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PLASTICITY OF CIRCADIAN ACTIVITY AND BODY TEMPERATURE RHYTHMS IN GOLDEN SPINY MICE

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Most animals can be categorized as nocturnal, diurnal, or crepuscular. However, rhythms can be quite plastic in some species and vary from one individual to another within a species. In the golden spiny mouse (Acomys russatus), a variety of rhythm patterns have been seen, and these patterns can change considerably as animals are transferred from the field into the laboratory. We previously suggested that these animals may have a circadian time-keeping system that is fundamentally nocturnal and that diurnal patterns seen in their natural habitat reflect mechanisms operating outside of the basic circadian time-keeping system (i.e., masking). In the current study, we further characterized plasticity evident in the daily rhythms of golden spiny mice by measuring effects of lighting conditions and access to a running wheel on rhythms in general activity (GA) and body temperature (Tb).

Before the wheel was introduced, most animals were active mainly during the night, though there was considerable inter-individual variability and patterns were quite plastic. The introduction of the wheel caused an increase in the level of nighttime activity and Tb in most individuals. The periods of the rhythms in constant darkness (DD) were very similar, and even slightly longer in this study (24.1 ± 0.2 h) than in an earlier one in which animals had not been provided with running wheels. We found no correlation between the distance animals ran in their wheels and the period of their rhythms in DD. Re-entrainment after phase delays of the LD cycle occurred more rapidly in the presence than absence of the running wheel. The characteristics of the rhythms of golden spiny mice seen in this study may be the product of natural selection favoring plasticity of the circadian system, perhaps reflecting what can happen during an evolutionary transition as animals move from a nocturnal to a diurnal niche. (Author correspondence: nogaks@tauex.tau.ac.il)

Keywords Wheel running, Acomys, Plasticity, Circadian rhythms, Diurnal

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INTRODUCTION

Virtually all animals, such as fruit flies (Keny et al., 2007), bees (Oda et al., 2007), spiny mice (Levy et al., 2007), amphipods (Rossano et al., 2008), and humans (Pati et al., 2007), exhibit 24 h activity rhythms, and most can be categorized as either nocturnal, diurnal, or crepuscular. However, rhythms can be quite plastic in some species and vary from one individual to another within a species in both natural and laboratory settings (reviewed by Hagenauer & Lee, 2008; Kronfeld-Schor & Dayan, 2003, 2008; Refinetti, 2008). One variable that can, in some species, alter fundamental characteristics of rhythms, such as phase, period, and patterns of coupling to the day-night cycle, is the availability of a running wheel. For example, activity becomes substantially more nocturnal when wheels are provided to Nile rats (Blanchong et al., 1999), degus (Kas & Edgar, 1999), and Mongolian gerbils (Weinert et al., 2007). In the present study, we examined effects of access to a running wheel on daily rhythms of the golden spiny mouse (*Acomys russels*), a species in which a variety of different rhythm patterns have been observed in both natural and captive conditions (Cohen & Kronfeld-Schor, 2006; Elvert et al., 1999; Haim & Borut, 1975; Kronfeld et al., 1994; Kronfeld & Dayan, 1998; Kronfeld-Schor et al., 2001a; Levy et al., 2007; Shkolnik, 1966, 1971).

The golden spiny mouse is an omnivorous desert rodent with a limited distribution in the rocky deserts in northeastern Egypt, southern Israel, and Jordan (Mendelson & Yom Tov, 1999). These animals are day-active in most conditions in their natural habitat (Elvert et al., 1999; Haim & Borut, 1975; Kronfeld et al., 1994; Kronfeld-Schor et al., 2001a; Levy et al., 2007; Scott & Dunstone, 2000; Shkolnik, 1966, 1971). Diurnality in Israel has been ascribed to competitive exclusion from the nocturnal niche by its congener, the common spiny mouse (*Acomys cahirinus*, Shkolnik, 1966, 1971). Indeed, when common spiny mice are removed from the shared habitat, the golden spiny mouse becomes active during both day and night (Gutman & Dayan, 2005; Shkolnik, 1966). In the high mountains of the Sinai desert in Southern Egypt, Haim and Borur (1975) found that golden spiny mice are diurnal, even though common spiny mice are absent. Those authors attributed the diurnal activity of these animals in their relatively cold environment to thermoregulatory requirements.

