

Daily rhythms of food-anticipatory behavioral activity do not require the known circadian clock

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When food availability is restricted to a particular time each day, mammals exhibit food-anticipatory activity (FAA), a daily increase in locomotor activity preceding the presentation of food. Considerable historical evidence suggests that FAA is driven by a food-entrainable circadian clock distinct from the master clock of the suprachiasmatic nucleus. Multiple food-entrainable circadian clocks have been discovered in the brain and periphery, raising strong expectations that one or more underlie FAA. We report here that mutant mice lacking known circadian clock function in all tissues exhibit normal FAA both in a light–dark cycle and in constant darkness, regardless of whether the mutation disables the positive or negative limb of the clock feedback mechanism. FAA is thus independent of the known circadian clock. Our results indicate either that FAA is not the output of an oscillator or that it is the output of a circadian oscillator different from known circadian clocks.

food-anticipatory activity | mouse genetics

When food availability is limited to a several-hour interval at a particular time each day, mammals quickly develop a new component of daily behavioral activity, a second period of arousal and increased locomotor activity that occurs shortly before the time of daily food presentation (1). This so-called food-anticipatory activity (FAA) is robust, stable over many daily cycles, and occurs even if the time of food availability lies within the light phase of the light–dark cycle, the resting period of the daily behavioral cycle for a nocturnal laboratory animal. Because feeding strategies are fundamental to survival, it is thought that FAA represents an evolutionary adaptation providing mammals with a highly flexible and efficient food-seeking program, one that is able, if necessary, to take advantage of food sources available at unusual times with respect to the animal's typical daily rest–activity cycle (2).

The mechanisms underlying FAA have been under investigation for nearly 30 years. The accumulated evidence suggests that FAA is more likely to be generated by a food-entrainable circadian oscillator than by plausible alternatives, such as a passive hourglass mechanism or an associative memory process (1). In general, an unequivocal demonstration that a rhythmic process is driven by an oscillator requires observation of the persistence of the rhythm over multiple cycles following removal of the entraining stimulus. In the case of daily rhythms entrained to a light–dark cycle, testing for a postulated underlying circadian oscillator simply requires switching off the lights and monitoring the daily rhythms for persistence in constant darkness. For example, daily rhythms of locomotor activity, feeding, and drinking in a light–dark cycle persist indefinitely after a transition to constant darkness, and were thus long ago demonstrated to be driven by a light-entrainable circadian oscillator (3). In contrast, a compelling demonstration that FAA relies on a self-sustained, food-entrainable oscillator has been difficult to obtain because laboratory animals cannot generally tolerate more than a few days of food deprivation. A further complication is that FAA is masked by a change from scheduled daily feeding to constant food availability (4), precluding demonstration of free-running rhythms of FAA under this condition as well.

To bypass these obstacles, a number of studies have examined the responses of FAA to acute shifts in the timing of food availability or alterations in its periodicity to probe the nature of the underlying processes. Although complex and in some ways puzzling, the results from these indirect paradigms make a reasonable circumstantial case that FAA is driven by a food-entrainable oscillator with a period in the circadian range (1). FAA is robust after a complete bilateral lesion of the suprachiasmatic nucleus (SCN) (5), indicating that it does not depend on the master clock driving circadian rhythms of behavioral activity under constant food availability. Thus was born the arduous search for the site of the postulated food-entrainable circadian clock underlying FAA (6–14), a clock that is privileged, like that of the SCN, to govern overt behavior, endowing it with particular importance.

The terms of this search were abruptly transformed by the discovery, made possible by the initial identification of molecular components of the clock, that circadian clocks are widely distributed in mammals, rather than being restricted to a few special sites, like the SCN and retina. Cultured cell lines, essentially all peripheral tissues, and multiple brain regions were found to have intrinsic circadian clocks capable of autonomous function (15–19). Especially striking was the finding that these distributed circadian clocks exhibit robust entrainment to scheduled daily feeding, with the notable exception being the SCN clock, which is readily entrained to light–dark cycles but has been proven to be impervious to manipulations of feeding time (17, 18, 20).

Thus, the field went suddenly from rags to an embarrassment of riches. Previously, it had seemed that identifying a hypothetical food-entrainable oscillator would be tantamount to discovering the circadian clock that drives FAA. Now, we know not only that food-entrainable circadian clocks exist but also that they are widespread in the brain and virtually ubiquitous in the periphery. In principle, any such clock could drive FAA.

