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Comparison of voluntary and foraging running wheel activity on food demand in mice

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Abstract

The effects of running wheel activity on food intake and meal patterns were measured under several cost conditions for food in CD 1 mice. In a first experiment, voluntary wheel running activity increased daily food intake relative to a sedentary group, and runners consumed bigger but fewer meals. Although they ate more, runners had significantly lower body fat than sedentary mice. In a second experiment, running was used as an approach cost and food access was contingent on running wheel activity. Mice were able to emit more wheel revolution responses compared to a condition in which nose poking was the approach response. In both voluntary and foraging running protocols mice had inelastic demand functions compared to the non-running groups. When running was voluntary (experiment 1), the day-night cycle for activity was more pronounced compared to when running was a foraging or approach activity (experiment 2).

Keywords

Mouse; food intake; meal size; foraging; exercise

1. Introduction

Obesity in modern societies is related to the confluence of several factors, two of which are increased availability of palatable high-energy foods and a decrease in physical activity. Elective energy expenditure as physical exercise has been shown to reduce the risks for obesity and obesity-related diseases in animals and humans [1-3].

For rodents many other terrestrial species, locomotor activity is an integral part of foraging to obtain food, or more precisely what we have classified as ‘approach cost’ [4]. This is in contrast to ‘unit price’ which occurs when food is nearby. In rodents housed under standard (sedentary) laboratory conditions, food intake declines as unit price increases. The mathematical function relating intake to price is called a demand function [4-8]. In these studies, price was equated with number of defined behavioral responses required to obtain a unit amount of food. For example, we found that mice emitting nose pokes for food consumed slightly more than those emitting lever presses, but the demand functions were similar in shape [4]. Wheel running has been used as a unit price in mice [9] and hamsters [10].

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While the ‘currency’ of cost is defined by the experimenter, it is not clear how these costs are perceived by the test subject. Thus, emitting responses will entail some increase in metabolic rate (energy cost), an increase in time to obtain food (time cost), and in natural environments for small animals, an increase in risk of predation. Some ecological models of energy balance have attempted to incorporate these elements [11]. Running can be regarded as a natural foraging behavior, and many laboratory rodents spontaneously run large distances when given access to wheels, with a quite low associated energy expenditure (<1 kJ per km) [12,13].

In the first experiment to be reported, we compared the food demand functions of voluntarily running and non-running (sedentary) mice. In the second experiment, we examined the effects of wheel running as an approach cost with concurrent unit price using a lever press response. For comparison, another group had a nose poke as the access response. The question we address is about net energy gain: high levels of activity will cost energy, so the actual net gain per unit of food will be less than at low activity levels. Thus, we examine whether the demand function in running mice is more or less steep (elastic) than in sedentary mice. It could be hypothesized that mice either will run high amounts at high costs to sustain intake (inelastic demand) or they will run less at high costs to conserve energy expenditure (elastic demand).

2. Methods

2.1. Subjects and Housing

A total of 44 naïve male albino (ICR:CD1, Harlan, Indianapolis IN) were used in the protocols. These mice were chosen because they are outbred and have food intake near the middle of a range of several strains of mice [14]. Mice were housed individually in polycarbonate cages with Purina 5001 Chow pellets and tap water available ad libitum for 1-2 weeks between receipt and the start of the experiments. The vivarium was temperature ($23\pm 2^{\circ}\text{C}$) and humidity (40-70%) controlled, with a 12:12 light cycle (lights on 0700). During the experiments, mice lived in test chambers for 23 h per day. The mice were weighed daily and kept in empty holding cages during a 1 h cleaning period without food, although water was available. In the testing phases, mice obtained 20 mg nutritionally-complete pellets (Purina Test Diet 5TUM, a grain-based tablet with 10.4% kcal from fat and 24.1% from protein) when they completed a ratio cost determined by the particular reinforcement schedule that was in effect. All animal use was approved by the Institutional Animal Care and Use Committee.

