

# Chapter 2

## General Feature of Circadian Rhythms



Kenji Tomioka

**Abstract** The circadian rhythm is an endogenous rhythm with a period of approximately 24 h. Organisms, including insects, possess the rhythm to live with the daily environmental and ecological cycles. This chapter describes and discusses the general characteristics and properties of circadian rhythms. The rhythm is driven by the circadian clock system that often consists of two or more clocks, synchronizing to the environmental cycles to set behavioral and physiological events to occur at an appropriate time of day. Insects use various zeitgebers for synchronization with light, which is the most important and powerful approach. Light not only resets the clock in a phase-dependent manner but also has long-lasting aftereffects that are observed in the free-running period and waveform of the rhythm. Constituent clocks form bilaterally paired or hierarchical structures that are important to adapt to environmental cycles with seasonal or day-to-day changes.

**Keywords** Aftereffects · Endogenous · Entrainment · Phase response curve · Relative coordination · Temperature compensation

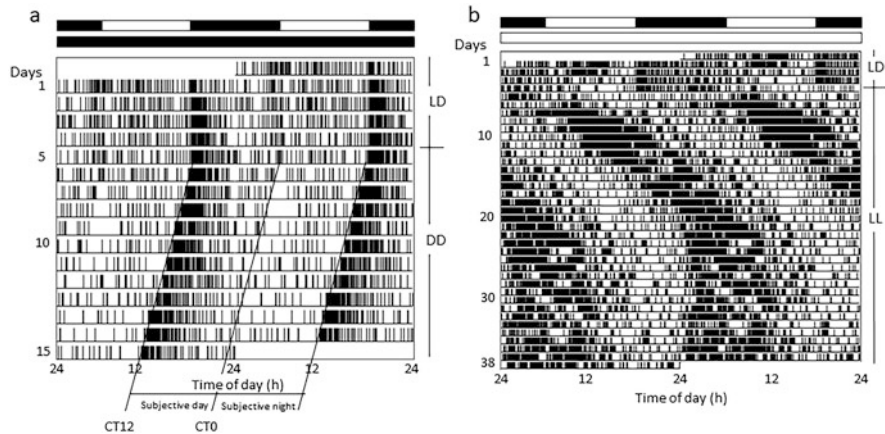
### 2.1 Introduction: Self-Sustaining Rhythm

After the genesis of our planet, organisms have been exposed to daily cyclic environments. To cope with the cyclic changes in the environment has been the most important challenge for the organisms living on this planet. Today, organisms live in ecosystems that are changing daily in terms of not only geophysical but also biological aspects. Thus, organisms, including insects, possess daily rhythms to adapt to the daily changing environment. The rhythm is called a circadian rhythm because it persists with a period near but not exactly 24 h even after organisms are transferred to constant conditions, i.e., constant darkness (DD) or constant light (LL), and at a constant temperature.

---

K. Tomioka (✉)

Graduate School of Natural Science and Technology, Okayama University, Okayama, Japan  
e-mail: [tomioka@cc.okayama-u.ac.jp](mailto:tomioka@cc.okayama-u.ac.jp)



**Fig. 2.1** Circadian locomotor rhythms of the cricket *Gryllus bimaculatus* under light/dark cycle (LD), constant dark (DD) (a) and constant light (LL) (b). Under LD, crickets show a nocturnal activity rhythm that persists for a period shorter (a) or longer (b) than 24 h under DD and LL, respectively. Under prolonged LL, the period becomes gradually shorter. The white and black bars above the actograms indicate light (white) and dark (black) conditions

Circadian rhythms are expressed in various behaviors, including locomotor (Tomioka and Chiba 1982b), stridulatory (Loher 1972), flight (Clopton 1984), feeding (Xu et al. 2008), oviposition (Loher 1979), egg hatching (Tomioka et al. 1991a), larval molting (Truman 1972; Fujishita and Ishizaki 1981), eclosion (Pittendrigh et al. 1958; Truman 1971), and mating activities (Sakai and Ishida 2001). Physiological functions also show circadian rhythms, including light sensitivity of compound eyes (Tomioka and Chiba 1982a; Wills et al. 1985), visual interneurons (Saifullah and Tomioka 2002; Uemura and Tomioka 2006), chemoreception in antennae (Saifullah and Page 2009), and cuticle formation (Wiedenmann et al. 1986; Ito et al. 2008). Figure 2.1a shows an example of the circadian rhythm of locomotor activity in the adult male cricket *Gryllus bimaculatus*. In the free-running state, the period is called the free-running period, and the phases corresponding to the original daytime and nighttime are called the subjective day and subjective night, respectively (Fig. 2.1a). The term circadian time (CT) is often used to determine phases in the free-running state. CT0 corresponds to the beginning of the subjective day, and CT12 corresponds to the beginning of the subjective night. Activity onsets are usually used to determine the phase and correspond to CT0 in diurnal insects and to CT12 in nocturnal insects. In this way, the CT of the rhythm is determined by dividing one circadian cycle from the activity onset to the next into 24 h.

The rhythm is essentially generated by an endogenous mechanism called the circadian clock that oscillates with a period of nearly 24 h, but under environmental cycles, it is modified by some direct responses to environmental factors, and the modification is called masking effects. The clock has flexibility to change its phase, period, waveform, or amplitude in response to daily or seasonal changes in environmental cycles. Insects possess two or more circadian clocks that compose

bilaterally symmetrical or hierarchical structures, which allow insects to cope with those day-to-day or seasonal changes in daily environmental cycles. This chapter outlines these general features of insect circadian rhythms.