As part of a broad study of the physiological functions of circadian clocks outside the SCN, we recently constructed a mouse line with a targeted conditional allele of the *Bmal1* gene, allowing tissue-specific genetic ablation of circadian clock function (21, 22). One of our early plans for this system was to generate mice selectively lacking clock function in all CNS neurons, in all peripheral tissues, or in particular CNS structures or peripheral tissues to determine in an unbiased fashion which circadian clocks were important for FAA. Unexpected results in routine preliminary studies for this intended project led to the detailed investigations described below of FAA in mice with defective circadian clocks in all tissues. Contrary to widely held

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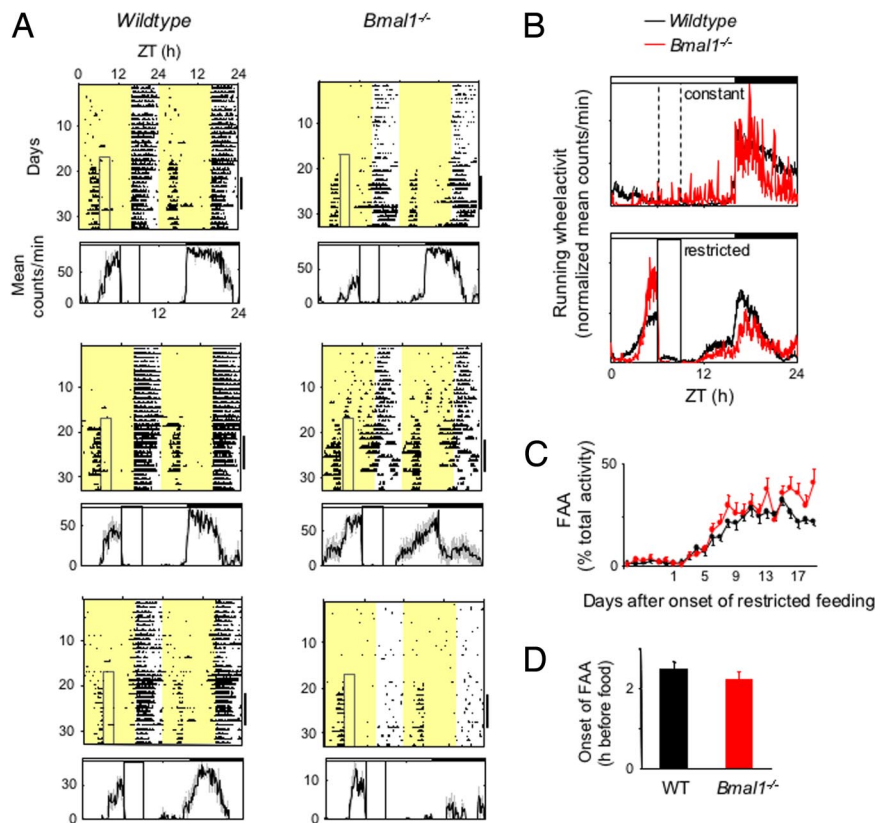


Fig. 1. Normal FAA in *Bmal1^{-/-}* mice. (A) Representative double-plotted actograms of daily running-wheel activity of 3 *Bmal1^{-/-}* mice and 3 wild-type littermates (as indicated) during constant food availability and under subsequent temporal restricted feeding. The boxed area toward the left side of each actogram indicates the daily interval of food availability under temporal food restriction, and yellow areas indicate time of lights-on (16:8 light–dark cycle in these experiments). Under a light–dark cycle, *Bmal1^{-/-}* mice show a diurnal variation in locomotor activity because of the acute suppressive effect of light on the behavior (masking). For clarity, the 4-day gradual narrowing of the interval of food availability is not included in the boxed area (Fig. S1). The graphs below each plot show the profile of daily running-wheel activity for each animal, averaged across 7 days during temporal food restriction (marked by the black bar on the right of each actogram). Gray vertical lines represent \pm SEM. A similar FAA was observed with *Bmal1^{-/-}* mice in a 12:12 light–dark cycle. ZT, Zeitgeber time. (B) Mean locomotor activity profiles of *Bmal1^{-/-}* mice and wild-type littermates ($n = 10$ for each genotype) under constant food availability (Upper) and after subsequent temporal food restriction (Lower). Individual mean 7-day profiles have been normalized by total daily activity so that each animal contributes equally to the shape of the profile; each data point represents normalized counts per minute averaged across a 6-min bin (mean \pm SEM). Time of light–dark cycle is indicated by white (light) and black (dark) bars at the top of each panel. Broken vertical lines (Upper) indicate, for comparison, the daily interval corresponding to subsequent restricted food availability; solid vertical lines (Lower) indicate the daily interval of food availability under temporal food restriction. (C) Time course of the development of FAA in *Bmal1^{-/-}* mice ($n = 22$) and wild-type littermates ($n = 20$). Shown is the daily percentage of running-wheel activity (mean \pm SEM) allocated to a 3-h time interval, ZT3–6. After 4 days of a gradually narrowing window of food availability, the final temporal food restriction started on day 1 (food available from ZT6–9). (D) Number of hours by which FAA anticipated daily food availability in *Bmal1^{-/-}* mice and wild-type littermates ($n = 20$ for each genotype). For each animal, the running-wheel activity profile was averaged over 7 consecutive days during stable temporal food restriction (as in B), and the average time of onset of FAA was defined as the time before food presentation at which the FAA peak rose to its half-maximum (mean \pm SEM). The difference between genotypes is not statistically significant.