2.2. General Methods

Sixteen behavior test chambers (Med Associates, St. Albans, VT: 13×13×12 cm), with Plexiglas and alloy walls and stainless steel grill floor, were used in the first experiment. Each was contained within a ventilated, noise attenuating cabinet with the same 12:12 light cycle as the vivarium via a 7 w bulb in a night light fixture run from a 24 h timer. All chambers were equipped with a nose poke device with a small cue light above. The nose poke hole was located approximately 2 cm above the floor and adjacent to a food receptacle. Tap water was supplied freely from sipper tubes mounted on the wall opposite the food receptacle. Eight chambers were additionally fitted with an external running wheel with free wheel resistance of 4–5 g and 55.8 cm outer circumference (Med Associates, St. Albans, VT: ENV-3042; ~1800 revolutions/km) to which the mice had free and voluntary access as described below. An additional 8 chambers were used in the second experiment; these were equipped with both nose poke and lever press (ENV310M; ~2 g force) devices placed symmetrically on either side of the food receptacle.

A record of total pellets obtained and number of responses (nose pokes, lever presses and running wheel revolutions) were collected by MED-PC IV computer software (Med Associates). Revolutions were also recorded by a magnetic counter on the wheel. Data were accumulated in 15 min time bins throughout each 23 h period. Mice were weighed daily.

2.3. Experiment 1: Voluntary Running Wheel Activity and Food Demand

Fifteen mice were divided randomly into two groups, one sedentary (N=8) and the other with access to running wheels (runners, N=7). In order to habituate mice to the operant chambers and to the novel 20-mg pellets, a 1 h training period was applied with free food available in the food receptacle at no cost; during this time, access to the wheel was blocked by a removable panel. Then, for the next 2-4 days and with wheel access still blocked in the runners, one food pellet was delivered contingent upon two nose poke responses. This will be referred to as a fixed unit price 2 (FUP2). Mice were deemed to have learned the contingency when they earned enough pellets over 23 h to maintain their body weight; this typically occurred within 2-4 days. No food deprivation was imposed at any time during the training or experimental periods.

After this training, access to the wheels was allowed for the runner group and all mice were exposed an ascending series of unit price schedules for food with a nose poke operant. FUPs of 2, 5, 10, 25 and 50 responses per pellet were tested contiguously, with 4 days at each cost.

After the last day at FUP50, mice were terminally anesthetized (Sleepaway) and abdominal and inguinal subcutaneous fat pads dissected, combined, and weighed.

2.4. Experiment 2: Running Wheel Activity as Food Foraging

Twenty-nine mice were used in this protocol which was completed in two parts. In the first part, 22 mice were randomly divided in three groups (Ns=7-8). Two experimental groups, run and poke, were tested in a chained schedule of access cost (AC) and FUP. The third group was sedentary with only a low cost (FUP5 nose pokes) for food imposed throughout the protocol. Mice were familiarized with the food and operant tasks for 2-4 days as described in experiment 1, but with FUP5. For the run group, running wheel activity was designated as the AC response and lever press was the FUP response. For the poke group, a nose poke operant was used as the AC response and lever press was the FUP response. For the control group a nose poke was used as the FUP response throughout the study to create minimal effort for these animals [4]; no AC was applied. After initial training, the run group was tested in a series of AC (25, 50, 100, 500, 1000) with a constant FUP5, with each in effect for 4 consecutive days. Based on our previous studies [4,15], a lower range of AC (5, 10, 25, 50, 100) was used in the poke group, again with the same constant FUP5. For run and poke groups, completion of the designated AC caused a cue light above the lever to illuminate, indicating its availability for food responding at the prevailing FUP5. A house light was illuminated concurrently so that animals in the wheels would have a general ambient cue. Mice could take as many pellets as they wished at FUP5. However, when 15 min elapsed for animals in the experimental groups without a response on the lever, a meal was declared finished, the lever was inactivated and the cue and the house lights extinguished. For the controls, a cue light was lit at all times above the nose poke device. Total pellets and responses were recorded every 5 min throughout 23 h sessions.

At the end of the above protocol, a second but otherwise identical batch of runners (N=7) was added to the protocol to increase the sample size. Hour-by-hour running patterns were recorded in this batch (these data were unavailable for the first batch). Data from both run groups were combined for analysis of mean number of pellets, meal size, meal numbers and distance run.