Under laboratory conditions, in the absence of the common spiny mouse, the golden spiny mouse displays 24 h rhythms of body temperature (Tb), oxygen consumption (Gutman et al., 2006; Kronfeld-Schor et al., 2000; Rubal et al., 1992), and wheel running (Freidman et al., 1997; Kronfeld-Schor et al., 2001a) typical of nocturnal mammals. In our laboratory colony, we recently found that most individuals show general activity (GA) and Tb rhythms typical of those seen in nocturnal species (Cohen & Kronfeld-Schor, 2006; Gutman et al., 2006, 2007),

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although some individuals remained diurnal, and inter-individual variation was unusually high. Moreover, when golden spiny mice were transferred from field enclosures in their natural habitat, where they were diurnal, into constant darkness (DD) or a natural light-dark (LD) cycle in the laboratory, the phases of these rhythms were instantly inverted. That is, the rhythms in both GA and Tb were immediately 12 h out of phase with what they had been in the field condition (Kronfeld-Schor et al., 2001a; Levy et al., 2007). These findings have led us to suggest that golden spiny mice may have a circadian time-keeping system that is fundamentally nocturnal and that the diurnal patterns seen in most of their natural habitat reflect mechanisms operating outside of the basic circadian time-keeping system (Levy et al., 2007), processes referred to sometimes as “masking” (e.g., Hagenauer & Lee, 2008; Mrosovky, 2003).

Coordination of rhythms in golden spiny mice could represent a phase that other animals have gone through during evolutionary transitions from a nocturnal to a diurnal pattern of adaptation to the day-night cycle (Kronfeld-Schor & Dayan, 2003, 2008; Roll et al., 2006). This hypothesis is supported by the existence in these animals of a mosaic pattern of traits typically seen in either nocturnal or diurnal species. Adaptations for a day-active existence include dark skin pigmentation and high concentration of ascorbic acid in the eyes (Koskela et al., 1989), both of which protect against intense solar radiation in diurnal species (Chaplin, 2004; Jablonski, 2004; Koskela et al., 1989). Adaptations for a night-active existence include a retinal structure composed of rods, typical of those seen in nocturnal mammals, including its nocturnal congener the common spiny mouse (Kronfeld-Schor et al., 2001b). The golden spiny mice also show behavioral thermoregulation, avoiding environmental heat by remaining in the shade (Kronfeld-Schor et al., 2001b; Shkolnik, 1971) and switching from a unimodal pattern of activity in winter to a bimodal one in summer, thereby avoiding midday heat (Kronfeld et al., 1994; Kronfeld-Schor et al., 2001a). Moreover, their ability to reduce water loss in the feces (Kam & Degen, 1993) and produce highly concentrated urine (Shkolnik, 1966; Shkolnik & Borut, 1969) enables golden spiny mice to use evaporative cooling, which helps support activity during the day, when ambient temperatures are elevated (Kronfeld-Schor et al., 2001c; Shkolnik & Borut, 1969).

In the current study, we further characterized plasticity of the daily rhythms of golden spiny mice in an effort to better understand the nature of the systems that determine whether they are most active during the day or night. Specifically, we examined the effects of lighting conditions and access to a running wheel on the circadian rhythms in GA and Tb in descendents of animals trapped at Ein Gedi, near the Dead Sea, where they are diurnal (Elvert et al., 1999; Kronfeld et al., 1994; Kronfeld-Schor et al., 2001a; Levy et al., 2007; Shkolnik, 1966).
METHODS

The experimental protocol conformed to international ethical standards for the treatment of animals (Portaluppi et al., 2008), and all procedures were conducted in accordance with, and approved by, the Institutional Animal Ethics Committee (L-02-45) of Tel Aviv University, Tel Aviv, Israel.