views, the results of our genetic studies indicate that FAA is entirely independent of the known circadian clock.

Results

Our planned conditional genetic analysis of FAA was based on the assumption that it is driven by at least one of the many food-entrainable circadian clocks discovered recently. To confirm this assumption, we performed a preliminary study of FAA in mice (N5, C57BL/6) lacking *Bmal1* (*Mop3*), a core clock component acting in the positive limb of the circadian clock feedback loop (23) that is required for clock function (24). If correct, the assumption predicts that *Bmal1^{-/-}* mice, lacking circadian clocks in all tissues, should fail to develop FAA when placed under temporal food restriction, whereas their wild-type littermates should show normal FAA. Because at about 14 weeks of age *Bmal1^{-/-}* mice develop an arthropathy and begin in some cases to exhibit decreased locomotor mobility (25), we used mice aged 7–9 weeks at the start of the experiment. Initially, we used

a paradigm for FAA in which animals were shifted acutely from constant food availability to a single, brief window of daily food availability (4); in this case, a 3-h window. To our surprise, *Bmal1^{-/-}* mice, but not wild-type littermates, became sluggish, then moribund, and ultimately suffered a mortality rate of 80% during the first 7–10 days of the experiment. Subsequently, this outcome became less mysterious with the finding that *Bmal1^{-/-}* mutants and mice with mutations in other circadian clock genes have defects in glucose homeostasis, lipid metabolism, and energy balance (22, 26, 27), providing a plausible context for the selective vulnerability of *Bmal1^{-/-}* mice to a sudden reduction in the duration of food availability.

We then adopted a more gentle temporal food restriction paradigm, in which the duration of daily food availability was decreased gradually (28) from constant to a final 3-h window over a 4-day interval (Fig. S1). Under these conditions, both *Bmal1^{-/-}* mice and wild-type littermates survived, appeared active and healthy, and exhibited robust behavior over the entire

