

MAXIMAL RUNNING SPEEDS OF BIPEDAL AND QUADRUPEDAL RODENTS

MINOU DJAWDAN AND THEODORE GARLAND, JR.

Department of Ecology and Evolutionary Biology, University of California, Irvine, CA 92717
Present address of TG: Department of Zoology, University of Wisconsin, Madison, WI 53706

ABSTRACT.—Maximal running speeds of both bipedal (*Dipodomys*, *Microdipodops*) and quadrupedal (*Chaetodipus*, *Perognathus*) heteromyid rodents, and some sympatric nocturnal cricetids and diurnal sciurids, were measured in the laboratory (17 species, 131 individuals) and in the field (eight species, 138 individuals). We found significant, repeatable differences among individuals within species. Significant differences also were found among species: *Perognathus longimembris* (8.9 g, 9.9 km/h) and *Onychomys torridus* (19.3 g, 10.3 km/h) were relatively slow; *Microdipodops megacephalus* (12.3 g, 10.9 km/h) and *Peromyscus crinitus* (13.7 g, 11.4 km/h) were somewhat faster; *Chaetodipus baileyi* (39.1 g, 12.4 km/h), *Perognathus parvus* (24.4 g, 12.5 km/h), *Chaetodipus fallax* (18.0 g, 12.8 km/h), *Peromyscus eremicus* (19.8 g, 13.1 km/h), and *Peromyscus maniculatus* (18.2 g, 13.4 km/h) attained similar speeds; *Peromyscus truei* (19.3 g, 14.3 km/h) was faster still; *Neotoma lepida* (110.6 g, 17.1 km/h) and three squirrel species were the fastest tested in the laboratory. Kangaroo rats (*Dipodomys*) did not exert themselves maximally in the laboratory, but attained speeds significantly higher than pocket mice (*Chaetodipus*, *Perognathus*) or other sympatric rodents in the field. In addition, *Dipodomys* displayed erratic escape behavior (zig-zagging) when pursued in the field significantly more frequently than *Chaetodipus* or *Perognathus*. Higher sprint speeds and erratic escape behavior may allow kangaroo rats to escape from some predators (e.g., raptors, canids), and hence exploit open microhabitats (of presumed higher predation risk) to a greater extent than slower sympatric rodents.

Direct measures of organismal performance perhaps are the most appropriate starting point for attempting to integrate physiological and ecological approaches to the study of adaptation (Arnold, 1983; Huey and Stevenson, 1979). Motivated by this perspective, a number of workers have studied locomotion, because various aspects of locomotor performance (e.g., speed and stamina) are thought to be important determinants of the success of animals in such natural activities as foraging and escaping from predators (Garland, in press; Huey and Hertz, 1984). Although reptilian locomotion has been the subject of several studies (Bennett, 1980; Garland, 1984, 1985, in press, 1988; John-Alder et al., 1986; van Berkum et al., 1986), direct measures of mammalian locomotor performance are rare (Garland, 1983a; Layne and Benton, 1954). Most recent physiological studies of mammalian locomotion focused on energetic costs (MacMillen, 1983; Taylor et al., 1982; Thompson, 1985).

One notable feature of mammalian locomotion is bipedality, which evolved independently several times (e.g., primates, macropod marsupials, members of five families of rodents). Neither the selective regimes prevailing during the origin of bipedality nor the ecological conditions favoring the maintenance of bipedality are well understood (Bartholomew and Cary, 1954; Bartholomew and Caswell, 1951; Eisenberg, 1975; Howell, 1944; Mares, 1980, 1983; Nikolai and Bramble, 1983). Bipedals and quadrupeds do not show differences in energetic costs of locomotion (Garland, 1983b; MacMillen, 1983; Taylor et al., 1982; Thompson, 1985). However, several authors suggested that bipedal and quadrupedal small mammals may differ in other aspects of locomotor performance, such as acceleration, speed, and stamina (Bartholomew and Caswell, 1951; Eisenberg, 1975; Garland, 1983a; MacMillen, 1983). These putative differences have been suggested to play a role in determining the relative abilities of different species to forage or to escape from predators (Rosenzweig, 1973; Rosenzweig and Winakur, 1969; Thompson, 1982a, 1982b).

