hypotheses to Burdach's, European scientists were among the first to postulate the existence of "internal clocks." The origins of empirical rhythm research also date back to the turn of the 19th century. In his 1800 Sorbonne dissertation Claude Bernhard described how the systematic oscillation of various functions helps sustain balance within the human organism. Johanson of Stockholm also demonstrated that the effectiveness of quinine varies according to the time of day it is taken. In 1848, Herrmann von Helmholtz pointed to the rhythmic development of various bodily functions as well, and Arthur Jores discovered that liver activity conforms to a daily rhythm (Menzel, 1987). The concept of *bodily rhythm* finally made its way into the textbooks in 1848, with the publication of physician Johannes Müller's handbook of physiology, in which he described the functions of the entire human organism as rhythmical.

However, the true origins of human chronobiology date back to a conference held in 1937 in the small fishing village of Ronneby in South Sweden – and the founding of the *International Society for Biological Rhythms*. Erik Forsgren, senior consultant at a Swedish clinic for tuberculosis, was appointed its chairman. He had already started outlining the rhythmic pattern of liver functioning as early as 1917, but it was not until 1927 that the University of Stockholm authorities accepted his work as a dissertation. His findings were too avant-garde for them, with important statements such as the fact that the liver cannot produce glycogen and bile simultaneously, and that it was merely the time of day that dictates when to produce either substance. Despite Jores's earlier work on the subject, the academic world had believed up to this point that the liver would start working precisely after eating. Forsgren went on to prove that body temperature depends on the time of day, that kidneys produce different levels of urine in the morning, afternoon, evening, and at night, and that the activity of a number of other organs and body functions waxes and wanes throughout the day.

This enabled rhythm researchers to introduce everyday medical practice to the concept that the human body works on a rhythmic basis and is a function of the time of day. This contrasted to the thinking at the time, namely that the body was a machine whose output depended on a whole variety of factors, but not on the time of day. These researchers described themselves in methodological terms as medicinal-clinical "empiricists" who observed specific clinical single cases. By default, they focused primarily on the sick, comparing their rhythms to those of healthy people, and in so doing gathering huge amounts of material.

In 1947, the internist Ludwig R. Grote coined the term "chronopathology" to specifically describe the rhythmical aspects of certain human disorders. Accordingly, the intensity of ailments such as asthma and phantom limb pain varies throughout the day; they are rhythmical (Zulley, 2003).

# 3 Basic Rhythm Research

After the Second World War, while clinical experts had already made progress in certain fields of chronobiology, academic physiologists embarked upon basic research, which meant working on healthy organisms – especially animals, but also human subjects – on an experimental and theoretical basis. In Europe, the best-known exponents were Professor Jürgen Aschoff (1913–1998) in Andechs near Munich and Professor Gunther Hildebrandt (1924–1999) in Marburg.

The physiologist Jürgen Aschoff in particular focused his research specifically on "internal clocks", driven by his conviction that the rhythms of humans and animals are generally free from external influences and come from within. He thus embarked upon a range of experiments with his colleague, Rütger Wever (Wever, 1979). Entering into the true spirit of research, he became one of his own first experimental subjects, “going underground” to find out what would happen away from all indicators (*zeitgeber*) of the time of day. During the years that followed, Aschoff, Wever and Zulley invited 450 volunteers to undergo similar experiments (Zulley, 1993; Zulley & Knab, 2009). Since the 1950s, Gunther Hildebrandt also carried out a variety of isolation experiments, including free run studies. His later work, too, was carried out in climatic chambers at the university hospital in Marburg. Unfortunately, the results of his experiments were only ever shared within exclusive circles.

The pioneers of chronobiology in the USA were Franz Halberg from Minnesota and Colin Pittendrigh from California. Back in the 1920s, one of the founding fathers of sleep research also examined biological rhythms, outlining his findings in his ‘bible’ text, *Sleep and Wakefulness*. His name: Nathaniel Kleitman (1895–1999) from Chicago (Kleitman, 1963).

The work of chronobiologists and sleep researchers only really started to merge at the end of the 1970s. Simultaneously, yet independent from each other, Aschoff and Zulley in Germany as well as Weitzman and Czeisler in the USA carried out sleep recordings in isolation studies. Fortunately, both studies came to the same conclusion: There is an interdependence between sleep and circadian rhythm (Zulley, 1980, 1981).

## 4 The Andechs Isolation Studies

In the isolation facility of the Max-Planck Institute for Behavioural Physiology in Andechs, Germany, experiments have been conducted to analyze the endogenous origin of circadian rhythms (Zulley & Knab, 2009). In these standard conditions for research on free-running rhythms in humans, an experimental procedure was carried out in which those factors have been eliminated which could influence the sequence of sleeping and waking. The subjects were required to live alone for about four weeks in a room completely isolated from the outside world. During this time they had no possibility of knowing the time of day and no social contacts whatsoever. In addition, further experiments have been carried out in which the degree of monotony in such situations was varied (Zulley, 1990).