## 2.2 Free-Running Period: Dependency on Environmental Conditions

Although the free-running period of the circadian rhythm is generally quite accurate and stable, it changes in response to environmental lighting and temperature conditions. Light usually has significant effects on the free-running period. In vertebrates, J. Aschoff established an empirical rule called Aschoff's rule for the light dependency of the free-running period: the free-running period is shorter in LL than in DD and becomes shorter with an increase in light intensity in diurnal animals, while the opposite is seen in nocturnal animals (Aschoff 1960; Pittendrigh 1960; Aschoff 1979). This is successfully applicable to most nocturnal insects: the free-running period is shorter in DD than in LL. For example, in the cricket *G. bimaculatus*, the free-running period under LL is longer than 24 h, which is significantly longer than that under DD (Fig. 2.1) (Tomioka and Chiba 1982b). Similar light-dependent changes in the free-running period have been known for several other nocturnal insect species, including the cockroaches *Rhyarobia (Leucophaea) maderae* and *Periplaneta americana* (Roberts 1960) and the beetle *Carabus problematicus* (Weber 1967), with some exceptions where the free-running period is shorter in LL, e.g., nocturnal pit-building activity in larvae of the ant-lion *Myrmeleon obscurus* (Youthed and Moran 1969). However, for diurnal insects, several *Nasonia* wasps are the only species that are thus far known to follow Aschoff's rule, showing a shorter free-running period in LL than in DD (Bertossa et al. 2013). Most other diurnal insects violate Aschoff's rule, with the free-running period being shorter under DD than LL. These include the dung beetle *Geotrupes sylvaticus* (Geisler 1961), the mosquito *Aedes aegypti* (Taylor and Jones 1969), the bean bug *Riptortus pedestris* (Numata and Matsui 1988), the blow fly *Calliphora vicina* (Hong and Saunders 1994), and the fruit fly *Drosophila melanogaster* (Konopka et al. 1989).

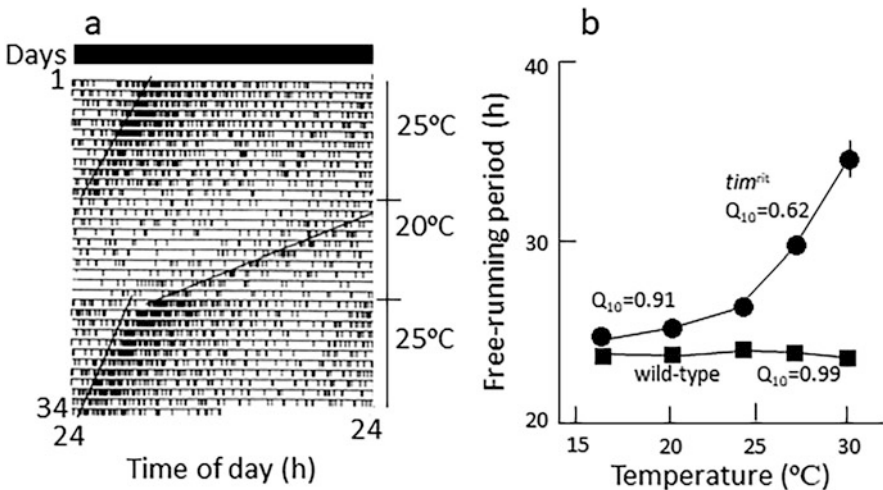
However, spontaneous changes in the free-running period sometimes occur under DD or LL. For example, some of the New Zealand weta *Hemideina thoracica* show locomotor rhythm free running with a period shorter than 24 h for the first several days in DD, but the period abruptly becomes longer, and in some cases, the period repeatedly becomes longer and shorter (Lewis 1994). Similar repetitive period changes were reported for the brow fly *Calliphora vicina* kept under DD (Kenny and Saunders 1991) and the onion fly *Delia antiqua* (Watari and Arai 1997). In the cricket *G. bimaculatus*, the period initially longer than 24 h after transfer to LL gradually becomes shorter and, in some cases, even shorter than 24 h, as shown under DD (Fig. 2.1b). The gradual period shortening caused by long-term exposure to LL is attributable to a single optic lobe clock, since the period change occurs after

unilateral ablation of the optic lobe. This seems not caused by reduced photoreceptor sensitivity because the expression level of the circadian photoreceptor gene (*opsin-long wavelength (opLW)*) is higher in crickets kept under LL for long term than in those kept under LD (Moriyama et al. 2022).

Under LL, the rhythm often disappears, resulting in behavioral arrhythmicity. It is debatable whether this LL-induced arrhythmicity is attributable to arrest of the clock at a specific phase called singularity, whether the clock maintains its oscillation but its control to overt rhythms is somehow disturbed or whether it is caused by desynchronization of multiple oscillators that control the overt rhythm. With careful experiments in *Drosophila pseudoobscura* eclosion rhythms, Winfree (1970) found that treatment of *Drosophila* pupae with 50-sec dim blue light ( $10 \mu\text{W}/\text{cm}^2$ ) at 6.8 h after LL/DD transition led the eclosion to be arrhythmic and suggested that the clock can be stopped by falling the oscillation to singularity.

### 2.3 Temperature Compensation

The free-running period of the circadian rhythm is well known to be rather stable against changes in temperature. Figure 2.2a shows an example of the temperature independence of the period in the cricket *G. bimaculatus*. This particular cricket was kept at 25 °C for the first 10 days and then transferred to 20 °C under constant darkness. The average free-running periods were 23.8 h and 22.9 h at 25 °C and 20 °C,



**Fig. 2.2** Temperature compensation of free-running rhythm under DD. (a) Circadian locomotor rhythm of an adult male cricket *Gryllus bimaculatus* at 25 °C (days 1–12), 20 °C (days 13–22), and 25 °C (days 23–34). (b) Free-running periods of wild-type (Canton-S) and *tim<sup>rit</sup>* mutant *Drosophila melanogaster* at various temperatures under DD. Redrawn from Ikeda and Tomioka (1993) and Matsumoto et al. (1999)