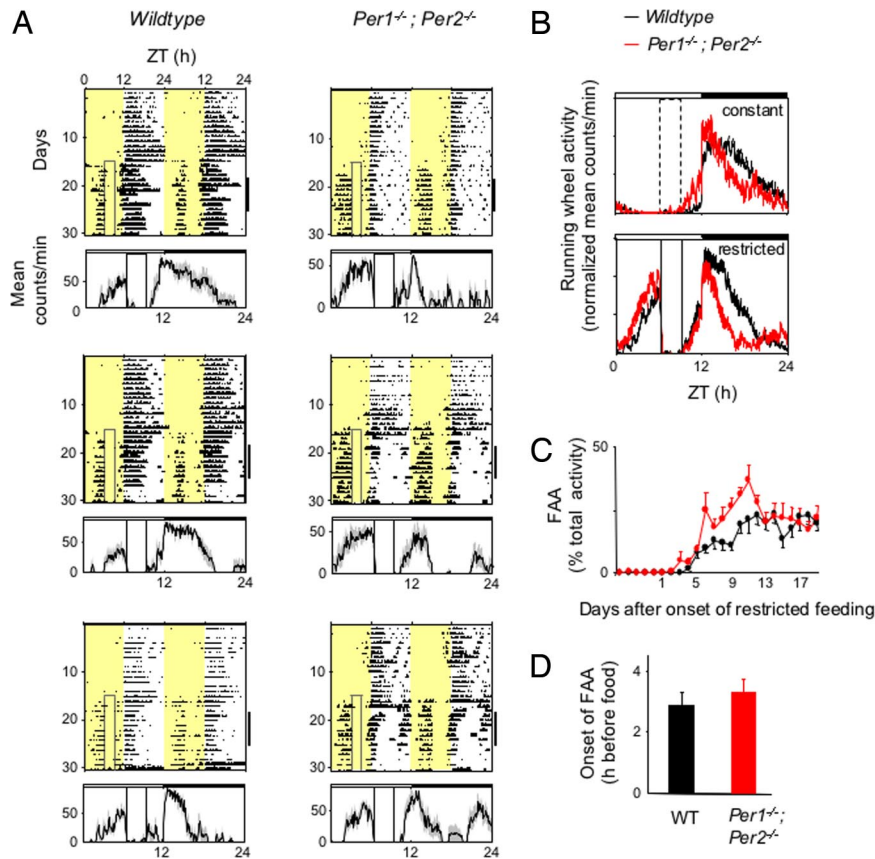


Fig. 2. Normal FAA in *Per1^{-/-}; Per2^{-/-}* double-mutant mice. (A) Representative double-plotted actograms of daily running-wheel activity of 3 wild-type and 3 *Per1^{-/-}; Per2^{-/-}* mice (as indicated) during constant food availability and under subsequent temporal food restriction. Data are displayed as in Fig. 1A. Under a light–dark cycle, *Per1^{-/-}; Per2^{-/-}* mice show a diurnal variation in locomotor activity because of the acute suppressive effect of light on behavior. (B) Mean locomotor activity profiles of wild-type ($n = 9$) and *Per1^{-/-}; Per2^{-/-}* mice ($n = 8$) under constant food availability (Upper) and after subsequent temporal food restriction (Lower). Data are displayed as in Fig. 1B. (C) Time course of the development of FAA in wild-type and *Per1^{-/-}; Per2^{-/-}* mice ($n = 8$ for each genotype). Data are displayed as in Fig. 1C. (D) Number of hours by which FAA anticipated daily food availability in wild-type and *Per1^{-/-}; Per2^{-/-}* mice ($n = 8$ for each genotype). Data are displayed as in Fig. 1D. The difference between genotypes is not statistically significant.

course of the experiments, which were 6–8 weeks in duration. Contrary to our expectations, *Bmal1^{-/-}* mice exhibited robust and stable FAA, essentially identical to that of wild-type littermates (Fig. 1). Even in those several cases in which *Bmal1^{-/-}* mice exhibited low baseline levels of running-wheel activity, FAA was nonetheless robust (Fig. 1A Lower Right).

Detailed and quantitative aspects of FAA were preserved in mice lacking *Bmal1*. The normalized mean FAA profiles of the 2 populations after temporal food restriction were similar (Fig. 1B). The tendency of *Bmal1^{-/-}* mice to allocate, on average, a slightly larger proportion of total activity to FAA than did wild-type littermates (Fig. 1B) resulted from the subset of *Bmal1^{-/-}* mice with low baseline activity but strong FAA (as exemplified in Fig. 1A Lower Right). The time course of the appearance of FAA after initiation of temporal food restriction was essentially identical in *Bmal1^{-/-}* mice and wild-type littermates, with FAA emerging at about 3 days and reaching a plateau at 8–9 days (Fig. 1C). The mean time by which FAA anticipated the daily onset of food availability (the phase angle with respect to food presentation) was slightly more than 2 h in both *Bmal1^{-/-}* mice and wild-type littermates, statistically indistinguishable in the 2 genotypes (Fig. 1D).

These results indicate that the *Bmal1* gene is not required for FAA, at least under the usual conditions of temporal food restriction in a light–dark cycle. Because *Bmal1* is essential for all circadian clock functions documented to date, these findings strongly imply that the known circadian clock is not required for

robust, quantitatively normal FAA. But, given the broad evidence suggesting that a circadian clock likely underlies FAA, we considered the possibility that a hypothetical circadian clock driving FAA could be an unusual exception that is based on the known mechanism but nonetheless not requiring *Bmal1*—perhaps, for example, because of a rarely expressed transcription factor that is redundant with *Bmal1* in clock function. To examine this possibility further, we studied FAA in *Per1^{-/-}; Per2^{-/-}* double mutants. These mice lack circadian clock function as a consequence of targeted disruptions of 2 of the 3 *Period* (*Per*) genes (29), core clock components acting, in contrast to *Bmal1*, in the negative limb of the circadian clock feedback loop (30).