These experiments necessitated an alternation of sleeping and waking which was entirely self-selected, but which continued to be remarkably regular. Such a so-called “free-running” (i. e., without external influence) or “autonomic” circadian rhythm revealed, in the vast majority of cases, a mean periodicity which was longer than 24 hours (on average, 25 hours).

However, since there is no 25-hour periodicity in the natural world, it may be assumed that the sequence of sleeping and waking is regulated by an endogenous mechanism comparable to an “internal clock” (Wever, 1979). More recent studies have shown that in some subjects the free-running period may be close to 24 hours (Campbell, Dawson, & Zulley, 1993).

## 5 The *Zeitgeber*

The isolation studies also showed that the rhythms controlled by the “internal clock” can be synchronized with a particular period by a regularly occurring external stimulus, a time cue, or, in German: “Zeitgeber”. Artificial alternation of darkness and light, the regular signals or timing of the meal times have been used as an artificial *zeitgeber*. As well as finding out which stimuli can affect the sleeping and waking periodicity, it was possible at the same time to determine limits of synchronisation (“range of entrainment”) of the variables. In this way the differing effectivity of the various kinds of *zeitgeber* could be investigated (Wever, 1979).

It was found that the simple alternation of darkness with normal indoor lighting (about 400 lux) is not sufficient to entrain the normal daily rhythm. Entrainment was very much greater if the strength of the light was increased to that of broad daylight (more than 2,000 lux). It therefore follows that daylight must be regarded as the most effective *zeitgeber* (Wever, Polasek, & Wildgruber, 1983). Other important *zeitgeber* are the regular timing of the meals as well as motor activity and social contacts.

In normal everyday life, the *zeitgeber* is environmental (the alternation of night and day with its changes in light and temperature, for instance), and is synchronized with a 24-hour rhythm. In humans, it appears that the additional “social relevance” of such a zeitgeber also contributes to synchronisation. This means that the subjective valuation of a stimulus contributes to its efficiency. If the significance of a stimulus is reduced, a disturbance of the circadian system may be expected.

## 6 Ultradian Periodicity

The characteristic time course of the various functions, each with a maximum and minimum value during the day, does not represent the only type of periodic change. Shorter ultradian fluctuations also take place. One example is *orthostatic dysregulation*, failure of the body to accommodate for sudden changes in blood pressure. Investigations have established that this instability reaches two maximum values during the course of a 24-hour day. In addition to a pronounced maximum value at about three o'clock in the morning, there is a further maximum around noon. This signifies that people are subject to a more unstable orthostatic regulation in the middle of the day as well as at night, whereas more stable values are found at other times (Aschoff, 1969). Therefore, there are not only courses during the day with one maximum and one minimum to be taken into account (*circadian periodicity*), but also those with more than one fluctuation (*ultradian periodicity*).

Do such ultradian fluctuations also apply to the alternation of sleep and wakefulness? If so, this would mean that sleep is not only associated with the night, but that the basic regulation is also effective during the day. Experiments which provided opportunities for sleeping during the day revealed that, in addition to the main period of sleep at night, there was a further time at which it was particularly favoured. Sleep during the day is not left to arbitrary choice, but occurs at a particular time. The appearance of a second period of sleep during the day corresponds to the normal "siesta".

The biological basis of this second preferential phase of sleep does not mean that people are under any compulsion to sleep at this time, since environmental conditions and personal taste can make them decide otherwise. Apparently, the need for daytime sleep is less compelling than that in the night. This also holds true for the other variables which run a comparable course to that found in the second half of the night. Reduced vigilance, an increased rate of error performance and a lowering of body temperature – all of which are independent of food intake – indicate that the organism is experiencing rearrangements during the day similar to those which characterize the second half of the night. This suggests that a resting phase belongs to this time. The organism is therefore not strictly adjusted to constant activity with only a single recovery phase within the circadian rhythm, but shows a change during this active phase towards a period of relaxation. This point, which can ordinarily be passed by adults without difficulty, becomes relevant when there is serious need for sleep or under conditions of monotony, shift work or "jet lag", or stress.

After further time-isolation experiments (Zulley, 1990), the so-called "bedrest studies", which allowed sleep in a "constant-routine protocol", it became possible to recognise a still more frequent and regular need for sleep at preferential intervals of four hours: at about 10 A.M., 2 P.M., and 6 P.M. An increased need for sleep is normal in small children, and this has a four-hour periodicity which is superimposed upon the circadian fluctuations, and which diminishes during the course of development. However, a four-hour alternation of sleeping and waking has been reported for pathological conditions in advanced old age. There have been speculations about whether this ultradian periodicity is the basis of the circadian rhythm. It should be noted that with an increase in sleep propensity, a monophasic pattern (one major sleep episode per 24 hours) can develop into a biphasic pattern (with an additional daytime nap) and then into a polyphasic pattern (one major sleep episode and three daytime naps; Zulley & Campbell, 1985).