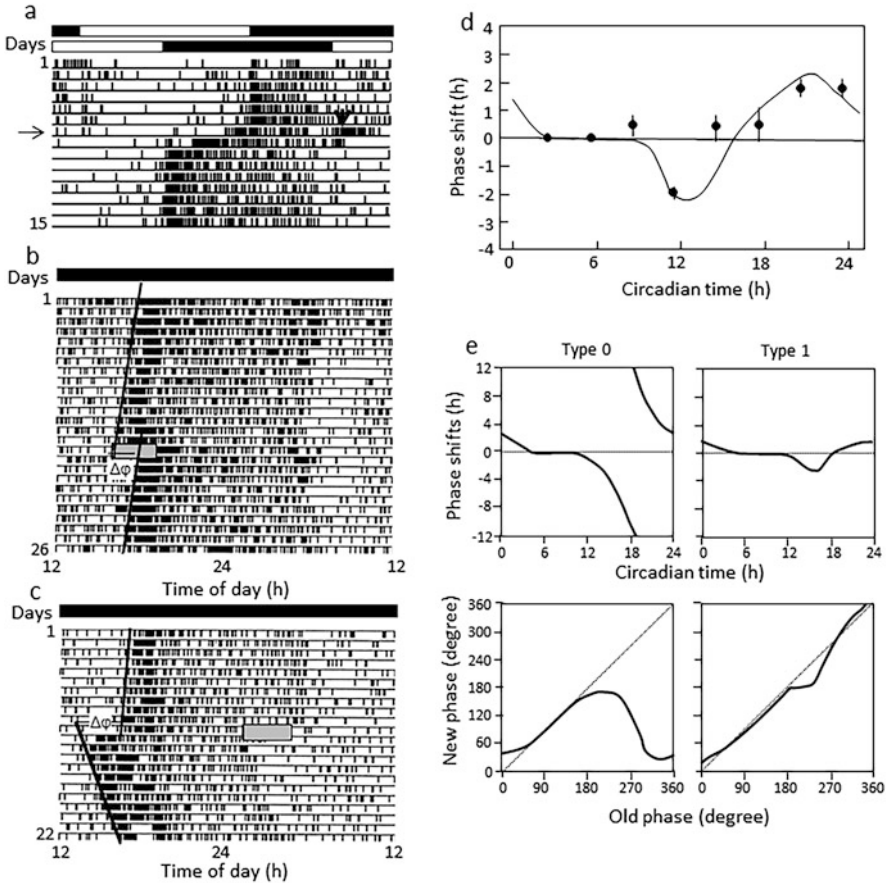
respectively (Ikeda and Tomioka 1993). The temperature coefficient  $Q_{10}$  in this species was 0.91, slightly smaller than 1.0. Similar values of  $Q_{10}$  have been reported for the fruit fly *D. melanogaster* (Fig. 2.2b) (Konopka et al. 1989; Matsumoto et al. 1999), the brow fly *C. vicina* (Saunders and Hong 2000), and the cockroach *R. maderae* (Pittendrigh and Caldarola 1973). Biochemical reactions occurring in biological systems, including insects, are temperature-dependent, and  $Q_{10}$  is usually 2.0–3.0. Therefore, there is a mechanism that maintains the free-running period to be constant irrespective of temperature, and the mechanism is called temperature compensation. The exact mechanism of temperature compensation remains to be elucidated. Although there are some possible hypotheses for the mechanism, it is apparently regulated by biochemical reactions because some mutations of clock-related genes, e.g., *timeless*<sup>ritu</sup> and *timeless*<sup>blind</sup>, deeply affect temperature compensation (Fig. 2.2b) (Matsumoto et al. 1999; Singh et al. 2019).

## 2.4 Entrainment to Environmental Cycles

One of the most important functions of the circadian clock is to set daily events at an appropriate time of day. To pursue this entrainment, the clock must synchronize to daily environmental cycles. The clock uses some environmental cues, called zeitgebers, to achieve this. Insects use various zeitgebers, including light (Helfrich-Förster 2020), temperature (Tomioka and Yoshii 2006), food (Frisch and Aschoff 1987), and interindividual interactions (Levine et al. 2002). Among these, the most powerful zeitgeber is the light to dark cycle (LD).

When LD is shifted, the rhythm resynchronizes to the newly phased LD by gradual phase advances or delays. Figure 2.3a exemplifies the resynchronization or re-entrainment in the cricket *G. bimaculatus*. The process of re-entrainment requires several cycles, called transients, to restore the original phase relationship (Pittendrigh 1981a). The existence of transients is a sign of the endogenous nature of rhythm.

The resetting of the clock by light occurs in a circadian time-dependent manner. This trait is explored by experiments with a single light pulse exposure to free-running rhythms under DD. As shown in Fig. 2.3b, c, a light pulse given at early subjective night causes a delay shift of the rhythm, whereas it causes an advance shift when given at late subjective night. On subjective days, the pulse causes little phase shifts. The relationship between the CT at which the light pulse is given and the magnitude of the shifts thus caused is illustrated in the phase response curve (PRC) (Fig. 2.3d). The PRC for circadian rhythms has been obtained in a wide variety of insects, including the fruit flies *D. pseudoobscura* (Pittendrigh 1960) and *D. melanogaster* (Orr 1982), the brow flies *Lucilia cuprina* (Smith 1983) and *C. vicina* (Cymborowski et al. 1993), the cockroach *R. maderae* (Wiedenmann 1977), and the cricket *G. bimaculatus* (Okada et al. 1991). Although the shape of the PRC is basically shared among the tested species, the PRC is classified into two types, type 1 and type 0, based on the amplitude (Fig. 2.3e) (Winfree 1970). Type



**Fig. 2.3** Phase shifts of circadian rhythms. (a–c) Resynchronization to shifted LD (a), phase delay (b) or phase advance (c) caused by a 3-h light pulse (gray bars) in the adult male cricket *Gryllus bimaculatus*. In (a), an arrow indicates the day of phase shift, and a thick arrowhead indicates a positive masking effect. (d) Phase response curve obtained for locomotor rhythm by a 3-h light pulse in the adult male cricket *G. bimaculatus*. (e) Type 0 and type 1 PRCs and their PTCs. Redrawn from Okada et al. (1991) and Pittendrigh (1981b)

1 PRC has low amplitude, and if the time of activity onset is plotted with the phase before the pulse (old phase) on the horizontal axis and the phase after the pulse (new phase) on the vertical axis, the slope of the plot, called the phase transition curve (PTC), is approximately 1. In contrast, type 0 PRC has high amplitude, and the slope of the PTC is approximately 0. The amplitude of PRC depends on the light intensity and duration of light pulses. Thus, the type of PRC could be changed. For example, in the cockroach *Nauphoeta cinerea*, white light of 3-h duration causes type 1 PRC with low amplitude while that of 12-h duration type 0 PRC with high amplitude (Saunders and Thomson 1977).