Limited observations suggest that bipedal kangaroo rats (Heteromyidae) may be faster than quadrupedal mammals of similar size (Garland, 1983a; Kenagy, 1973). However, there are no data available for maximal running speeds of quadrupedal heteromyids, or for any other small

rodents that occur sympatrically with kangaroo rats. We, therefore, measured maximal running speeds of both bipedal and quadrupedal heteromyids and several other rodent species that occur with them.

MATERIALS AND METHODS

Rodents were trapped January–August 1985, in Sherman live traps at four locations in California: 1) mixed Joshua tree (*Yucca brevifolia*) woodland and creosote bush (*Larrea tridentata*) scrub, 3.3 km S Joshua Tree, San Bernardino Co.; 2) Quail Springs Wash, a boulder-strewn hillside 4 km S Joshua Tree, San Bernardino Co.; 3) Dale Dry Lake, a creosote bush and sand-dune habitat 38 km E 29 Palms, San Bernardino Co.; 4) Benton Valley, a Great Basin sage brush (*Artemisia tridentata*) community 6.4 km N Benton, Mono Co. These sites were chosen because they provided syntopic bipedal and quadrupedal species of different size, and because previous ecological studies had been conducted at each site (Thompson, 1980, 1982a, 1982b, 1985 for sites 1 and 3; Eidemiller, 1982 for site 2; Day, 1981 for site 3; Lawhon, 1984 for site 4). *Chaetodipus baileyi* was collected for us by Scott Osborne at sites 10–30 km N Tucson, Pima Co., Arizona (site 5).

Laboratory and field timing.—Maximal running speeds were obtained by timing animals as they were chased along a microprocessor-controlled, photocell-timed racetrack (Garland, 1985; Hucy and Hertz, 1984). Timing of all species began within 3 days of capture, with exception of *C. baileyi*, for which testing began within 4–21 days of capture. The track was 8 m long by 25 cm wide, with plywood walls 60 cm high. Twelve sets of six vertically-aligned photocells were placed at 10–50 cm intervals over the first 4 m of the track. Artificial grass carpet was used as floor covering to provide good traction for the animals. A darkened cardboard refuge was placed at the end of the runway, toward which the rodents ran.

To familiarize animals with the track, each individual was chased slowly back and forth along the track a few times before timing. During timed runs, rodents were chased down the track with a padded meterstick, then walked slowly back to the beginning. For each individual, five to 15 timed trials were recorded until no increase in speed occurred with subsequent trials. Various methods of making noise, including rattling pieces of cardboard and plastic bags against the track walls, clapping of the hands, and yelling also were used to prompt animals to run. Each animal was tested for 2 or 3 consecutive days. For each timed run, the fastest 1.0-m interval (≥ 3 consecutive photocells) was recorded. Preliminary tests indicated that animals tested at night were not significantly faster than those tested during the day; subsequently, all trials were conducted during the day.

For field trials, clearings were selected at collecting sites 1, 3, and 4. Distances of 3, 7, and 11 m were measured from a center point in the clearing and marked with half-circles of spray paint. Animals were livetrapped at night and taken to the clearing early the next morning. Individuals were shaken out of traps, allowed to sit for a few seconds, then startled by dropping the trap immediately behind them. Rodents then were chased by one of us, and they usually ran toward the largest bush at the edge of the clearing. They were timed with hand-held, digital stopwatches to the nearest 0.01 s as they crossed the marked distances. Distances other than between the marked half-circles were measured to the nearest 0.1 m immediately following each trial. For each trial we also noted whether rodents ran in a zig-zag pattern, in a straight line, or in a gentle arc. When animals did not run in a straight line, paths run were estimated from memory and measured with a tape measure; these distances were used for calculations of speed. Three or four people timed each run, and average speeds were used in the analyses. Laboratory simulations (using a tennis ball rolled at various speeds over marked distances of ≥ 4 m) indicated that our field times are reliable within about 10% (Belkin, 1961).