# 7 Sleep Studies

Normally, sleep stage structure has been studied in major sleep episodes either at night or at different times of day (Webb, Agnew, & Williams, 1971; Bryden & Holdstock, 1973), or at different phase positions within the circadian temperature cycle in the absence of the natural 24-hour day (Karacan, Finley, Williams, & Hursch, 1970; Moses, Hord, Lubin, Johnson, & Naitoh, 1975). In isolation studies, the sleep structure of the major sleep episodes was measured during free-running circadian cycles. It has been shown that, in addition to sleep onset and sleep duration (Zulley, Wever, & Aschoff, 1981), sleep stage structure exhibits a circadian variation (Zulley, 1980).

The findings show that the absolute amount of REM sleep is in synchrony with the amount of Total Sleep Time (TST) exhibiting a pronounced circadian rhythm. The course of Slow Wave Sleep (SWS) does not depend on the duration of a sleep episode. SWS occurs at the beginning of sleep, independently of the circadian phase. Its amount depends on the duration of preceding wakefulness. Thus, a loss of SWS is compensated for by an increased amount of SWS, leading to a compensation within the first hours of sleep. With regard to sleep stage structure, TST, REM sleep, sleep onset, and sleep duration underlie a circadian regulation, whereas SWS is under homeostatic control (Zulley, 1993).

The knowledge of circadian rhythms is a basic prerequisite for understanding sleep regulation and its application to both clinical and applied fields.

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Wolfgang Engelmann

# Bioclocks and Biocalendars

How Organisms Measure Time

## 1 Introduction

Life on earth is embedded into a structured time. Day and night impose a 24h rhythm on organisms. In addition, they have to adapt to an annual rhythm of warmer and colder or dryer and more humid seasons during the course of the year. At the coasts of the oceans, the moon's orbit leads to tidal and monthly rhythms of the sea level marine organisms have to cope with. I would like to introduce you to daily (section 3) and annual rhythms (section 4) of organisms by showing you a few examples for both and by outlining the underlying mechanisms as far as they are known. In further sections (5 and 6), diapause and photoperiodic reactions are presented, which represent ways organisms recognize and cope with the seasons. I will not talk about tidal and other lunar rhythms, but refer to a book instead (Engelmann, 2007b).

## 2 The Headclock of Humans and the Time Memory of Bees

Some people are able to wake up at a certain time of the night without the help of an alarm clock. This ability has probably been widespread in earlier times when clocks were not available, and was termed *headclock* (Clauser, 1954). You might belong to these persons. How can you find out? At a school in Tübingen, I offered students alarm clocks which I had set to 12 o'clock. They would not run, because I had inserted a strip of paper between one pole of the battery and the contact. The students were asked to take the alarm clock home and try to wake up at a certain time in the night (for instance, at 2 A.M.) and pull out the stripe (and continue to sleep afterwards). The clock would then run. In the morning, let's say, at 7 A.M., they would check the time that had elapsed since they had woken up (for example, 3:14 h) and determine the wake-up time point by subtracting the time the alarm clock showed from the time when they had checked it (7-3:14=3:46). In this particular case, the wake-up time would have been 1:46 h after the planned night time – surely not an indication of a well-working headclock. However, some of the students did awake close to the planned time, and further examples are given in the cited book.

The ability to do something regularly at a certain time of day is also found in honey bees. A Swiss physiologist, Auguste Forel, noticed, when he was having breakfast with his family on the garden terrace, that bees were visiting the jam jar on the table each day around the same time, and were doing so in increasing numbers. They finally had to move inside, but to his surprise the bees still visited the table, although it was now empty. He concluded that bees possess a kind of time memory (Forel, 1910). Wahl (1932), a student of von Frisch's (1965), studied the time sense further by doing experiments in a cellar with only slight variations in temperature and under continuous artificial light. The training period was remembered for a few days even if no food was offered, which shows that an internal daily clock (called *circadian clock*[1]) is involved. This is an adaptation of honey bees to flowers which offer pollen and nectar preferentially at certain times of the day only. The information where and how far away the food is from the bee hive can be communicated to coworker bees by a special dance performed on the combs. Whether the headclock of humans is also based on a circadian clock is not yet known. Perhaps you can find out!

# 3 Internal Clocks and the Clockwork

Let us have a look at such an internal clock with a 24h cycle. The flowers of the "Flaming Kate" *Kalanchoe blossfeldiana* open during the day and close in the evening. They do so also if broken off from the plant and if kept in continuous weak green light (see Figure 1). However, the period length[2] of the rhythm is not exactly 24 hours any more, but 22 hours only. Thus, a circadian clock is effective in the flower. Circadian clocks are free running under constant conditions but synchronized by light-dark cycles (e. g., 12L/12D), and also (or additionally) by temperature cycles (e. g., 12h 15°/12h 20°). Furthermore, these clocks, like all reliable clocks, must run at the same speed at different temperatures. Finally, the clocks have a genetic basis, as is shown by appropriate mutants which show different period lengths.

[1] from *circa* and *dies,* Latin for "day".
[2] Period length is the interval between corresponding phases of the cycle, e. g., minima or maxima.