Animals and Housing

Twelve adult (ca 1 yr of age) golden spiny mice (six males and six females) from our breeding colony at the I. Meir Segals Zoological Garden at Tel Aviv University were studied. The source of the animals in this colony was Ein Gedi, near the Dead Sea; new wild-trapped individuals are added to the colony every year. The mice were individually housed in 50 × 29 × 15 cm plastic cages, under controlled laboratory conditions of LD 12:12 (800 lux), with food (standard rodent chow) and water provided ad libitum. Ambient temperature was maintained at 29°C, which is approximately (Shkolnik & Borut, 1969) or just below (Ehrhardt et al., 2005) the low critical temperature of the thermoneutral zone of the golden spiny mouse. A 20 cm-diameter running wheel was introduced into the cage at different phases of the experiment, as indicated below. Experiments were conducted during winter.

Monitoring of Tb, GA, and Wheel Running

Tb and GA were recorded throughout the study, and wheel running was monitored during specific phases when wheels were available to the animals (see below). Tb was measured using temperature sensitive single stage implanted transmitters (Sirtrack, New Zealand; accuracy ± 0.1°C, resolution 0.0625°C) and RX-900 scanner-receiver (Televilt, Sweden). Infra-red detectors (Intrusion detector model MH10, Crow group, Israel) were used to measure GA, and wheel revolutions were measured using a proximity switch (XS1N18PA34912-24D, AECO, Italy). The infra-red detector and the proximity switch were connected to a PC computer. Data were collected and stored using Strawberry tree software. GA, wheel revolutions, and Tb were recorded every 6 min.

Animal Surgery

Spiny mice were anesthetized with isoflurane in medical grade oxygen using an anesthetic machine (Ohmeda), and implanted with the single stage transmitters in the abdominal cavity. Both the abdominal wall and skin were sutured with absorbable surgical suture using a cutting needle.
(5-0 Dexon), and the incision was treated with topical antibiotic (silver sulfadiazine 1%; Silverol cream). Prophylactic antibiotics (Baytril 5% 24 mg/kg) and artificial tear ointment (to prevent desiccation) were administered preoperatively. A minimum of two weeks was allowed for the animals to recover from surgery and initiation of data collection.

**Experimental Protocol**

Animals were monitored for 15 days under LD 12:12 conditions without a running wheel (phase 1). A running wheel was then introduced into each of the cages for 33 days (phase 2) and then removed for another 25 days (phase 3). The wheels were then reintroduced for 22 days (phase 4). This was followed by a 6 h phase advance (phase 5) and then, 67 days later, by a 6 h phase delay of the LD cycle (phase 6). Thirty-five days later, lights were turned off and animals were then kept in constant darkness (DD) for 61 days (phase 7).

**Data Analysis**

Data were collected in 6 min bins in all experiments and were analyzed using the Clocklab program (Actimetrics, Wilmette, Illinois, USA), which was also used to generate all actograms (of normalized data). Microsoft Excel was used to generate the figures. Data are presented as means ± SEM; statistical tests include paired t-test, repeated measures, one-way and two-way ANOVA, and Scheffe or Fischer post-hoc test (Statistica 7.1, StatsSoft, Inc., Tulsa, Oklahoma, USA). Results were considered significant when $p < 0.05$. As in Cohen and Kronfeld-Schor (2006), no differences between sexes were found. Therefore, the results for males and females were combined.