2.5. Data Analysis

Spilled pellets found beneath the cage floor were subtracted from the total earned; in every case spillage was small (typically <5% of the number earned). The temporal record of pellets earned was divided into meals using a criterion of 15 min inter-meal-interval as in our previous reports [4,15,16]. After the numbers of meals per day were determined for each mouse, the mean meal size was derived by dividing the number of total pellets by the number of meals for each day. Running revolutions, meal numbers, meal sizes and the number of pellets consumed did not differ significantly across the 4 days that a given schedule was in force. Thus, to reduce the data for presentation and further statistical analysis, revolutions and meal parameters were averaged across the 4 days to give a single mean value for each mouse at each price (FUP), and group means ($\pm$ SEM) computed from these individual means. Data were examined using a repeated measures analysis of variance (ANOVA; SPSS) with the activity level (sedentary or runner) as a between-subject variable and the cost schedules as a within-subject variable. For experiment 2, operant type (nose poke and running wheel turns) was used as the independent variable. Follow up pairwise comparisons and LSD tests were employed to assess specific differences ($\alpha = 0.05$) where necessary.

Data were also analyzed for hour-by-hour daily running (experiment 2, batch 2) and unit price response (nose poke for experiment 1 and lever press for experiment 2) patterns.

3. Results

3.1. Experiment 1: Voluntary Running Wheel Activity and Food Demand

The number of pellets consumed per day by the sedentary mice declined monotonically as unit price increased while the intake of runner mice was relatively constant across FUP (Figure 1, top panel). Table 1 shows corresponding energy intake, derived using the manufacturer's physiological energy value of 3.3 kcal/g. Two-way ANOVA revealed that food intake differed significantly between the runner and sedentary groups ($p < 0.001$) due in part to a prominent interaction ($p < 0.001$) between unit price and running condition, with less elasticity in runners. Between-group post hoc tests showed that runners ate significantly more than sedentary mice at FUP10, 25 and 50 and less at FUP2 (all $ps < 0.05$). Within-group comparisons showed that sedentary mice decreased their intake at every increase in the unit price (all $ps < 0.05$, Table 1), while runner mice did not change their intake across the entire range of FUPs.

The corresponding meal frequency data are shown in the middle panel of Figure 1. Across the entire range of FUPs, runners took fewer meals than sedentary mice. Thus, two-way ANOVA found a between-group effect ($p < 0.001$). There was also an overall main effect of unit price ($p < 0.01$) with number of meals decreasing as unit price increased, although this is more evident in the sedentary group. Between-group pairwise comparisons showed that runners took fewer meals than sedentary mice at FUP2,5,10 and 25 ($ps < 0.05$).

The corresponding meal size data are shown in the bottom panel of Figure 1. Across the entire range of FUPs, runners ate consistently larger meals than sedentary mice. Thus, two-way ANOVA revealed a between-group effect ($p < 0.001$). There was no main effect of unit price or a group $\times$ price interaction. Between-group pairwise comparisons showed that runners ate larger meals at every FUP ($ps < 0.05$).

All mice in the runner group voluntarily ran substantial amounts in their wheels, usually in excess of 9,000 revolutions or 5 km/day; running wheel activity did not change as a function of the FUP (Table 2, left columns). As required by the FUP schedule, the number of nose poke responses increased with unit price for both sedentary and runner groups ($ps < 0.001$).

These increases were greater in the running group at higher FUPs because they consumed more pellets (cf Figure 1).

The mean body weights during the experiment are shown in Figure 2. Initially, body weights of runner and sedentary groups were identical. As soon as wheels were available, runners lost weight and maintained ~15% lower mean body weight throughout the whole experiment. Thus, body weight differed overall as a function of group ($p<0.001$). Between-group comparisons revealed differences at every FUP. Dissected body fat (Figure 2, insert) at the end of the experiment was ~60% lower in runners than sedentary groups ($p<0.001$).

3.2. Experiment 2: Running Wheel Activity as Food Foraging

The mean number of pellets taken by the control (nose poke, FUP5) group was ~230/day and did not change across the study (dashed lines, Figure 3). The numbers of pellets taken by the run and poke experimental groups as a function of access cost are shown in the top panels of Figure 3, and the corresponding energy intakes are shown in Table 3. Mice in the run group ate consistently more than either the poke or the control groups ($ps<0.001$), and their intake was constant across all AC conditions. The intake of the poke group was steady and slightly less than that of controls at AC costs 5 through 50, but declined markedly at AC100.

The corresponding meal frequency data are shown in the middle panels of Figure 3. Across the entire study, the control group took significantly more meals than either run ($p<0.05$) or poke ($p<0.001$) groups. Mice in the run group took more meals than those in the poke group at each AC ($p<0.05$) except at the highest cost condition (AC1000). The number of meals taken by the poke group declined as AC increased, except for a steep reversal of this trend at AC1000. Due to high within-group variability at AC1000, this increase was not statistically significant.