Statistical analyses.—To compare maximal running speeds among species in the laboratory, we conducted one-way analysis of variance using SPSS^x (SPSS Inc., 1985). For these comparisons, we used only the single fastest speed recorded for each individual (Garland, 1985). Data were \log_{10} transformed before analysis to achieve homogeneity of variances among species. We employed Scheffé's procedure because this is the most conservative multiple-range comparison for unequal sample sizes (Neter and Wasserman, 1974; Nie et al., 1975). Statistical significance was judged at $P < 0.05$ in all cases.

For laboratory data, we also sought to determine if maximal running speeds of individuals within species differ significantly and if maximal running speeds change following extended periods of captivity. We conducted two-way analysis of variance for each species, using each individual's single fastest speed on each trial day (Sokal and Rohlf, 1981). We report intraclass correlation coefficients (r_i = proportion of variance among individuals) as a measure of repeatability (Lessells and Boag, 1987; Sokal and Rohlf, 1981). For species that showed significant differences in speed between trial days, the mean square between trial days was excluded before computation of among-individual components of variance (r_i).

TABLE 1.—Maximal running speeds of rodents measured in the laboratory.

Family and species	n		Body mass (g)			Speed (km/h)	
	♂	♀	$\bar{X} \pm SD$	Range	Fastest individual	$\bar{X} \pm SD$	Range
Cricetidae							
<i>Neotoma lepida</i>	4	6	110.6 ± 24.4	81.3–160.1	105.2	17.1 ± 1.3	14.9–19.2
<i>Onychomys torridus</i>	3	2	19.3 ± 3.2	16.0–24.5	16.0	10.3 ± 0.7	9.3–11.0
<i>Peromyscus crinitus</i>	8	6	13.7 ± 1.6	11.1–16.3	16.3	11.4 ± 0.8	9.9–12.5
<i>Peromyscus eremicus</i>	4	3	19.8 ± 3.1	15.4–24.6	18.6	13.1 ± 1.1	11.2–14.2
<i>Peromyscus maniculatus</i>	6	6	18.2 ± 3.2	12.0–23.0	22.7	13.4 ± 1.2	11.1–15.9
<i>Peromyscus truei</i>	1	1	19.3 ± 2.1	17.8–20.8	17.8	14.3 ± 0.2	14.2–14.4
Heteromyidae							
<i>Chaetodipus baileyi</i>	9 ^a		39.1 ± 5.9	27.7–46.4	39.7	12.4 ± 1.4	10.8–14.9
<i>Chaetodipus fallax</i>	9	3	18.0 ± 2.2	15.0–21.6	16.0	12.8 ± 0.9	11.4–14.2
<i>Dipodomys deserti</i>	4	1	97.6 ± 24.0	73.3–133.3	73.3	15.0 ± 2.5	12.0–18.3
<i>Dipodomys merriami</i>	4	5	35.7 ± 4.7	28.0–44.0	32.0	11.4 ± 1.2	10.1–14.0
<i>Dipodomys ordii</i>	4	3	47.8 ± 7.1	34.0–55.5	50.0	14.1 ± 0.9	12.7–15.3
<i>Microdipodops megacephalus</i>	5	3	12.3 ± 1.6	10.0–15.0	11.0	10.9 ± 1.6	9.4–14.2
<i>Microdipodops megacephalus</i> (pregnant)		3	13.5 ± 0.5	13.0–14.0	13.5	9.9 ± 0.9	9.0–10.9
<i>Perognathus longimembris</i>	7	6	8.9 ± 0.6	8.0–10.0	8.6	9.9 ± 0.7	8.7–11.7
<i>Perognathus parvus</i>	5	4	24.4 ± 2.3	21.0–29.0	26.0	12.5 ± 1.6	10.4–14.6
Sciuridae							
<i>Ammospermophilus leucurus</i>		2 ^a	75.9 ± 0.4	75.7–76.2	76.2	17.2 ± 2.1	15.7–18.7
<i>Eutamias minimus</i>	2	1	29.3 ± 1.2	28.0–30.0	28.0	16.8 ± 0.8	15.9–17.4
<i>Spermophilus tereticaudus</i>		1	112.6			15.2	

^a Sex unknown.

RESULTS

Laboratory speeds: interspecific and individual differences.—A total of 17 species and 131 individual rodents was timed in the laboratory (Table 1). All species appeared to run at maximal speeds, with exception of kangaroo rats, which consistently refused to run at top speed in the racetrack (compared to previous studies and our field trials). Even a mild electric shock failed to elicit maximal performance from *Dipodomys* in the laboratory. Prior familiarization with the racetrack, for several hours or over night, also failed to improve their performance.