We use standard (though admittedly somewhat arbitrary) definitions of animal activity patterns; we refer to animal activity patterns as being nocturnal if more than 50% of the GA occurred during the dark phase and diurnal if more than 50% of GA occurred during the light phase. We attempted to define activity onset and offset on both the Clocklab program using various settings according to published papers (e.g., onset, the first active bout that was preceded by at least 20 min of inactivity; offset, the last bin of activity that was followed by at least 20 min of inactivity; onset, 30 min of activity, subsequent to 3 h of inactivity), and by visual inspection, but we could not clearly identify either onsets or offsets in most individuals. Therefore, as in Cohen and Kronfeld-Schor (2006), responses to phase shifts were analyzed using the phase of the peaks (maximum) of the activity rhythms of each animal. The day of re-entrainment after a phase advance was defined as the day after the peak of activity that no longer advanced, and the day of re-entrainment after a phase delay was
defined as the day after the onset of the activity peak that no longer delayed. Average time of peak activity during the last 10 days of the LD cycle before the shift was set to 0, and the changes in the activity rhythms were described in relation to that time point.

RESULTS

Before the wheel was introduced, most animals were active mainly during the night, though there was considerable variability across individuals and plasticity within individuals. All spiny mice used the running wheel. Running distance averaged 1500 ± 308 m per day (range 453–6759 m). All but one individual used the wheel mainly during the dark phase, with 81 ± 3% of wheel running occurring then (see Figure 1); the exception was male 430, for which 52% of wheel running occurred during the light phase (see Figure 2c).

There was a clear influence of the wheel on the distribution of GA between the day and night in all individuals (F = 7.98, df = 2, p < 0.005; see Figures 1 and 2). In phase 1, before the introduction of

FIGURE 1 The distribution of average % general activity (GA) occurring at night of golden spiny mice (N = 12) under 12:12 LD conditions, during phase 1 without a running wheel (15 days, gray), phase 2 in the presence of a running wheel (35 days, black), and phase 3 without a running wheel (25 days, white). In the presence of the running wheel, GA shifted toward the night (the lines represent fitting to a normal distribution).
the running wheels, two males and one female (e.g., Figures 2b and 2c) concentrated 50% or more of their GA during the day and were classified as diurnal, while the other nine animals were nocturnal (e.g., Figures 2a, 2d, and 2e). Some $61.25 \pm 4.2\%$ ($n=12$) of the overall average GA occurred during the night. During phase 2, in the presence of the running wheel, a significantly larger portion of the GA occurred during the night ($77.4 \pm 3.9\%$) than day ($df=22, p<0.005$; see Figure 1).

***Figure 2*** General activity (GA), wheel running activity, and body temperature (Tb) in golden spiny mice during the 15 days before introduction of the wheel (phase 1), 33 days in the presence of the wheel (phase 2), and 25 days after its removal (phase 3), under 12:12 LD conditions (normalized). Wheel running affected the GA and Tb temporal patterns. Black bars at top of plot represent the light/ing schedule. The implanted body temperature transmitter of mouse 510 (e) ceased working, and the recording unit of the running wheel of mouse 540 (b) stopped recording after 16 days in the presence of the wheel. Female 5001 (a) was nocturnal in phase 1 (86% of the activity occurred during the dark phase), increased its nocturnal activity to 99% of total activity in the presence of the running wheel, and decreased it to 72% after its removal. Male 540 (b) increased its nocturnal activity from 50 to 80% in the presence of the running wheel, and decreased it to 69% after its removal. Male 430 (c) was diurnal in phase 1, increased its nocturnal activity (to 48%) in the presence of the running wheel, and turned nocturnal (73% of the activity occurred during the dark phase) after its removal. Female 520 (d) was nocturnal in phase 1; in the presence of the running wheel, it increased its nocturnal activity from 61 to 93%, and after the removal of the wheel, it decreased it to 56%. Male 510 (e) was nocturnal in phase 1, increased its nocturnal activity to 78% in the presence of the running wheel, and became diurnal after its removal (only 38% of its activity occurred during the dark).