Using the gradual temporal food restriction protocol described above, we monitored FAA in *Per1^{-/-}; Per2^{-/-}* double mutants and wild-type mice derived from the same breeding colony (pure 129 background). The result was the same as that for *Bmal1^{-/-}* mice: *Per1^{-/-}; Per2^{-/-}* mice exhibited robust, stable, and quantitatively normal FAA (Fig. 2). The normalized average FAA profiles of wild-type controls and *Per1^{-/-}; Per2^{-/-}* mice were nearly superimposable (Fig. 2B); the time course of the appearance of FAA after initiation of temporal food restriction was very similar in the 2 genotypes (Fig. 2C), and the mean time by which FAA anticipated the daily onset of food availability was statistically indistinguishable in the 2 genotypes—about 3 h in this genetic background (Fig. 2D). These results indicate that together, the *Per1* and *Per2* genes are not required for FAA under the usual conditions of temporal food restriction

in a light–dark cycle. We observed the same full preservation of FAA in *Per2*^{-/-} single-mutant mice (*SI Text* and *Fig. S2*). Thus, FAA is unaffected, regardless of whether the mutation disrupts the negative limb (*Per1*^{-/-}; *Per2*^{-/-}) or the positive limb (*Bmal1*^{-/-}) of the circadian feedback loop, indicating that under these conditions, FAA is independent of the function of known circadian clocks.

Because the results described above were obtained with mice under a light–dark cycle, standard conditions for studying FAA, they do not formally exclude the possibility that a circadian clock of the known type drives FAA. If a light–dark cycle drives oscillations of core components of a hypothetical FAA clock, thereby mimicking intact clock function, then light-driven molecular oscillations could, in principle, support entrainment to scheduled feeding, and thus drive FAA in circadian clock mutants. Because we observed quantitatively normal FAA in mice with mutations disabling different parts of the circadian feedback loop (Figs. 1 and 2), this scenario seemed improbable. However, if it were correct, then this hypothesis predicts that mutants lacking clock function would exhibit FAA in a light–dark cycle (as we observed) but would lack FAA in constant darkness. Alternatively, if FAA is fully independent of known circadian clocks, then robust FAA should persist in constant darkness in the mutants. To distinguish these alternatives, we performed studies of FAA in constant darkness in *Bmal1*^{-/-} and *Per1*^{-/-}; *Per2*^{-/-} mice.

In constant darkness, mice lacking SCN circadian clock function, whether because of mutations that ablate clock function generally or because of an SCN lesion, display high-frequency (ultradian) bouts of locomotor activity that could potentially obscure FAA and make it difficult to recognize. As a guide to how FAA might look if present in constant darkness in *Bmal1*^{-/-} or *Per1*^{-/-}; *Per2*^{-/-} mice, we performed control experiments in SCN-lesioned wild-type mice known to exhibit FAA (28). Despite the prominent ultradian activity, FAA was recognizable in the individual behavioral records of SCN-lesioned wild-type mice (Fig. 3*B*), and its presence was unequivocal in the averaged population profiles (Fig. 3*C*), which showed a specific and highly statistically significant increase in locomotor activity in the 4-h period immediately preceding the onset of food availability compared with other times of day (Fig. 3*D*).

Thus informed of how FAA might look if present in the mutants, we next studied *Bmal1*^{-/-} and *Per1*^{-/-}; *Per2*^{-/-} mice in constant darkness. *Bmal1*^{-/-} mice exhibited an FAA in constant darkness that was essentially identical to that of the SCN-lesioned wild-type controls shown in Fig. 3. In individual records of *Bmal1*^{-/-} mice, FAA was clearly recognizable, partially obscured by, but nonetheless standing out above, the baseline ultradian activity (Fig. 4*A*). The population activity profile indicated unambiguous FAA (Fig. 4*B*) that was highly statistically significant (Fig. 4*C*).

FAA was also fully preserved in *Per1*^{-/-}; *Per2*^{-/-} mice in constant darkness. FAA was apparent in individual activity records (Fig. 5*A*), and the population activity profile showed prominent FAA (Fig. 5*B*) that was highly statistically significant (Fig. 5*C*).