Species differed significantly in \log_{10} maximal running speeds ($F = 29.0$; $d.f. = 9, 89$; $P < 0.0001$). Scheffe's procedure indicates homogeneous subsets, in order of increasing speed, as follows: (*Perognathus longimembris* = *Onychomys torridus* = *Microdipodops megacephalus* = *Peromyscus crinitus*) ≤ (*M. megacephalus* = *P. crinitus* = *Chaetodipus baileyi* = *Perognathus parvus* = *C. fallax*) ≤ (*P. crinitus* = *C. baileyi* = *P. parvus* = *C. fallax* = *Peromyscus eremicus* = *Peromyscus maniculatus*) < *Neotoma lepida*. Kangaroo rats were omitted from the analysis of variance because their laboratory speeds were not considered maximal. We also omitted *Peromyscus truei* and the sciurids from the analysis of variance because of small sample sizes. At least two of the three sciurids are approximately as fast as *Neotoma* (Table 1).

Considering only the heteromyids, there also was significant heterogeneity in \log_{10} maximal speeds ($F = 13.8$; $d.f. = 4, 46$; $P < 0.0001$). Homogeneous subsets were: (*P. longimembris* = *M. megacephalus*) ≤ (*M. megacephalus* = *C. baileyi* = *P. parvus*) ≤ (*C. baileyi* = *P. parvus* = *C. fallax*). Considering only cricetids, heterogeneity also was significant ($F = 49.7$; $d.f. = 4$,

TABLE 2.—Maximal running speeds of rodents timed in the field.

Species	Tested (n)	Zig- zagged (n)	Actually timed (n)	Speed (km/h)	
				$\bar{X} \pm SD$	Range
<i>Dipodomys deserti</i>	39	22	35	18.3 \pm 3.0	13.9–29.9
<i>Dipodomys merriami</i>	76	15	67	14.8 \pm 3.1	9.5–25.8
<i>Dipodomys panamintinus</i>	4	1	4	13.4 \pm 0.9	11.7–14.2
<i>Chaetodipus fallax</i>	11		9	11.4 \pm 2.3	6.9–15.0
<i>Perognathus longimembris</i>	19	2	15	9.9 \pm 1.5	7.7–13.7
<i>Perognathus parvus</i>	1		1	12.2	
<i>Microdipodops megacephalus</i>	4		2	9.9 \pm 0.8	9.3–10.4

43; $P < 0.0001$), with the following homogeneous subsets: (*O. torridus* = *P. crinitus*) < (*P. eremicus* = *P. maniculatus*) < *N. lepida*.

Within most species, individuals showed consistent and statistically significant differences in speed. Two-way analyses of variance demonstrated significant among-individual components of variance for *C. baileyi* (run 3 days, $n = 9$, $F = 7.00$, $P = 0.001$, $r_i = 0.67$), *C. fallax* (run 2 days, $n = 12$, $F = 5.96$, $P < 0.005$, $r_i = 0.73$), *M. megacephalus* (run 2 days, $n = 11$, $F = 8.19$, $P < 0.0001$, $r_i = 0.79$), *P. parvus* (run 2 days, $n = 9$, $F = 3.65$, $P < 0.05$, $r_i = 0.60$), *P. eremicus* (run 3 days, $n = 7$, $F = 4.92$, $P = 0.009$, $r_i = 0.57$), and *P. maniculatus* (run 3 days, $n = 12$, $F = 11.63$, $P < 0.0001$, $r_i = 0.77$). For *N. lepida* (run 3 days), *P. longimembris* (run 2 days), and *P. crinitus* (run 2 days), among-individual components of variance in speed were not significant.

Speed and body mass were not correlated significantly within any species.

Four species showed significant increases in speed from day 1 to day 2 (*C. baileyi*, +12.0%; *N. lepida*, +15.8%; *P. crinitus*, +14.7%; *P. eremicus*, +17.0%). These differences in speed were adjusted for in the calculations of r_i . No species showed a significant increase in speed from day 2 to day 3.