## 2.5 Range of Entrainment

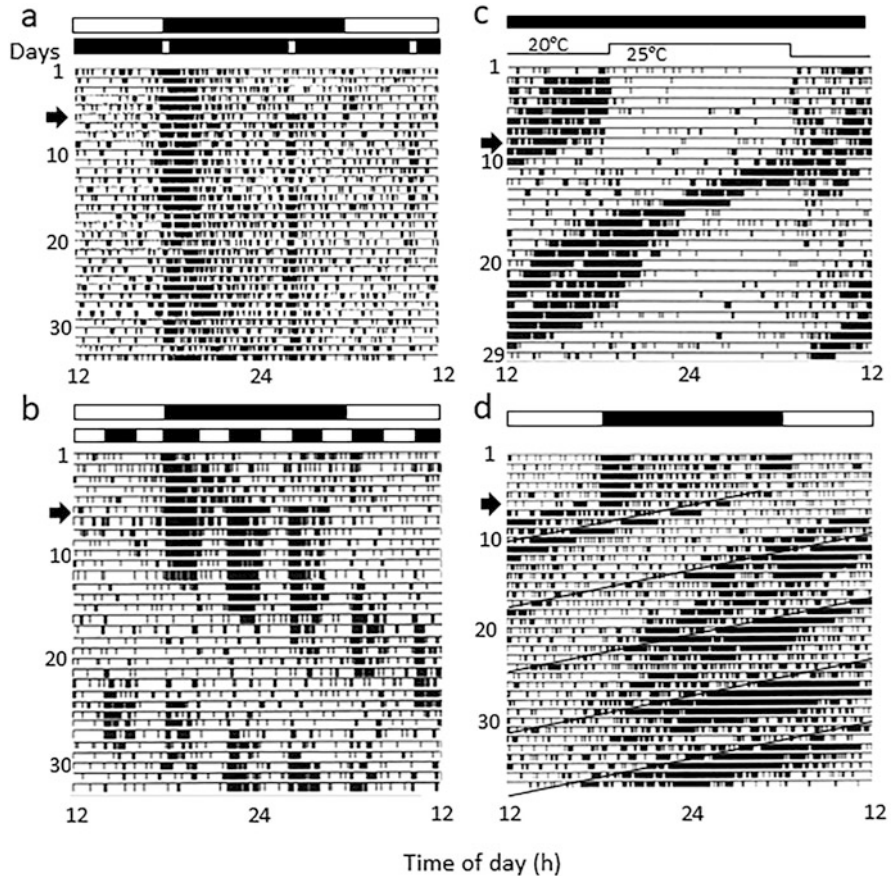
The rhythm can be entrained to light cycles with periods ( $T_s$ ) longer or shorter than 24 h but close to 24 h. The PRC predicts not only the phase relationship between the rhythm and the light cycle in a steady-state entrainment but also the range of  $T_s$  that can entrain the rhythm. For example, when the cricket *G. bimaculatus* kept in DD is repetitively given a 3-h light pulse with a period of 26 h, then the cricket's rhythm could be predicted to synchronize to the cycle as the 3-h light pulse falls at CT 11. This is because a 3-h light pulse falling at CT11 is expected to cause a 2-h delay from the PRC (Fig. 2.3d) so that the period of the cricket's rhythm, which is close to 24 h, becomes 26 h. The limit of entrainment could also be predicted by the greatest delay and advance shift induced by a light pulse. In the cricket, with a 3-h light pulse, the maximal advance and delay are 2 h and 2.5 h, respectively (Fig. 2.3d) (Okada et al. 1991), so that the predicted range of entrainment is 22 h–26.5 h. The predicted range of entrainment matches well with the experimental results using LDs with L and D of the same duration in the cricket *G. bimaculatus*; the shorter limit is near  $T = 21$  h, while the longer limit is close to 27 h (Tomioka 1993).

The rhythm is sometimes entrained to or free runs under LD cycles beyond the range of entrainment, e.g., shorter than 24 h, such as 12, 8, and 6 h. However, in such a shorter period, the rhythm rigidly maintains the entrained state or free-running state with a period of or close to 24 h (Fig. 2.4a, b). When entrained to the given LD, the clock reads the given LD cycles into a 24-h cycle. It is also known that the rhythm synchronizes to LD cycles with longer periods, e.g., 48 h. To such LDs, the rhythm entrains by repeating the 24-h rhythm twice or more in a given LD cycle.

## 2.6 Relative Coordination

When the power of the zeitgeber is weak, circadian rhythms are not entrained to the zeitgeber but only show a phase-dependent modulation of the free-running period. This state is called relative coordination (Aschoff 1981). Figure 2.4c shows an example of the relative coordination. In this particular case, the locomotor rhythm of the cricket *Grylodes sigillatus* was recorded under constant darkness with a temperature cycle of 12 h 20 °C and 12 h 25 °C. The cricket cannot synchronize to the temperature cycle but shows a clear change in the free-running period, which is lengthened at 20 °C but shortened at 25 °C.

Relative coordination can also be observed when the rhythm is exposed to LD cycles outside the range of entrainment, as exemplified in Fig. 2.4d (Tomioka 1993). In this case, the cricket *G. bimaculatus* is exposed to LD 10.5:10.5 ( $T = 21$  h). The cricket cannot be entrained to the given LD, free running with a relative coordination in which  $\tau$  fluctuates as a function of the phase angle relationship with the light cycle. The period lengthens when the light onset falls during the subjective day, while it shortens if the light onset occurs during the subjective night.



**Fig. 2.4** Locomotor rhythms of adult male crickets *Gryllus bimaculatus* (**a**, **b**, **d**) and *Gryllodes sigillatus* (**c**) showing entrainment to LD1:7 (**a**), free-running under LD 2:2, and relative coordination under a 24-h temperature cycle (**c**) and under LD 10.5:10.5. (**d**) Arrows indicate the day when new lighting conditions or temperature cycles were started. Redrawn from Germ and Tomioka (1998) and Tomioka (1993)

## 2.7 Masking Effect of Light

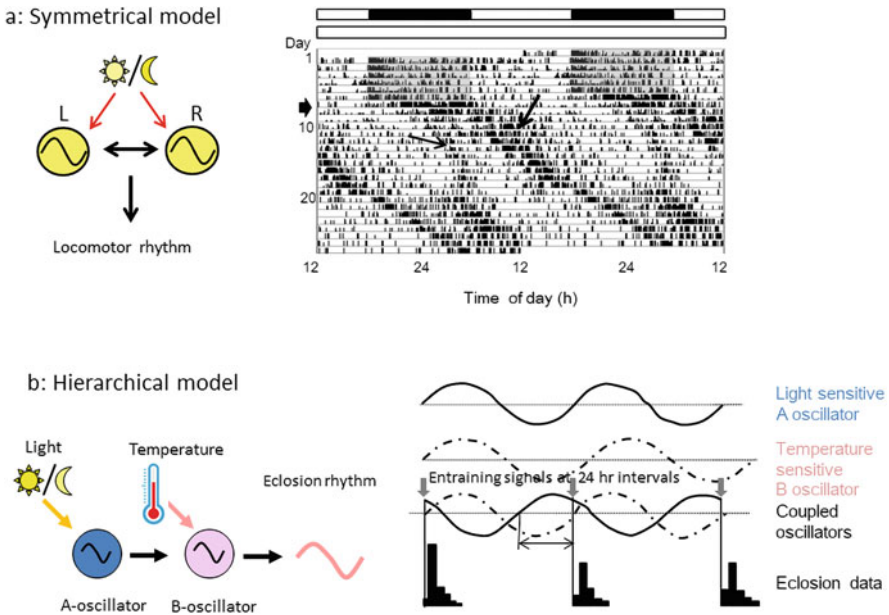
Light has direct effects on behavior bypassing the clock. For example, lights on and off often modulate the activity rhythm in a time-dependent manner. There are two types of masking effects: positive and negative. Positive masking is an enhancement of activity by light, as shown for the cricket *G. bimaculatus* in Figs. 2.3a and 2.4a. In the cricket shown in Fig. 2.3a, intense locomotor activity occurred at lights on when the LD cycle was 6 h advanced, but this activity soon disappeared as the rhythm restored the original phase relationship with the shifted LD. Thus, positive masking often occurs in a phase-dependent manner, e.g., during late subjective night to early subjective day for nocturnal animals (Tomioka and Chiba 1987). Negative masking