These results indicate that the *Bmal1* or the *Per1* and *Per2* genes are not required for FAA in constant darkness. We conclude that FAA does not require the known circadian clock.

Discussion

It has long been argued that FAA is the behavioral output of a postulated food-entrainable circadian oscillator (1, 2). The recent discovery of widely distributed food-entrainable circadian clocks with the same molecular mechanism as that of the SCN clock (20) has evoked the widespread and reasonable expectation that FAA is driven by one or more of these known clocks (10, 13).

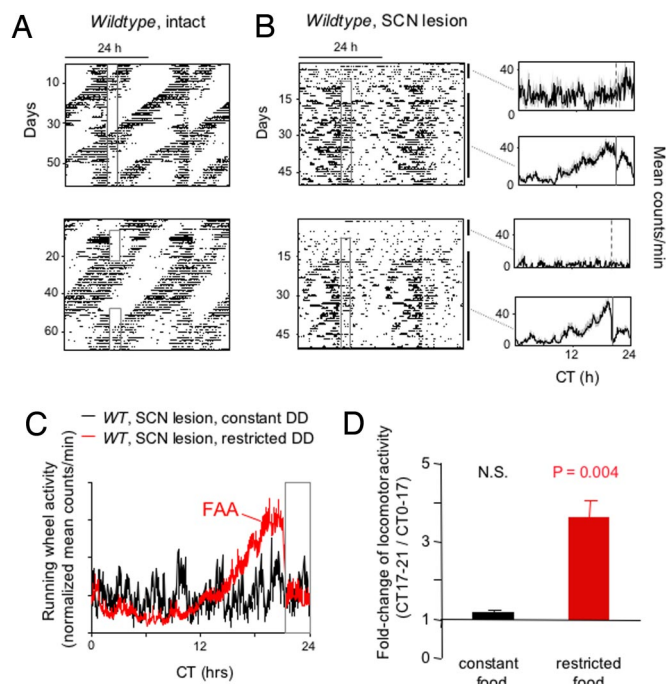


Fig. 3. Detection of FAA in constant darkness in behaviorally arrhythmic mice with prominent ultradian activity. (A) Representative double-plotted actograms of daily running-wheel activity of 2 wild-type mice (C57BL/6) during constant food availability and under temporal food restriction in constant darkness. Actograms are displayed as in Fig. 1*A*. (B) (Left) Representative double-plotted actograms of daily running-wheel activity of 2 SCN-lesioned wild-type mice (C57BL/6) during constant food availability and under subsequent temporal food restriction in constant darkness. Actograms are displayed as in Fig. 1*A*. (Right) Profile of daily running-wheel activity averaged across the days marked by the associated black bars to the right of each actogram, one during constant food availability and one during subsequent temporal food restriction. Gray vertical lines represent \pm SEM. CT indicates circadian time (time of day during constant darkness conditions). (C) Mean locomotor activity profiles of SCN-lesioned wild-type mice ($n = 7$) during constant food availability (black) and after subsequent temporal food restriction (red), calculated as in Fig. 1*B*. Gray open box at right indicates the daily interval of food availability under temporal food restriction (CT21–24). (D) Quantification of FAA in SCN-lesioned mice in constant darkness ($n = 7$). Shown is the fold change of locomotor activity (running-wheel counts per minute; mean \pm SEM) in each mouse for CT17–21 (when FAA would be expected under restricted food availability, see C) compared with CT0–17 (the rest of the day, except for CT21–24, the time when food was available under food restriction conditions). This latter interval was omitted from the computations because of the acute suppressive effect of food presentation on running-wheel activity (e.g., red trace in C). Under temporal food restriction, increased running-wheel activity (counts per minute) during CT17–21 compared with CT0–17 was highly significant (paired *t* test), but there was no significant difference under constant food access. N.S., not significant.

Previous studies of FAA in various circadian clock mutant genotypes have left open the question of the relationship of FAA to the known circadian clock mechanism. *Clock* mutant mice were reported to have intact FAA (31), but *Clock* mice have circadian clocks that are capable of free-running for a week or more, and they show normal behavioral entrainment to a light–dark cycle (32), so the persistence of FAA in this genotype could reflect the substantial residual clock function. *Cryptochrome* (*Cry*)-deficient mice were reported to exhibit FAA, but the study emphasized apparent alterations in the kinetics and stability of FAA in the mutants, arguing for a possible role of the clock in FAA (33).