Nine individuals of *C. fallax* were maintained in captivity in plastic cages (27.5 by 20 by 15 cm) with wire tops and tested on days of captivity 1–6, 15, 16, 29, 30, 71, 72, 180, and 181. Among-individual components of variance were significant ($F = 8.38$; $d.f. = 8, 104$; $P < 0.0001$; $r_i = 0.35$) across all 14 trial days; however, mean running speed was not consistent across all 14 trial days ($F = 6.94$; $d.f. = 13, 104$; $P < 0.0001$). Two-way analyses of variance of various combinations of trial days indicated that speed did not vary significantly over days 1–6, dropped 13.4% between days 6 ($\bar{X} \pm SD$ of speed = 11.8 \pm 1.28 km/h) and 15 (10.2 \pm 1.97 km/h), then showed no further change. Four *P. maniculatus* individuals maintained in captivity and tested on days 1–6, 15, 16, 29, 30, 71, and 72 showed significant among-individual components of variance across all 12 trial days ($F = 5.04$; $d.f. = 3, 33$; $P < 0.01$; $r_i = 0.28$), but no significant change in speed ($F = 0.59$; $d.f. = 11, 33$; $P = 0.827$).

Field trials.—We tested eight species and 160 individuals in the field; of these, speeds were obtained for 138 individuals (Table 2). *Dipodomys* species attained higher speeds than *Chaetodipus* or *Perognathus* in the field. Considering the two *Dipodomys*, one *Chaetodipus*, and one *Perognathus* species with adequate sample sizes, there was significant heterogeneity in maximal running speeds ($F = 44.2$; $d.f. = 3, 122$; $P < 0.0001$). Homogeneous subsets were: (*P. longimembris* = *C. fallax*) < *D. merriami* < *D. deserti*.

We also compared laboratory and field speeds for these four species using *t*-tests for independent samples. We used \log_{10} -transformed data and separate variance estimates because field data were significantly more variable than laboratory data (except for *D. deserti*). Laboratory (Table 1) and field speeds (Table 2) did not differ significantly for either *P. longimembris* or *C. fallax*, however, field speeds of *D. merriami* ($t = 5.74$; $d.f. = 18.43$; $P < 0.001$) and *D. deserti* ($t = 2.69$; $d.f. = 38$; $P = 0.010$) were significantly higher than laboratory speeds. These results agree with our subjective impressions that *Dipodomys* did not run at maximal speed in our laboratory racetrack.

Kangaroo rats zig-zagged during field runs significantly more frequently than pocket mice.

Generally, changes of direction occurred with each 1–2 m hop. Thirty-eight of 119 kangaroo rats (but only two of 33 pocket mice) zig-zagged (Table 2; G test with Yate's correction for continuity = 4.60; *d.f.* = 1; *P* < 0.05).

To compare kangaroo rats and other bipeds with quadrupeds, we have compiled fastest speeds ever reported (Garland, 1983a) for rodents smaller than 200 g (Fig. 1). *Dipodomys* species appear to be faster than any other rodents of similar or smaller size for which data are available.

DISCUSSION

Speeds that we measured in the laboratory are as high or higher than those reported previously in the literature for *Eutamias minimus*, *P. maniculatus*, and *Notomys cervinus* (Garland, 1983a). Highest field speeds for our *D. merriami* (25.8 km/h) and *D. deserti* (29.9 km/h) are higher than values reported by Thompson (1985) for these two species (22.21 km/h and 26.66 km/h, respectively) during spontaneous activity in the field. This comparison suggests that speeds we measured may be maximal or near maximal. Conversely, the "mean maximal speed" reported by G. J. Kenagy (1973; pers. comm.) for *D. merriami* in the field is 32 km/h, considerably higher than the single highest speed we observed for this species in the field. Kenagy (1973) ran *Dipodomys* in the same fashion as we did, except that some of his animals were released on runways familiar to the animals. Thus, differences in running speed may be caused by the greater familiarity of his kangaroo rats with the area of release, differences in substrate, or interpopulation differences in sprint speed. Interpopulation differences in sprint speed exist in lizards (R. B. Huey, pers. comm.).