(Continued)
At that stage, two of the nocturnal individuals, one male and one female, decreased the proportion of GA occurring at night by $6 \pm 1.6\%$, while the other ten individuals increased it by $20.6 \pm 0.2\%$. Of these animals, the three individuals that were diurnal in phase 1 (e.g., Figures 2b and 2c) increased this proportion by $21 \pm 3.1\%$ (from 39, 48, and 50\% in phase 1 to 48, 73, and 80\%, respectively, in phase 2). After removal of the wheel (phase 3), the %GA occurring during the night decreased significantly ($df = 22, p < 0.05$), becoming comparable to that seen in phase 1, before the wheel was introduced ($df = 22, p = 0.83$). However, animals did not resume their original activity patterns: six of the ten individuals that were nocturnal in phase 1 increased their GA during the light hours during phase 3 (e.g., Figure 2a, 2d, and 2e), and one became diurnal (see Figure 2e). The three individuals that were diurnal in phase 1 were nocturnal in phase 3 (one of them, male 430, increased its %GA at night from 39 to 73\%; see Figure 2c). To summarize, six individuals were significantly less nocturnal in phase 3 (after removal of the running wheel) as compared to phase 1 (before the wheel was introduced), and six were significantly more nocturnal in phase 3 as compared to phase 1.

The presence of the running wheel changed not only the relative levels of activity during the day and night, but also the pattern of activity. In most animals, before the introduction of the wheel (phase 1), there were two peaks in GA, one starting toward the end of the light phase and ending a few hours after lights off, and the other, a smaller peak, occurring toward the end of the dark phase. For example, when individual 540 (see Figure 2b) did not have a running wheel, GA onset occurred ca 4 h before lights off, and continued for ca 6 h. A second bout of activity began 2 h before lights on and lasted approximately 2 h. In the presence
of the running wheel, however, activity was more unimodal and continued all night: for example, in that same individual (540), GA in the presence of the running wheel started ca 1 h before lights off, and continued all night, with a short rest period of 1–2 h toward the end of the night (see Figure 2b).

Tb (individual average) increased as a result of wheel running in 11 of the 12 animals and decreased in one (see Figure 2a). Nevertheless, average Tb did not change significantly between phases, and was 36.3 ± 0.2°C, 36.5 ± 0.2°C, and 36.2 ± 0.2°C in phases 1–3, respectively. We found a significant effect of running in the wheel on Tb when comparing the light and dark phases (p < 0.05, df = 2, F = 4.09). In phase 1, before the introduction of the running wheel, the average Tb during the dark phase was 36.5 ± 0.3°C; this increased to 36.9 ± 0.2°C in phase 2 in the presence of the running wheel (p < 0.01, df = 23.8) and decreased significantly again to 36.5 ± 0.2°C in phase 3 after the wheel was removed (p < 0.05, df = 23.8). Average Tb during the light phase was 36.2°C ± 0.2, 36.1°C ± 0.2, and 35.9°C ± 0.2 in phases 1–3, respectively (NS).

Two individuals decreased their GA at night when the wheel was introduced. Unfortunately, in one of these individuals, the transmitter ceased functioning at this stage. However, in the other individual, the proportion of GA occurring during the dark phase decreased in the presence of the running wheel from 64 to 52%. Tb was higher than average in this animal and did not change during the dark phase (37.0 and 37.1°C, with and without wheels, respectively); however, daytime Tb rose from 36.4 to 36.7°C when the wheel was introduced. When patterns of activity and Tb were reversed after the introduction or removal of the wheel, the change was abrupt, with no evidence of transients.