Our results document that mutant mice lacking circadian clocks of the known kind in all tissues have FAA that is

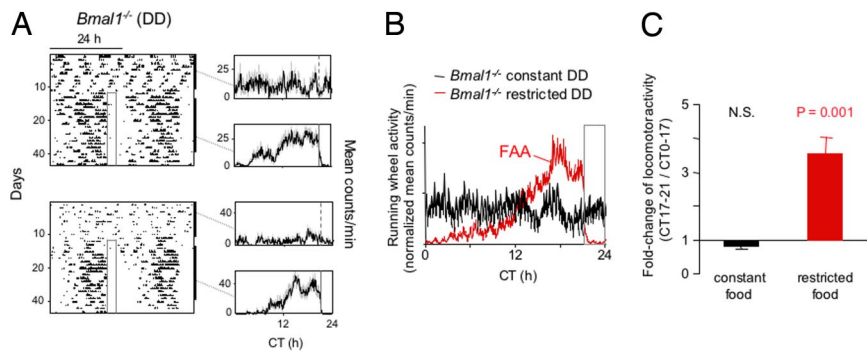


Fig. 4. Normal FAA in *Bmal1*^{-/-} mice in constant darkness. (A) Representative double-plotted actograms of daily running-wheel activity of 2 *Bmal1*^{-/-} mice during constant food availability and under subsequent temporal food restriction in constant darkness. Data are displayed as in Fig. 3B. Note arrhythmic, ultradian activity before temporal food restriction. (B) Mean locomotor activity profiles of *Bmal1*^{-/-} mice ($n = 7$) during constant food availability (black) and after subsequent temporal food restriction (red), displayed as in Fig. 3C. (C) Quantification of FAA in *Bmal1*^{-/-} mice ($n = 7$) in constant darkness. Data are displayed as in Fig. 3D.

qualitatively and quantitatively indistinguishable from that in wild-type littermates in both a light–dark cycle and constant darkness, regardless of whether the mutation disables the positive or negative limb of the circadian clock feedback mechanism (*Bmal1*^{-/-} or *Per1*^{-/-}; *Per2*^{-/-} mice, respectively). Thus, daily rhythms of FAA are independent of the function of the known circadian clock.

Two recent papers have offered a different conclusion. One found that FAA was lacking in mice with a mutation in *Per2*, specifically the *Per2*^{Brdm1} allele (34). We bred mice homozygous for a targeted disruption of *Per2* (*Per2*^{-/-} mice; ref. 29) in the same mixed genetic background as in the FAA study of *Per2*^{Brdm1} mice, and we found that *Per2*^{-/-} mice exhibited normal FAA, indistinguishable from that of wild-type littermates (SI Text and Fig. S2). It is possible that the apparently discrepant findings result from the different *Per2* alleles. In general, loss of a behavioral response in a mutant genotype is more likely due to nonspecific factors than is the persistence of a normal behavior. Given our additional findings of normal FAA in *Per1*^{-/-}; *Per2*^{-/-} double mutants and in *Bmal1*^{-/-} mice, we suggest that *Per2*^{Brdm1} might not act as a pure loss-of-function allele. It is conceivable that *Per2*^{Brdm1}, a small in-frame internal deletion in *Per2* (35), has a deleterious effect on behavior independent of any defect in circadian clock function, particularly given evidence that *Per2*^{Brdm1} encodes a functional PER2 protein with abnormal properties (36).

The second paper reported a lack of FAA in *Bmal1*^{-/-} mice (37). This study used a protocol with an abrupt shift from

constant food availability to restricted food availability, like the initial protocol we used that caused *Bmal1*^{-/-} mice to become lethargic and suffer a very high rate of mortality (see above). Notably, the study reported that under this acute food restriction, *Bmal1*^{-/-} mice developed a torpor-like state, requiring manual stimulation to feed. On the basis of our similar initial food restriction experiments with the same mice, we suggest that the failure of *Bmal1*^{-/-} mice to exhibit FAA under these conditions reflects a nonspecific effect of a severely compromised physiological or nutritional state, a point also raised recently by others (38).