Available data suggest that the generally larger kangaroo rats are faster than the smaller coexisting pocket mice. Both mode of locomotion and body size can affect locomotor performance (Garland, 1983a, 1985). Thus, we cannot determine whether the higher maximal running speeds of kangaroo rats are related to greater body size, bipedality, or both factors. *D. merriami* is faster than the similarly sized *C. baileyi*. However, the bipedal *M. megacephalus* is no faster than similarly sized quadrupedal *Chaetodipus* or *Perognathus*. Some much larger (225–500 g) diurnal squirrels not sympatric with kangaroo rats are the only rodents reported to attain speeds greater than *Dipodomys* (Garland, 1983a, G. J. Kenagy, pers. comm.). Other bipedal species (*Notomys alexis*, *N. cervinus*, *M. megacephalus*) do not exhibit exceptional maximal running speeds, nor do the zopodid rodents (Fig. 1) which possess somewhat enlarged hind limbs but are not truly bipedal (Nikolai and Bramble, 1983).

Many investigators have shown that kangaroo rats are trapped in open microhabitats more frequently than are sympatric, quadrupedal pocket mice (Garland and Bradley, 1983; Nikolai and Bramble, 1983; Rosenzweig and Winakur, 1969; Thompson, 1982a, 1982b). Regardless of why they occur in open microhabitats more frequently (for example, whether or not they actually forage there), kangaroo rats probably face a higher risk of predation per unit while in open microhabitats than when near or under shrubs (Clarke, 1983; Kotler, 1985; Mares, 1983). From an ecological perspective, it may not matter whether kangaroo rats are relatively fast because of bipedality or body size, but only that they are faster than sympatric nocturnal rodents. Absolute speed, not speed relative to body size, should be important for escaping from predators.

The erratic avoidance behavior (Bartholomew and Caswell, 1951; Humphries and Driver, 1970) and apparently higher maximal running speeds of kangaroo rats (as compared with sympatric rodents) may enhance their ability to escape from predators, therefore their ability to use open microhabitats. Slower species or those without erratic predator-escape behavior may be constrained from using open microhabitats because of high risks of predation. Conversely, it is possible that the locomotor patterns of quadrupedal heteromyids are in some way more effective for escaping from predators or for foraging in and near bushes (for example, quadrupeds might possess better climbing abilities). It would be of interest to compare maximal acceleration of small bipeds and quadrupeds, because acceleration also may be a critical determinant of predator-escape abilities (Huey and Hertz, 1984).

Microdipodops is bipedal, yet not fast for its size. Whether this genus fits the foregoing scenario

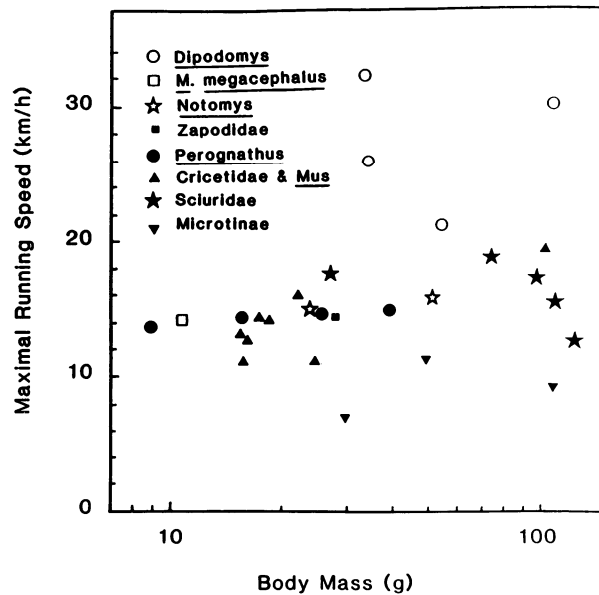


FIG. 1.—Maximal running speeds of 28 species of rodents (*D. merriami* represented twice) with adult body mass <200 g. Open symbols are bipeds, closed symbols are quadrupeds. Data are from this study (Tables 1 and 2), Biewener (1983; *Spermophilus tridecemlineatus*), Garland (1983a; *Mesocricetus brandti*, *Microtus pennsylvanicus*, *Mus musculus*, *Peromyscus leucopus*, *Pitymys pinetorum*, and *Tamias striatus*); speeds for two species of zapodid rodents were excluded because they do not appear to be maximal, Kenagy (1973; *D. merriami*, *D. microps*), and Garland et al. (1988; racetrack methods identical to those used herein; *Notomys alexis*, *N. cervinus*, *Zapus trinotatus*).