is induced when light is given during the subjective night. When a short LD cycle is given, the locomotor rhythm often free runs, but the light phase strongly suppresses activity during subjective night so that the active phase is divided into pieces (Fig. 2.4b). To determine whether the activity observed under LD is caused by an endogenous clock or exogenous masking of light, the rhythm should be observed after transfer to DD, where endogenous components persist but exogenous masking disappears.

## 2.8 Multioscillator System and Internal Desynchronization of Rhythms

The daily temporal rhythms are often controlled by two or more circadian clocks. Splitting of the rhythm into two separately running components is strong evidence for the multioscillator nature of the circadian system. Splitting often occurs spontaneously under constant conditions or is artificially induced by blocking the light input to the clock on one side (Wiedenmann 1983; Tomioka et al. 1991b). Figure 2.5a exemplifies the spontaneous rhythm splitting in the cricket *G. bimaculatus* kept under LL. The splitting occurred through internal



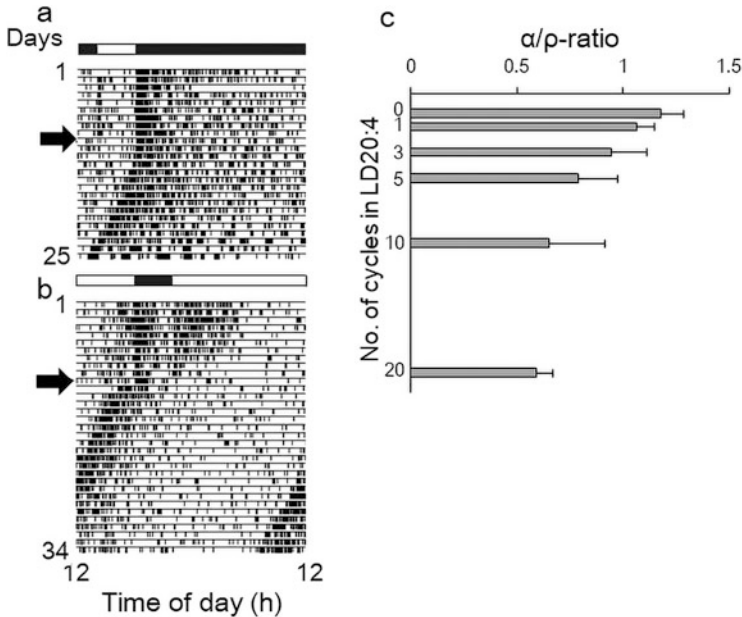
**Fig. 2.5** Two-oscillator models. (a) Symmetrical two-oscillator model and splitting of locomotor rhythm caused by internal desynchronization of the two clocks in adult male cricket *Gryllus bimaculatus*. (b) Hierarchical two-oscillator model and controlled eclosion rhythm of *Drosophila pseudoobscura*. Redrawn from Moriyama et al. (2022) and Pittendrigh et al. (1958)

desynchronization of the two clocks. In crickets and cockroaches, the two clocks are located one in each optic lobe (Page 1982, 1983; Tomioka and Chiba 1984, 1992). The bilaterally paired nature of the clocks is revealed by surgical removal of the optic lobe in insects with split rhythms: unilateral lobe removal eliminates either of the two rhythms, often with significant changes in the free-running period of the remaining rhythm (Page 1978; Tomioka et al. 1991b; Lewis 1994). This period change suggests that the period of the system is determined by mutual interaction of the two clocks.

In addition to the bilaterally paired organization, there is a system with clocks that have a hierarchical relationship. The best-known clock system is that of the fruit fly *D. pseudoobscura*, which regulates eclosion rhythms. Adult emergence from pupal cases occurs in the early morning in *D. pseudoobscura*. With light pulse and temperature pulse experiments, the underlying regulatory mechanism was revealed to include a light-sensitive circadian oscillator (A oscillator) and a temperature-sensitive oscillator (B oscillator) (Pittendrigh 1981b). In this A-B two-oscillator model, the A oscillator is the master, entraining the B oscillator, which is the slave and determines the timing of eclosion (Fig. 2.5b). Light resets the A oscillator immediately but not the B oscillator, which gradually restores the original phase relationship with the A oscillator through the entraining effect from the A oscillator (Tackenberg et al. 2017). The resynchronizing process of the B oscillator appears as transients.

## 2.9 Aftereffects

The circadian rhythm is genetically programmed, and insects show the rhythm without experiencing any periodic environment. However, the rhythm is known to change its waveform to tune to a given photoperiod (Pittendrigh and Daan 1976). Figure 2.6 exemplifies the waveform modulation by entrainment to LDs of variable L-to-D ratios in the cricket *G. bimaculatus* (Koga et al. 2005). When experiencing longer light phases, the ratio of the active phase to the rest phase ( $\alpha/\rho$ -ratio) was smaller, and the free-running period was shorter. The magnitude of changes in the  $\alpha/\rho$  ratio was dependent on the number of cycles experienced. These phenomena are comparable to the aftereffects found in vertebrates: the white-footed mouse, *Peromyscus leucopus*, for example, the subjective night length and the free-running period were clearly dependent on the light cycle in which the animal had been exposed (Pittendrigh and Daan 1976). In vertebrates, these changes in the free-running period and circadian waveform are explained by photoperiod-dependent changes in the coupling state of two circadian oscillators, which regulate the lights-on (morning) peak and lights-off (evening) peak, respectively (Pittendrigh and Daan 1976). Additionally, in insects, there are some lines of evidence suggesting a similar role of oscillator coupling in controlling the circadian waveform (Wiedenmann and Loher 1984; Helfrich-Förster 2001; Koga et al. 2005). However, the waveform modulation could be attributable at least in part to a single optic lobe clock because