The corresponding meal size data are shown in the bottom panels of Figure 3. In general, meal size varied reciprocally with meal frequency. Collapsed across the entire study, the control group took smaller meals than either run ($p<0.01$) or poke ($p<0.05$) groups. The run and poke groups had comparable meal sizes throughout the study except at the highest cost. One-way ANOVA showed that there was an effect of AC on meal size ($p<0.001$). In the run group (panel E), meal size was significantly greater at AC500 and 1000 ($p<0.05$) than in controls. In the poke group (panel F), meal size progressively increased from AC5-50, and was significantly greater than control at AC25 and 50. However, at AC100 there was an abrupt reversal of this trend.

The distances covered by the run group at each AC are shown in the right column of Table 2, and the actual revolutions in Table 4. All mice ran substantial amounts, ranging from ~8,000 revolutions (>4 km) per day at the lowest AC(25) to ~11,000 revolutions (>6 km) per day at the highest AC(1000). The distance covered at AC25 was significantly lower ($p<0.05$) than at the higher ACs.

The range of AC response ratios was programmed to be 5-10-fold higher in the run condition compared with the poke condition, so the total number of responses emitted on the AC device was much higher in runners (Table 4; $p<0.001$). The number of AC responses emitted by the poke group was relatively low, and increased significantly only at AC100 (Table 4). Table 4 also indicates the minimum number of AC responses that would have been required to sustain the observed number of meals at each AC cost (*viz.*: mean meal number multiplied by the AC).

Body weight changes are shown in Figure 4. One-way ANOVAs showed that the average body weight was matched at the beginning of the experiment, but differed at every AC change (every 4th day) thereafter ($p < 0.05$). For reasons that are not clear, the control group lost a little weight in the second phase of the study, but thereafter they and the run group maintained or slightly increased body weight. In contrast, the poke group lost weight initially, and maintained that lower weight until a sharp decline during the final highest AC phase of the study.

Figure 5 shows the mean wheel revolutions during each hour in each phase of experiment 2 (panels A-E) and in the voluntary run group of experiment 1 (panel F). In all cases, mice ran more during the dark compared to the light phase. This was most marked at intermediate ACs (panels B-D) when a distinct early night peak of running was observed.

4. Discussion

The present experiments show that mice who are running either voluntarily or in order to gain access to food eat more than sedentary controls and work harder to maintain that higher intake; that is, demand functions of runners are less elastic than sedentary mice. To place these results in the context of the literature, we summarize some key studies in Table 5. Mayer [17] was the first to report on the effects of voluntary exercise on food intake of mice. His aim was to study genetically obese (*ob/ob*) mice, but they did not run, so the data in the table refer to their lean littermates. They sustained a small weight loss (from 26.9 to 25.7 g) during the 21 day study; rodent chow was available at no cost, but food intake was not measured.

The total distance covered by voluntary runners in experiment 1 was similar to Mayer's mice, despite substantially different wheel sizes. The nycthemeral activity ratios (~70% nocturnal) were similar between the two studies. Weight loss was greater (~15%) in our mice than those in Mayer's study, possibly because they had higher initial weights (~50 vs ~25g) and/or because our mice had to emit nose poke responses for food while Mayer's had no such cost. Since intake of our runners did not decline as FUP increased, we believe that the difference in initial weight is the more likely explanation. The difference in dissected fat mass between our sedentary and runner mice was ~4.6 g (derived from data in Figure 2), while their body weight difference was ~7 g. Dissected fat accounts for only a portion of total fat, so we infer that all of the weight loss in the runners was as body fat.

Perrigo & Bronson [9] examined the effect of exercise on food intake in CF-1 female mice studied between weaning and puberty. A voluntary running group had free access to a wheel and to 45 mg food pellets while for controls the wheel was immobilized. Runners ate the same cumulative amount of food as controls over the entire 24 day study, although they ate less than controls early in the study and ~10% more at the end. Runners gained 16% more weight than controls, suggesting that the metabolic cost of voluntary running is low in juvenile mice, and that runners are metabolically more efficient. Direct study of the energy cost of wheel running yield in mice have yielded estimates of <1 kJ/km, or <5% of total energy expenditure [12,13].