is unclear, because data on its microhabitat use are few. Lawhon (1984) found that *M. megacephalus*, like *Perognathus*, foraged under bushes at a study site where *Dipodomys* species were relatively abundant. However, at another study site with abundant *Perognathus* species, *Microdipodops* behaved like *Dipodomys* and foraged more in the open. Harris (1984) found that *M. megacephalus* foraged more in the open than *P. maniculatus*.

Individual differences in maximal sprint speed are known to be genetically based in fence lizards (*Sceloporus*; van Berkum and Tsuji, 1987) and garter snakes (*Thamnophis*; Garland, 1988). We do not know if the individual differences we have demonstrated herein are genetically based or result from "natural training" (Garland et al., 1987). It also is unknown whether individual differences in sprint speed have physiological or morphological correlates, as they do in lizards (Garland, 1984, 1985; T. T. Gleeson and J. M. Harrison, pers. comm.), and we have yet to test for repeatability of individual differences over long periods of time in the field (Huey and Dunham, 1987). Given the relative ease with which capture-recapture studies can be conducted for many species of small rodents (Garland and Bradley, 1983; Kenagy, 1973), it should be possible for future researchers to investigate ecological correlates and selective consequences of individual differences in sprint speed in rodents.

ACKNOWLEDGMENTS

We thank Karen Calloway, Debra Lawhon, Steve Jennings, Dick MacMillen, Alan Newsome, Carol Williams, Mike Winter, and Keith and Carol Justice for assistance in the field; the Justices also kindly allowed us to use their field facilities at Joshua Tree. Special thanks go to Scott Osborne, who kindly provided us with *Chaetodipus baileyi* from Arizona. Drs. A. F. Bennett, B. P. Kotler, R. E. MacMillen, H. B. Shaffer, S. D. Thompson, and several anonymous reviewers reviewed and improved earlier drafts of the manuscript. Financial support was provided by the Theodore Roosevelt Foundation of the American Museum of Natural

History, the Department of Ecology and Evolutionary Biology, and The U. C. White Mountain Research Station summer fund.