We used the phase of the peaks of activity rhythms to examine adjustment to shifts of the LD cycle because activity onsets and offsets were not possible to identify (see Figure 3; also see Cohen & Kronfeld-Schor, 2006). When the light cycle was delayed by 6 h, the circadian rhythm of GA re-entrained on average after 5.8 ± 1.8 days; the wheel running rhythm re-entrained on average after 4.5 ± 1.2 days (two-way ANOVA, NS). When lights were advanced by 6 h, the rhythms in GA on average re-entrained after 5.5 ± 1.8 days, and the wheel running rhythm on average re-entrained after 5.6 ± 1.0 days (two-way ANOVA, NS).

All individuals displayed free-running rhythms under DD conditions (see Figure 4). The average period of these rhythms (tau) was 24.1 ± 0.2 h; the distribution of periods of different lengths is depicted in Figure 5. There was no correlation between running distance and circadian tau.

DISCUSSION

All golden spiny mice used the wheel when they had access to it, and most running in it occurred during the dark phase of the LD cycle.
Before the wheel was introduced (phase 1), most animals were active mainly during the night, though variability was high both between and within individuals, as previously described (Cohen & Kronfeld-Schor, 2006). The introduction of the wheel (phase 2) caused an increase in the ratio of nighttime to daytime activity in 10 of the 12 animals. When the wheels were removed (phase 3), that ratio decreased. An inversion in the activity rhythm, as a result of voluntary wheel running, has been previously observed in three rodent species, *Octodon degus* (Kas & Edgar, 1999), *Arvicanthis niloticus* (Blanchong et al., 1999), and *Meriones unguiculatus* (Weinert et al., 2007), and in all cases the change was from a diurnal to a nocturnal pattern of activity (reviewed by Hagenauer & Lee 2008).

**FIGURE 3** A schematic representation of the peaks of activity rhythms as they re-entrained to a 6 h phase delay and a 6 h phase advance of the 12:12 LD cycle in the presence (current experiment) and absence (Cohen & Kronfeld-Schor, 2006) of the running wheel. The experiment of Cohen and Kronfeld-Schor (2006) was shorter; thus, to allow a comparison between experiments, the results for the entrainment to phase delay are separated on a random day during the entrained phase from the results of the phase advance. Re-entrainment to a phase delay was much more rapid in the presence than in the absence of the running wheel.
The effect of wheel running reported here was somewhat similar in that the basic patterns changed (see Figure 2), and the ratio of nighttime-to-daytime activity increased (see Figure 1), but it was different in that the patterns were more nocturnal to start with. Tb of the golden spiny mice also

FIGURE 4 Wheel running activity in two golden spiny mice under DD conditions (normalized). During days 11–15, the RX-900 scanner receiver malfunctioned; therefore, the data for these days are missing.

The distribution of circadian periods (tau) of free-running rhythms of golden spiny mice under DD conditions in the presence (current experiment) and absence (Cohen & Kronfeld-Schor, 2006) of a running wheel. In the presence of the running wheel, the average circadian tau was 24.1 ± 0.2 h, whereas without the running wheel the free-running circadian period was very similar, and significantly shorter (23.7 ± 0.1 h; Cohen & Kronfeld-Schor, 2006).

FIGURE 5 The distribution of circadian periods (tau) of free-running rhythms of golden spiny mice under DD conditions in the presence (current experiment) and absence (Cohen & Kronfeld-Schor, 2006) of a running wheel.
increased during the dark phase when a running wheel was introduced, as has been reported for \textit{Oxotodon degus} (Hagenauer & Lee, 2008; Kas & Edgar, 1999), \textit{Arvicanthis niloticus} (Blanchong et al., 1999), and \textit{Mesocricetus auratus} (Golombek et al., 1993), but there was no change in average Tb during the light phase.

Golden spiny mice are diurnal in most of their natural habitat, including the site where the founders of animals used in this study were captured (Elvert et al., 1999; Haim & Borut, 1976; Kronfeld et al., 1994; Kronfeld-Schor et al., 2001a; Levy et al., 2007; Shkolnik, 1966, 1971). Earlier work has shown that these animals become active primarily at night when they are transferred to the laboratory (Kronfeld-Schor et al., 2001a; Levy et al., 2007), and that they are predominantly nocturnal when bred in captivity (Cohen & Kronfeld-Schor, 2006; Friedman et al., 1997). In the present study, we found that the introduction of a running wheel appeared to strengthen the tendency toward nocturnality in this species.