Perrigo and Bronson [9] included an additional 5 foraging groups that had to complete 5 different FUPs (60-225 revolutions) to obtain 45 mg food pellets. Both sedentary controls and low FUP runners consumed ~4 g food per day and had comparable body weights (Table 5). This result is similar to our findings in experiment 2 (Figures 3 and 4). However, at the highest FUPs, their mice did not run sufficiently to maintain intake; instead, intake declined and the mice showed linear growth retardation indicating a different mode of energy homeostasis.

Day and Bartness [10] applied a similar protocol in Siberian hamsters. Hamsters that were running voluntarily logged ~3,000 revolutions per day, and showed a small (~10%) but not significant increase in food intake compared with a sedentary (locked wheels) group (Table 5). Other groups were placed on a series of FUPs (10, 50, 100 or 200 revolutions per 75 mg pellet). Hamsters consumed ~40 of these pellets per day, so FUP100 produced a workload only slightly in excess of voluntary running level and intake remained at ~40 pellets. However, at FUP200 intake declined to ~30 pellets per day. Like Perrigo & Bronson's mice, hamsters seem unwilling to increase their running much above baseline levels to sustain intake.

Vaanholt and colleagues [18] found a similar result in male ICR mice. The lowest FUP was determined by measuring the spontaneous running of each mouse, then dividing that by 150 to yield a baseline FUP: the mean was 218 revolutions or ~0.1 km per 45 mg food pellet. Thus, if in the FUP condition mice ran at exactly their spontaneous level, they would have earned 150 pellets (6.8 g). FUP was then increased in a stepwise manner to about twice the baseline value. Compared with sedentary controls, mice running under baseline FUP ate up to 50% more, but as the FUP became higher the animals did not increase running commensurately and so earned fewer pellets. When mice were maintained at 90% of the individual maximum revolutions per day, mice ate only the same as sedentary controls, so lost weight and fat mass. Metabolic measurements in these mice indicated an energy expenditure of ~2 kJ/km, a value which decreased slightly as running increased.

Together, these studies indicate that when food has an inescapable cost, as in the FUP protocol, rodents are willing to run somewhat in excess of voluntary levels but that when levels approach double the baseline animals are unable or unwilling to emit further running and so their intake drops and consequently body fat content declines. At total running levels below this drop-off point, food intake may be modestly increased relative to sedentary animals. Thus, the apparent strategy for energy homeostasis changes depending on activity level and/or body fat content. In the present experiment 1, mice were running voluntarily but were required to emit a nose poke FUP for food. Running did not change markedly across the FUP series and food intake was sustained across a range of nose poke FUPs, including at high values at which intake of sedentary controls declined or showed elasticity. This shows that running mice are willing to work harder for food even when the proximate response for food is not running. It would be of interest to examine the limits of this effect using still higher FUPs.

In FUP protocols, running or any other response is inescapable, as in the studies reviewed above [4-10,15,16]. A different category of foraging response is access cost, and we and others have shown that as AC increases then animals take fewer but larger meals, thereby reducing the number of times the cost has to be paid [4,5,19]. Foraging at a distance from food is most likely to involve running, whereas when food is nearby foraging may be more likely to involve non-running responses such as digging, poking, or gnawing. Thus, in experiment 2 we tested some parameters of running as AC.

From the levels of voluntary running observed in experiment 1, we chose for experiment 2 a range of ACs that would challenge the animal at the higher end of the range. In this protocol, both sedentary and exercising groups had a fixed but relatively low unit price for food (5 lever presses). For sedentary mice, a nose poke was used as the access device. Similar to our previous findings [4] we found that meal frequency declined while meal size increased at AC costs between 5 and 50, while total intake changed only slightly. Unexpectedly, at AC100 mice showed severe ratio strain despite a large increase in the number of nose pokes emitted (Table 4). In previous work [4,5] we used this AC without problem, but those mice may have had more experience with schedules.

Mice with running as AC ran significantly more than was required by schedule (Table 4), especially at the low costs. They ate more than sedentary mice at all costs, and did not show an increase in meal size and decrease in frequency until the two highest ACs. This implies that running as AC was an easy activity for mice and had less effect on their meal parameters than might have been expected. It should be noted that the relative numbers of AC responses was up to 10-fold higher for runners than pokers: although not measured, it seems unlikely that the time per response would be greater for a nose poke than a wheel revolution, in which case the runners would have spent much more time in their access activity than did pokers. Assuming a cost of running in the 1-2 kJ/km range, our mice in Experiments 1 and 2 would have expended an average of 5-12 kJ (1-3 kcal) per day, or <10% of their daily energy intake. From studies reviewed in Table 5, it appears likely that at higher costs animals do not expend above a certain amount of time or energy in running. Vanholt et al [20] reported that the maximum voluntary running speed in mice is ~2 km/h which is considerably higher than the maxima of ~0.6 km/h in the present work (Figure 5). These are hourly averages, so our animals may have paused more than those in a FUP running schedule. These data suggest that our running mice spent a maximum of 3 h/day actually running in the wheels. Thus, higher running ACs will be needed to see whether mice would show dramatic changes in meal frequency to avoid paying high ACs, either in time or energy.