**Fig. 2.6** History-dependent changes in locomotor activity rhythms in adult male crickets *Gryllus bimaculatus* after entrainment to (a) LD 4:20 and (b) LD 20:4. Arrows indicate the day of transfer from LD 4:20 (a) or LD 20:4 (b) to DD. (c) Effects of the number of experienced LD20:4 cycles on the  $\alpha/p$  ratio. Redrawn from Koga et al. (2005)

the modulated waveform persisted in isolated and cultured optic lobes (Koga et al. 2005). More clear evidence for this was obtained in the cockroach *R. maderae*: experience of T cycles with a period longer or shorter than 24 h causes long-lasting changes in the period of optic lobe clocks, and the change was maintained even after the optic lobe was transplanted to another individual (Page 1982, 1983). A remaining important issue is how these history-dependent changes occur and are maintained. This question deserves to be solved at the cellular and molecular levels.

## 2.10 Future Perspectives

As we have seen in this chapter, circadian rhythms have properties unique to biological rhythms. These properties were previously explored behaviorally and physiologically but are now being studied at cellular and molecular levels. In particular, the oscillatory and photic entrainment mechanisms of the circadian clock are already largely understood, albeit for some insects, including *D. melanogaster*. These will be discussed in other chapters. However, there are still some unresolved issues, such as temperature compensation and aftereffects. Comprehensive analysis of genes by next-generation sequencers and regulation of

gene expression by RNAi and gene editing techniques are now widely used in studies on insect circadian rhythms. These innovations in circadian rhythm research are expected to help us to deepen our understanding of the various properties of clocks and their adaptive significance.

## References

- Aschoff J (1960) Exogenous and endogenous components in circadian rhythms. *Cold Spring Harb Symp Quant Biol* 25:11–27. <https://doi.org/10.1101/sqb.1960.025.01.004>
- Aschoff J (1979) Circadian rhythms: influences of internal and external factors on the period measured in constant conditions. *Z Tierpsychol* 49:225–249. <https://doi.org/10.1111/j.1439-0310.1979.tb00290.x>
- Aschoff J (1981) Free-running and entrained circadian rhythms. In: Aschoff J (ed) *Behavioral neurobiology, Biological rhythms*, vol 4. Plenum Press, New York; London, pp 81–93
- Bertossa RC, van Dijk J, Diao W, Saunders D, Beukeboom LW, Beersma DGM (2013) Circadian rhythms differ between sexes and closely related species of *Nasonia* wasps. *PLoS One* 8: e60167. <https://doi.org/10.1371/journal.pone.0060167>
- Clopton JR (1984) Mosquito circadian flight rhythms: differential effects of constant light. *Am J Phys* 247:R960–R967. <https://doi.org/10.1152/ajpregu.1984.247.6.R960>
- Cymborowski B, Gillanders SW, Hong SF, Saunders DS (1993) Phase shifts of the adult locomotor activity rhythm in *Calliphora vicina* induced by non-steroidal ecdysteroid agonist RH 5849. *J Comp Physiol A* 172:101–108. <https://doi.org/10.1007/BF00214719>
- Frisch B, Aschoff J (1987) Circadian rhythms in honeybees: entrainment by feeding cycles. *Physiol Entomol* 12:41–49. <https://doi.org/10.1111/j.1365-3032.1987.tb00722.x>
- Fujishita M, Ishizaki H (1981) Circadian clock and prothoracicotropic hormone secretion in relation to the larval-larval ecdysis rhythm of the saturniid *Samia cynthia ricini*. *J Insect Physiol* 27:121–128. [https://doi.org/10.1016/0022-1910\(81\)90118-9](https://doi.org/10.1016/0022-1910(81)90118-9)
- Geisler M (1961) Untersuchungen zur Tagesperiodik des Mistkäfers *Geotrupes silvaticus* Panz. *Z Tierpsychol* 18:389–420. <https://doi.org/10.1111/j.1439-0310.1961.tb00233.x>
- Germ M, Tomioka K (1998) Circadian period modulation and masking effects induced by repetitive light pulses in locomotor rhythms of the cricket *Gryllus bimaculatus*. *Zool Sci* 15:309–316. <https://doi.org/10.2108/zsj.15.309>
- Helfrich-Förster C (2001) The locomotor activity rhythm of *Drosophila melanogaster* is controlled by a dual oscillator system. *J Insect Physiol* 47:877–887. [https://doi.org/10.1016/S0022-1910\(01\)00060-9](https://doi.org/10.1016/S0022-1910(01)00060-9)
- Helfrich-Förster C (2020) Light input pathways to the circadian clock of insects with an emphasis on the fruit fly *Drosophila melanogaster*. *J Comp Physiol A* 206:259–272. <https://doi.org/10.1007/s00359-019-01379-5>
- Hong S-F, Saunders DS (1994) Effects of constant light on the rhythm of adult locomotor activity in the blow fly, *Calliphora vicina*. *Physiol Entomol* 19:319–324. <https://doi.org/10.1111/j.1365-3032.1994.tb01058.x>
- Ikeda M, Tomioka K (1993) Temperature dependency of the circadian locomotor rhythm in the cricket *Gryllus bimaculatus*. *Zool Sci* 10:597–604. <https://doi.org/10.34425/zs001120>
- Ito C, Goto SG, Shiga S, Tomioka K, Numata H (2008) Peripheral circadian clock for the cuticle deposition rhythm in *Drosophila melanogaster*. *Proc Natl Acad Sci* 105:8446–8451. <https://doi.org/10.1073/pnas.0800145105>
- Kenny NA, Saunders DS (1991) Adult locomotor rhythmicity as “hands” of the maternal photo-periodic clock regulating larval diapause in the blowfly, *Calliphora vicina*. *J Biol Rhythm* 6: 217–233. <https://doi.org/10.1177/074873049100600303>