The robust, clear, and stable activity rhythms observed when running wheels were available may explain the general tendency to use wheels in experiments in which circadian rhythms are monitored (Mrosovsky et al., 1998; Weinert et al., 2007). However, when running wheels are used to monitor rhythms, the possibility that they can change the nature of the variables under investigation needs to be taken into consideration. Effects of wheels on the fundamental characteristics of circadian rhythms have now been seen in a number of species (Blanchong et al., 1999; Golombek et al., 1993; Kas & Edgar, 1999; Weinert et al., 2007). The current data suggest that running wheels also alter some basic characteristics of rhythms in spiny mice, such as the phase relationships between activity rhythms and the LD cycle, both in a steady state and when that cycle is shifted.

Several authors have suggested that changes in activity patterns observed as a result of wheel running in \textit{O. degus} and \textit{A. niloticus} represent changes in some form of masking (Hagenauer & Lee, 2008; Kas & Edgar, 1999; Nixon & Smale, 2004; Redlin & Mrosovsky, 2004). In both of these species, the inversion of the phase preference occurred rapidly following the introduction of a running wheel, without any evidence of the transients that one would expect if the phase angle of entrainment had changed. In the current study, the observed changes also occurred abruptly (in all animals but one; see Figure 2), suggesting the mechanism may indeed involve a masking effect, similar to that reported for \textit{O. degus} and \textit{A. niloticus} (Kas & Edgar, 1999; Nixon & Smale, 2004; Redlin & Mrosovsky, 2004). However, although the rhythms of golden spiny mice here did change immediately following removal of the wheel, they did not revert to their original patterns.

In response to a 6 h phase delay, all animals entrained to the new LD cycle in a relatively uniform way, and within the time frame reported for
other species (e.g., Katona & Smale, 1997; Weinert et al., 2002). The rate of re-entrainment to the delayed LD cycle seen here was similar to that seen previously in this laboratory in golden spiny mice of similar age that did not have access to a running wheel but were otherwise kept in the same conditions (i.e., same season, cages, ambient temperature, light level, and regime, etc.; \(t\)-test, NS; Cohen & Kronfeld-Schor, 2006). However, when the LD cycle was phase advanced, some differences between golden spiny mice of this and the earlier study, in which no wheels were available, became apparent (although it is not possible to exclude the possibility that some other parameter is the cause of the differences, as we did not perform a side-by-side comparison). In the absence of a running wheel, when the LD cycle was phase advanced, four of the 12 individuals responded by delaying their GA and Tb circadian rhythms until they were entrained to the new LD cycle (Cohen & Kronfeld-Schor, 2006). In the current study, no such cases were observed. Moreover, re-entrainment after a phase delay occurred far more rapidly in the presence of the running wheel in this study (5.5 days; see Figure 4) than it did when wheels were not available to animals in the earlier study (15.1 days, \(t\)-test, \(p < 0.001\), df = 14, t-Stat = −5.9; Cohen & Kronfeld-Schor, 2006).

It is important to clarify that in order to determine when re-entrainment was complete, we analyzed (in both studies) the phase of peak, rather than onset of activity in each animal. This parameter can be influenced by the waveform of the rhythm, as well as the phase, of the circadian clock. The presence of a running wheel led to a more condensed active phase with more clear onsets and offsets, and may have also affected the time of peak activity.