Like Vaanholt [18], we found some shifts in peak activity when running was a foraging rather than a purely voluntary activity (Fig 5). In particular, there was a shift in the peak activity from mostly at night into the daytime, and in particular to the last few hours of the light phase. In both studies, feeding was correlated with the activity (perhaps more loosely in our AC protocol than in Vaanholt's UP procedure), indicating that mice phase advance and lengthen their activity period when foraging is required. It may therefore be of interest to examine whether demand functions in runners or sedentary animals differ as a function of time of day.

In summary, we find that food demand functions in running mice are less elastic than corresponding demand functions in sedentary mice. Comparison with other published studies suggests that this effect may be modulated by initial body fat and/or age. Further, there is a distinct upper limit on the total amount that mice will run, and above that their strategy changes to eat (and run) less and reduce their metabolic mass to achieve energy homeostasis. These effects are achieved in continuous access economies. If the duration of access to food was restricted, a different type of result may pertain, such as in activity based anorexia [21]. There is a need to better define conditions under which exercise increases food demand in contrast to decreasing body mass, both of which may be considered adaptive strategies.

Research Highlights

- Voluntarily running mice increase food intake via meal size
- Compared with sedentary mice, exercisers have an inelastic food demand function
- When running is used as an access cost, mice show high response levels\
- High access costs may shift the circadian peak time of running earlier

5. References

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Fig 1.

A: Mean ($\pm$ SEM) food intake (number of 20 mg pellets) per day as a function of the fixed unit price (FUP) for food in mice that were either sedentary (N=8) or had voluntary access to running wheels (N=7). B: corresponding numbers of meals per day. C: corresponding mean size of each meal. Mice were tested for 4 days at each FUP.

Fig 2.

A: Mean ($\pm$ SEM) body weight of sedentary (N=8) and voluntary running (N=7) mice before the study, at the end of a training period, and at the end of each 4 day block of increasing fixed unit prices (FUP) for food pellets. Inset: Mean $\pm$ SEM dissected body fat, as % body weight, at the end of the FUP50 phase; the groups differ significantly ($p < 0.001$).

Fig 3.

The left panels show data for mice with running as an access cost (AC) for food. The right panels show data for mice with nose poking as AC. The unit price (FUP) for food was a constant 5 lever presses in both groups. The top two panels (A,B) show mean ($\pm$ SEM) daily food intake expressed as number of 20-mg pellets as a function of increasing AC. The middle two panels (C,D) show the corresponding mean meal sizes, and the bottom panels (E,F) the mean meal sizes. The horizontal dashed lines are the mean data from a sedentary control group that had no access cost and a minimal unit price throughout (FUP5, nose poke).

Fig 4.

Mean ($\pm$ SEM) body weight of mice with a food access cost (AC) of either nose poke or wheel running. Each 4 day block corresponds to an incrementing AC condition as specified in Figure 3. The weights shown are for the end of the last day in each AC condition. Shown also are the weights of the FUP5 control group that had no AC.

Fig 5.

Hourly mean ($\pm$ SEM; N=7) running distance (m) of foraging mice. Panels A-E are from experiment 2, in which mice had increasing ACs, with 4 days averaged at each cost. The gray bar indicates the 12 h night period when the chamber light was extinguished. The x-axis refers to hours from the start of each daily session (~5 h before lights out). Panel F shows data from voluntary runners (experiment 1) with no AC.

Table 1

Energy intake (kcal/day) at each FUP schedule in Experiment 1

Cost schedule	Sedentary (n=8)	Runner (n=7)
FUP2	17.8±0.7 ^a	15.3±0.9 ^b
FUP5	15.9±.5 ^b	16.3±.7 ^b
FUP10	14.2±.3 ^c	16.5±.5 ^b
FUP25	11.6±1.2 ^d	15.2±1.0 ^b
FUP50	8.1±1.7 ^e	14.7±1.2 ^b

Note: Shown are means±SEM. Entries with different superscripts are significantly different ($p<0.05$).