- Koga M, Ushirogawa H, Tomioka K (2005) Photoperiodic modulation of circadian rhythms in the cricket *Gryllus bimaculatus*. *J Insect Physiol* 51:681–690. <https://doi.org/10.1016/j.jinsphys.2005.01.006>
- Konopka RJ, Pittendrigh CS, Orr D (1989) Reciprocal behaviour associated with altered homeostasis and photosensitivity of *Drosophila* clock mutants. *J Neurogenet* 6:1–10. <https://doi.org/10.1080/01677060701695391>
- Levine JD, Funes P, Dowse HB, Hall JC (2002) Resetting the circadian clock by social experience in *Drosophila melanogaster*. *Science* 298:2010–2012. <https://doi.org/10.1126/science.1076008>
- Lewis RD (1994) Modelling the circadian system of the weta, *Hemideina thoracica* (Orthoptera: Stenopelmatidae). *J R Soc N Z* 24:395–421. <https://doi.org/10.1080/03014223.1994.9517476>
- Loher W (1972) Circadian control of stridulation in the cricket *Teleogryllus commodus* Walker. *J Comp Physiol* 79:173–190. <https://doi.org/10.1007/BF00697770>
- Loher W (1979) Circadian rhythmicity of locomotor behavior and oviposition in female *Teleogryllus commodus*. *Behav Ecol Sociobiol* 5:253–262. <https://doi.org/10.1007/BF00293674>
- Matsumoto A, Tomioka K, Chiba Y, Tanimura T (1999) *tim<sup>iii</sup>* lengthens circadian period in a temperature-dependent manner through suppression of PERIOD protein cycling and nuclear localization. *Mol Cell Biol* 19:4343–4354. <https://doi.org/10.1128/mcb.19.6.4343>
- Moriyama Y, Takeuchi K, Shinohara T, Miyagawa K, Matsuka M, Yoshii T et al (2022) *Timeless* plays an important role in compound eye-dependent photic entrainment of the circadian rhythm in the cricket *Gryllus bimaculatus*. *Zool Sci* 39:397–405. <https://doi.org/10.2108/zs220011>
- Numata H, Matsui N (1988) Circadian rhythm of oviposition in the bean bug, *Riptortus clavatus* Thunberg (Heteroptera: Alydidae). *Appl Entomol Zool* 23:493–495. <https://doi.org/10.1303/aez.23.493>
- Okada Y, Tomioka K, Chiba Y (1991) Circadian phase response curves for light in nymphal and adult crickets, *Gryllus bimaculatus*. *J Insect Physiol* 37:583–590. [https://doi.org/10.1016/0022-1910\(91\)90035-X](https://doi.org/10.1016/0022-1910(91)90035-X)
- Orr DP-Y (1982) Behavioral neurogenetic studies of a circadian clock in *Drosophila melanogaster*. Dissertation (PhD), California Institute of Technology, Pasadena. <https://resolver.caltech.edu/CaltechTHESIS:10222019-143344602>
- Page TL (1978) Interactions between bilaterally paired components of the cockroach circadian system. *J Comp Physiol* 124:225–236. <https://doi.org/10.1007/BF00657054>
- Page TL (1982) Transplantation of the cockroach circadian pacemaker. *Science* 216:73–75. <https://doi.org/10.1126/science.216.4541.73>
- Page TL (1983) Effects of optic-tract regeneration on internal coupling in the circadian system of the cockroach. *J Comp Physiol A* 153:231–240. <https://doi.org/10.1007/BF00612589>
- Pittendrigh CS (1960) Circadian rhythms and the circadian organization of living systems. *Cold Spring Harb Symp Quant Biol* 25:159–184. <https://doi.org/10.1101/SQB.1960.025.01.015>
- Pittendrigh CS (1981a) Circadian systems: general perspective. In: Aschoff J (ed) *Handbook of behavioral neurobiology, Biological rhythms*, vol 4. Plenum Press, New York; London, pp 57–80
- Pittendrigh CS (1981b) Circadian systems: entrainment. In: Aschoff J (ed) *Handbook of behavioral neurobiology, Biological rhythms*, vol 4. Plenum Press, New York; London, pp 95–124
- Pittendrigh CS, Caldarola PC (1973) General homeostasis of the frequency of circadian oscillations. *Proc Natl Acad Sci U S A* 70:2697–2701. <https://doi.org/10.1073/pnas.70.9.2697>
- Pittendrigh CS, Daan S (1976) A functional analysis of a circadian pacemaker in nocturnal rodents. V. Pacemaker structure: a clock for all seasons. *J Comp Physiol* 106:333–355. <https://doi.org/10.1007/BF01417860>
- Pittendrigh CS, Bruce VG, Kaus P (1958) On the significance of transients in daily rhythms. *Proc Natl Acad Sci U S A* 44:965–973. <https://doi.org/10.1073/pnas.44.9.965>
- Roberts SKF (1960) Circadian activity in cockroaches. I. The free-running rhythm in steady-state. *J Cell Comp Physiol* 55:99–110. <https://doi.org/10.1002/jcp.1030550112>
- Saifullah ASM, Tomioka K (2002) Serotonin sets the day state in the neurons that control coupling between the optic lobe circadian pacemakers in the cricket, *Gryllus bimaculatus*. *J Exp Biol* 205:1305–1314. <https://doi.org/10.1242/jeb.205.9.1305>