Our results indicate that FAA does not require the function of the known circadian clock, necessitating fresh thinking about FAA, its underlying mechanism, and its anatomical substrates. Our findings are consistent with either an oscillatory or a nonoscillatory mechanism underlying FAA. If FAA is driven by an oscillatory mechanism, as suggested by multiple lines of evidence (1, 2), then there must be at least one class of circadian oscillator with a mechanistic basis different from that of known circadian clocks. This possibility is consistent with the finding that FAA to 24-h scheduled feedings in rats was unaffected after deuterium administration, whereas light-entrained behavior exhibited so strong a period-lengthening effect that it could no longer be entrained to a 24-h light–dark cycle (39).

The results reported here do not address the question of which neural or peripheral structures drive FAA or are necessary for its expression. However, they do remove the rationale for hypotheses about anatomical sites underlying FAA that are

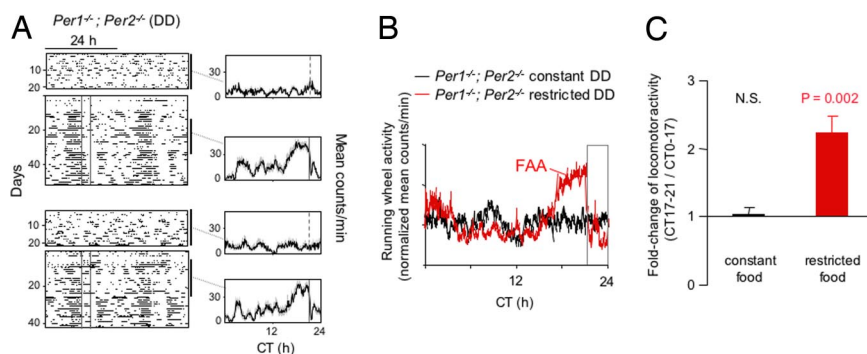


Fig. 5. Normal FAA in *Per1*^{-/-}; *Per2*^{-/-} double-mutant mice in constant darkness. (A) Representative double-plotted actograms of daily running-wheel activity of 2 *Per1*^{-/-}; *Per2*^{-/-} mice during constant food availability and under temporal food restriction in constant darkness. Data are displayed as in Fig. 3B. Note arrhythmic, ultradian activity before temporal food restriction. (B) Mean locomotor activity profiles of *Per1*^{-/-}; *Per2*^{-/-} mice ($n = 8$) during constant food availability (black) and after subsequent temporal food restriction (red). Data are displayed as in Fig. 3C. (C) Quantification of FAA in *Per1*^{-/-}; *Per2*^{-/-} mice ($n = 8$) in constant darkness. Data are displayed as in Fig. 3D.

based on the presence of known circadian clocks at those sites. It appears that there is still much work to be done before the enduring mystery of FAA is solved.

Materials and Methods

Mice, Genotyping, and SCN Lesions. Studies were performed in accordance with the protocol approved by the Harvard Medical School Standing Committee on Animals. For breeding, mice were housed in standard ventilated cages exposed to a 12:12 light–dark cycle. Genotyping was carried out as described (*Bmal1*^{-/-}, ref. 24; *Per1*^{-/-}; *Per2*^{-/-} and *Per2*^{-/-} mice, ref. 29). SCN lesions were performed as described previously (21) on 8-week-old C57BL/6J male mice.

Temporal Food Restriction. Mice were transferred to individual cages equipped with running wheels at 7–9 weeks of age and were exposed to 12:12 or 16:8 light–dark cycles for 14 days with ad libitum access to regular chow pellets (LabDiet 5001; PMI Nutrition International). On the first day of the 4-day gradual food restriction period (Fig. S1), regular chow was removed at ZT (or CT) 18, and 12 h later, at ZT (or CT) 6, enriched food (LabDiet 5001 powdered chow mixed with canola oil; 4:1 wt/wt) was provided in a 40-ml

glass jar (40). Each successive day, enriched food was removed 3 h earlier until food presentation was limited to 3 h, from ZT6 to ZT9 or CT6 to CT9 (Fig. S1). Under constant darkness, food removal and presentation and cage changes were carried out under infrared light with night-vision goggles.

Locomotor Activity Recordings and Data Analysis. Running-wheel activity was recorded with ClockLab (Actimetrics). Animals were placed in individual cages equipped with running-wheels and housed in light-tight, ventilated boxes. During lights-on, mice were exposed to 150 lux of light. In the displayed actograms, single data points (tick marks) represent revolutions per minute per 6-min time bin. Individual mean daily activity profiles were computed by using ClockLab, and group average profiles were generated with Microsoft Excel.

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