Table 2

Running distance (m/day) of mice in experiments 1 and 2 as a function of the cost of food

Experiment 1: Voluntary running		Experiment 2: Access cost running	
FUP2	3910±1163	AC25	4359±643
FUP5	8015±2111	AC50	5337±721
FUP10	6419±1575	AC100	5443±733
FUP25	5764±862	AC500	5478±637
FUP50	6255±1028	AC1000	6287±442

Note: Shown are group mean±SEM for Ns=7 (exp.1) and 15 (exp.2) There were no significant differences as a function of FUP (Experiment 1) or AC (Experiment 2).

Table 3

Energy intake (kcal/day) at each schedule in Experiment 2

Poke AC		Run AC	
AC5FUP5	14.5±0.6	AC25FUP5	18.2±0.5
AC10FUP5	14.7±0.8	AC50FUP5	18.3±0.4
AC25FUP5	13.6±0.8	AC100FUP5	18.0±0.3
AC50FUP5	13.2±0.3	AC500FUP5	16.6±0.6
AC100FUP5	2.9±1.2	AC1000FUP5	17.7±0.2

Note: Shown are group means ±SEM. The intake of the no AC group (FUP5 only) was 15.7±0.5 kcal/day.

Table 4

Mean number of schedule-required vs actual emitted access responses

Runners				
AC	Mean # of meals/day	Required responses	Actual responses	% actual/required
25	10.97 ± 0.55	274	7811 ± 1152	2848
50	11.76 ± 0.55	588	9564 ± 1293	1626
100	11.84 ± 0.60	1184	9754 ± 1314	824
500	9.52 ± 0.62	4760	9817 ± 1141	206
1000	7.83 ± 0.27	7830	11267 ± 731	144

Nose Pokers				
AC	Mean # of meals/day	Required responses	Actual responses	% actual/required
5	9.13 ± 0.90	46	130 ± 19	285
10	8.38 ± 0.97	84	118 ± 17	141
25	6.19 ± 0.94	155	178 ± 38	115
50	5.17 ± 0.61	258	289 ± 30	112
100	9.33 ± 3.64	933	2969 ± 1009	318

Note: Meals/day from data in Fig 3, actual responses from data in Fig 4.

TABLE 5
SELECT LABORATORY RUNNING/FORAGING STUDIES IN SMALL RODENTS

Voluntary running: food cost	Species	Sex/age	Wheel circumf.	Av/max km/day	Body wt change	Food int. vs control	Reference
No cost	C57BL mice	?/4 mo	110 cm	4.8	-4.5 g/3 wk	Not measured	Mayer [17]
No cost	CF1 mice	F; 3-6 wk	53 cm	8.0	+7.0/24 days	110%	Perrigo [9]
No cost	Siberian hamsters	F; 3.5 mo	53 cm	1.7	+1.0g/49 days	110%	Day [10] ^a
No cost	ICR mice	M; 5 wk	45 cm	7.7	n/a	n/a	Vanholt [18] ^b
Unit price – nose poke	ICR mice	M; 3 mo	56 cm	6.0	-7.0g/24 days	115%	This MS; expt. 1

Foraging running: reys/pellet	Species	Sex/age	Wheel circumf.	Av/max km/day	Body wt change	Food int. vs control	Reference
60	CF1 mice	F; 3-6 wk	53 cm	11.1	+1 g/24d	100%	Perrigo [9]
90				12.7	0g/24d	100%	
135				15.9	-1g/24d	100%	
180				15.9	-6g/24d	80%	
225	Siberian hamsters	F; 3.5 mo	53 cm	15.9	-8g/24d	70%	Day [10] ^a
10				2.1	-2g/7 wk	125%	
50				2.0	-1g/7 wk	100%	
100				2.8	0g/7 wk	114%	
200	ICR mice	M; 5wk	45 cm	3.3	-6g/7 wk	85%	Vanholt [18] ^b
Baseline ~200				10.2	0g/24d	149%	
Working ~500				20.2	-6g/24d	93%	
Access cost 25-1000 rev				5.4	+1g/24 d	120%	

^aDay & Bartness [10] also studied food hoarding; data shown here refer only to food consumed

^bVanholt et al [18] studied both unselected and selected runners; data shown here are for unselected.