- Saifullah ASM, Page TL (2009) Circadian regulation of olfactory receptor neurons in the cockroach antenna. *J Biol Rhythm* 24:144–152. <https://doi.org/10.1177/0748730408331166>
- Sakai T, Ishida N (2001) Circadian rhythms of female mating activity governed by clock genes in *Drosophila*. *Proc Natl Acad Sci* 98:9221–9225. <https://doi.org/10.1073/pnas.151443298>
- Saunders DS, Thomson EJ (1977) ‘Strong’ phase response curve for the circadian rhythm of locomotor activity in a cockroach (*Nauphoeta cinerea*). *Nature* 270:241–243. <https://doi.org/10.1038/270241a0>
- Saunders DS, Hong S-F (2000) Effects of temperature and temperature-steps on circadian locomotor rhythmicity in the blow fly *Calliphora vicina*. *J Insect Physiol* 46:289–295. [https://doi.org/10.1016/s0022-1910\(99\)00182-1](https://doi.org/10.1016/s0022-1910(99)00182-1)
- Singh S, Giesecke A, Damulewicz M, Fexova S, Mazzotta GM, Stanewsky R et al (2019) New *Drosophila* circadian clock mutants affecting temperature compensation induced by targeted mutagenesis of *timeless*. *Front Physiol* 10:1442. <https://doi.org/10.3389/fphys.2019.01442>
- Smith PH (1983) Circadian control of spontaneous flight activity in the blowfly, *Lucilia cuprina*. *Physiol Entomol* 10:323–336. <https://doi.org/10.1111/j.1365-3032.1983.tb00335.x>
- Tackenberg MC, Johnson CH, Page TL, Daan S (2017) Revealing oft-cited but unpublished papers of Colin Pittendrigh and coworkers. *J Biol Rhythm* 32:291–294. <https://doi.org/10.1177/0748730417716685>
- Taylor B, Jones MDR (1969) The circadian rhythm of flight activity in the mosquito *Aedes aegypti* (L.): the phase-setting effects of light-on and light-off. *J Exp Biol* 51:59–70. <https://doi.org/10.1242/jeb.51.1.59>
- Tomioka K (1993) Analysis of coupling between optic lobe circadian pacemakers in the cricket *Gryllus bimaculatus*. *J Comp Physiol A* 172:401–408. <https://doi.org/10.1007/BF00213522>
- Tomioka K, Chiba Y (1982a) Persistence of circadian ERG rhythms in the cricket with optic tract severed. *Naturwissenschaften* 69:355–356. <https://doi.org/10.1007/BF00396696>
- Tomioka K, Chiba Y (1982b) Post-embryonic development of circadian rhythm in the cricket, *Gryllus bimaculatus*. *J Comp Physiol A* 147:299–304. <https://doi.org/10.1007/BF00609663>
- Tomioka K, Chiba Y (1984) Effects of nymphal stage optic nerve severance or optic lobe removal on the circadian locomotor rhythm of the cricket, *Gryllus bimaculatus*. *Zool Sci* 1:375–382. <https://doi.org/10.2108/zsj.1.375>
- Tomioka K, Chiba Y (1987) Entrainment of cricket circadian activity rhythm after 6-hour phase-shifts of light-dark cycle. *Zool Sci* 4:535–542. <https://doi.org/10.2108/zsj.4.535>
- Tomioka K, Chiba Y (1992) Characterization of an optic lobe circadian pacemaker by in situ and in vitro recording of neuronal activity in the cricket *Gryllus bimaculatus*. *J Comp Physiol A* 171:1–7. <https://doi.org/10.1007/BF00195955>
- Tomioka K, Yoshii T (2006) Entrainment of *Drosophila* circadian rhythms by temperature cycles. *Sleep Biol Rhythms* 4:240–247. <https://doi.org/10.1111/j.1479-8425.2006.00227.x>
- Tomioka K, Wakatsuki T, Shimono K, Chiba Y (1991a) Circadian control of hatching in the cricket, *Gryllus bimaculatus*. *J Insect Physiol* 37:365–371. [https://doi.org/10.1016/0022-1910\(91\)90087-G](https://doi.org/10.1016/0022-1910(91)90087-G)
- Tomioka K, Yamada K, Yokoyama S, Chiba Y (1991b) Mutual interactions between optic lobe circadian pacemakers in the cricket *Gryllus bimaculatus*. *J Comp Physiol A* 169:291–298. <https://doi.org/10.1007/BF00206993>
- Truman JW (1971) The role of the brain in the ecdysis rhythm of silkmoths: comparison with the photoperiodic termination of diapause. In: Menaker M (ed) *Biochronometry*. National Academy of Sciences, Washington, pp 483–504
- Truman JW (1972) Physiology of insect rhythms. I. Circadian organization of the endocrine events underlying the moulting cycle of larval tobacco hornworms. *J Exp Biol* 57:805–820. <https://doi.org/10.1242/jeb.57.3.805>
- Uemura H, Tomioka K (2006) Postembryonic changes in circadian photo-responsiveness rhythms of optic lobe interneurons in the cricket *Gryllus bimaculatus*. *J Biol Rhythm* 21:1–11. <https://doi.org/10.1177/0748730406288716>
- Watarai Y, Arai T (1997) Effects of photoperiod and aging on locomotor activity rhythms in the onion fly, *Delia antiqua*. *J Insect Physiol* 43:567–576. [https://doi.org/10.1016/S0022-1910\(97\)00002-4](https://doi.org/10.1016/S0022-1910(97)00002-4)

- Weber F (1967) Die Periodenlänge der circadianen Laufperiodizität bei drei *Carabus*-Arten (Coleoptera, Ins.). *Naturwissenschaften* 54:122. <https://doi.org/10.1007/BF00640591>
- Wiedenmann G (1977) Weak and strong phase shifting in the activity rhythm of *Leucophaea maderae* (Blaberidae) after light pulses of high intensity. *Z Naturforsch* 32c:464–465
- Wiedenmann G (1983) Splitting in a circadian activity rhythm: the expression of bilaterally paired oscillators. *J Comp Physiol* 150:51–60. <https://doi.org/10.1007/BF00605287>
- Wiedenmann G, Loher W (1984) Circadian control of singing in crickets: two different pacemakers for early-evening and before-dawn activity. *J Insect Physiol* 30:145–151. [https://doi.org/10.1016/0022-1910\(84\)90118-5](https://doi.org/10.1016/0022-1910(84)90118-5)
- Wiedenmann G, Lukat R, Weber F (1986) Cyclic layer deposition in the cockroach endocuticle: a circadian rhythm? *J Insect Physiol* 32:1019–1027. [https://doi.org/10.1016/0022-1910\(94\)00092-U](https://doi.org/10.1016/0022-1910(94)00092-U)
- Wills SA, Page TL, Colwell CS (1985) Circadian rhythms in the electroretinogram of the cockroach. *J Biol Rhythm* 1:25–37. <https://doi.org/10.1177/074873048600100105>
- Winfree A (1970) The temporal morphology of a biological clock. In: Gerstenhaber M (ed) *Lectures on mathematics in the life sciences*. American Mathematical Society, Providence, pp 111–150
- Xu K, Zheng X, Sehgal A (2008) Regulation of feeding and metabolism by neuronal and peripheral clocks in *Drosophila*. *Cell Metab* 8:289–300. <https://doi.org/10.1016/j.cmet.2008.09.006>
- Youthed GJ, Moran VC (1969) The solar-day activity rhythm of Myrmeleontid larvae. *J Insect Physiol* 15:1103–1116. [https://doi.org/10.1016/0022-1910\(69\)90147-4](https://doi.org/10.1016/0022-1910(69)90147-4)