In mice, hamsters, and some strains of rats, the circadian tau is shorter in the presence than absence of running wheels (e.g., Edgar et al., 1991; Golombek et al., 1993; Mrosovsky, 1999; Pratt & Goldman, 1986; Yamada et al., 1988), and running distance and tau are inversely correlated (Mrosovsky, 1999). However, in their study involving the effect of locking and unlocking a running wheel on tau in three inbred strains of rats, Kohler and Wollnik (1998) found significant changes of tau only in one strain (LEW rats); in those animals, tau became shorter regardless of the direction of the change (i.e., locking or unlocking of the wheel). The authors of that study concluded that subtle environmental changes can affect tau in a strain-dependent manner, and that increases and decreases in activity level are neither necessary nor sufficient to induce changes in tau (Kohler & Wollnik, 1998). Among degus, the circadian tau was lengthened by the presence of a running wheel, but the effect was the same in the nocturnal Bridge’s Degu (Octodon bridgensi; Ocampo-Garces et al., 2005) as in the diurnal common degu (Octodon degus; Kas, 1999), suggesting that the effect is not related to activity pattern. The current data suggest that the availability of a running wheel has little or no effect on the circadian tau in golden spiny...
mice. Here, in the presence of the running wheel, tau was 24.1 ± 0.2 h, which was similar or even longer than that seen in an earlier study (23.7 ± 2 h) of animals from the same colony, when they did not have access to a running wheel but were otherwise maintained in the same conditions (same season, cages, ambient temperature, light level, regime, etc; t-test, p = 0.01, t = 1.7, df = 20; Cohen & Kronfeld-Schor, 2006, although we cannot exclude the possibility that some other parameter is the cause of the difference, as we did not perform a side-by-side comparison). Moreover, in the current study, we did not find a correlation between running distance and circadian tau as found by Mrosovsky (1999) in hamsters, even though the range in the distances animals ran was high (453–6759 m). Interestingly, while our results indicate that wheel running had little or no direct effect on the circadian tau in golden spiny mice, it did increase the rate at which rhythms adjusted to a phase shift of the LD cycle (i.e., 5.5 days here versus 15 days in earlier study; Cohen & Kronfeld-Schor, 2006).

The reason wheel running has an effect on GA rhythms is currently unclear, but it may be related to its effect on Tb (Hagenauer & Lee, 2008; Kas & Edgar, 1999). It has been suggested that in the high mountains of the Sinai desert golden spiny mice are diurnal because of thermoregulatory challenges (Haim & Borut, 1976). In this area, ambient temperatures may fall below 0°C. In winter, when the mountains are covered with snow, most activity is concentrated during the warmer hours of the early afternoon (Haim & Borut, 1976). Behavioral thermoregulation during the daytime was also observed in the diurnal population of the Judean desert near the Dead Sea. Here, in the winter, golden spiny mice are active during the warmer hours of midday, while they are active in the cooler early morning and late afternoon hours during the summer (Elvert et al., 1999; Kronfeld, 1994; Kronfeld-Schor et al., 2001a; Shkolnik, 1966, 1971). It could be that in the laboratory, the increase in Tb associated with wheel running causes the animals to shift their activity time to what would in nature be the cooler hours of the diel cycle (i.e., the night). A similar explanation for the effect of wheel running on the GA rhythm was suggested for Octodon degus (Hagenauer & Lee, 2008; Kas & Edgar, 1999), which under LD laboratory conditions in a thermal gradient (14–33°C) select cooler ambient temperatures when body temperature increases and vice versa (Refinetti, 1996), and may similarly shift their activity time in the presence of the running wheel to what would, in nature, be the cooler hours of the diel cycle. Another possibility is that activity shifts to the night because of changes in a masking response to light (reviewed by Hagenauer & Lee, 2008). When A. niloticus become night-active, wheel running is suppressed by light (Redlin & Mrosovsky, 2004), as is the case in Meriones unguiculatus (Weinert et al., 2007). Such a change in the masking response may contribute to the night active pattern seen in these animals.
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DECLARATION OF INTEREST

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

REFERENCES


Plasticity of Rhythms in Golden Spiny Mice