LITERATURE CITED

- ARNOLD, S. J. 1983. Morphology, performance and fitness. *Amer. Zool.*, 23:347-361.
- BARTHOLOMEW, G. A., AND G. R. CARY. 1954. Locomotion in pocket mice. *J. Mamm.*, 35:386-392.
- BARTHOLOMEW, G. A., AND H. H. CASWELL. 1951. Locomotion in kangaroo rats and its adaptive significance. *J. Mamm.*, 32:155-169.
- BELKIN, D. A. 1961. The running speeds of the lizards *Dipsosaurus dorsalis* and *Callisaurus draconoides*. *Copeia*, 1961:223-224.
- BENNETT, A. F. 1980. The thermal dependence of lizard behavior. *Anim. Behav.*, 28:752-762.
- BIEWENER, A. A. 1983. Locomotory stresses in the limb bones of two small mammals: the ground squirrel and chipmunk. *J. Exp. Biol.*, 103:131-154.
- CLARKE, J. A. 1983. Moonlight's influence on predator/prey interactions between short-eared owls (*Asio flammeus*) and deermice (*Peromyscus maniculatus*). *Behav. Ecol. Sociobiol.*, 13:205-209.
- DAY, L. P. 1981. Coexisting kangaroo rats: population parameters, behavior, and diet in *Dipodomys merriami* and *Dipodomys deserti*. Unpubl. Ph.D. dissert., Univ. California, Irvine, 175 pp.
- EIDEMILLER, B. J. 1982. Omnivory: its role in the ecology of desert cricetine rodents. Unpubl. Ph.D. dissert., Univ. California, Irvine, 145 pp.
- EISENBERG, J. F. 1975. The behavior patterns of desert rodents. Pp. 189-221, in *Rodents in desert environments* (I. Parkash and P. K. Ghosh, eds.). *Monogr. Biol.*, W. Junk, The Hague, The Netherlands, 624 pp.
- GARLAND, T., JR. 1983a. The relation between maximal running speed and body mass in terrestrial mammals. *J. Zool.*, 199:157-170.
- . 1983b. Scaling the ecological cost of transport to body mass in terrestrial mammals. *Amer. Nat.*, 121:571-587.
- . 1984. Physiological correlates of locomotor performance in a lizard: an allometric approach. *Amer. J. Physiol.*, 247:R806-R815.
- . 1985. Ontogenetic and individual variation in size, shape and speed in the Australian agamid lizard *Amphibolurus nuchalis*. *J. Zool.*, 207:425-439.
- . In press. Locomotor performance and activity metabolism of *Cnemidophorus tigris* in relation to natural behavior. In *Biology of Cnemidophorus* (J. Wright, ed.). Los Angeles Co. Mus. Los Angeles, California, and Univ. Washington Press., Seattle, Washington.
- . 1988. Genetic basis of activity metabolism. I. Inheritance of speed, stamina, and antipredator displays in the garter snake *Thamnophis sirtalis*. *Evolution* 42:335-350.
- GARLAND, T., JR., AND W. G. BRADLEY. 1983. Effects of a highway on Mojave desert rodent populations. *Amer. Midland Nat.*, 111:47-56.
- GARLAND, T., JR., P. L. ELSE, A. J. HULBERT, AND P. TAP. 1987. Effects of endurance training and captivity on activity metabolism of lizards. *Amer. J. Physiol.*, 252:R450-R456.
- GARLAND, T., JR., F. GEISER, AND R. V. BAUDINETTE. 1988. Comparative locomotor performance of marsupial and placental mammals. *J. Zool.* 215:505-533.
- HARRIS, J. H. 1984. An experimental analysis of desert rodent foraging ecology. *Ecology*, 65:1579-1584.
- HOWELL, A. B. 1944. Speed in animals, their specialization for running and leaping. Univ. Chicago Press, Chicago, 270 pp.
- HUEY, R. B., AND A. E. DUNHAM. 1987. Repeatability of locomotor performance in natural populations of the lizard *Sceloporus merriami*. *Evolution* 41:1116-1120.
- HUEY, R. B., AND P. E. HERTZ. 1984. Effects of body size and slope on acceleration of a lizard (*Stellio stellio*). *J. Exp. Biol.*, 110:113-123.
- HUEY, R. B., AND R. D. STEVENSON. 1979. Integrating thermal physiology and ecology of ectotherms: a discussion of approaches. *Amer. Zool.*, 19:357-366.
- HUMPHRIES, D. A., AND P. M. DRIVER. 1970. Protean defence by prey animals. *Oecologia*, 5:285-302.
- JOHN-ALDER, H. B., T. GARLAND, JR., AND A. F. BENNETT. 1986. Locomotory capacities, oxygen consumption, and the cost of locomotion of the shingle-back lizard (*Trachydosaurus rugosus*). *Physiol. Zool.*, 59:523-531.
- KENAGY, G. J. 1973. Daily and seasonal patterns of activity and energetics in a heteromyid rodent community. *Ecology*, 54:1201-1219.
- KOTLER, B. P. 1985. Owl predation on desert rodents which differ in morphology and behavior. *J. Mamm.*, 66:824-828.
- LAWHON, D. K. 1984. Spatial and temporal patterns of *Microdipodops megacephalus* in two California rodent communities. Unpubl. M.S. thesis, Univ. California, Irvine, 85 pp.
- LAYNE, J. N., AND A. H. BENTON. 1954. Some speeds of small mammals. *J. Mamm.*, 35:103-104.
- LESSELLS, C. M., AND P. T. BOAG. 1987. Unrepeatable repeatabilities: a common mistake. *Auk*, 104:116-120.
- MACMILLEN, R. E. 1983. Biology of desert rodents. *Great Basin Nat. Mem.*, 7:65-75.
- MARES, M. A. 1980. Convergent evolution among desert rodents: a global perspective. *Bull. Carnegie Mus. Nat. Hist.*, 16:1-51.
- . 1983. Desert rodent adaptation and community structure. *Great Basin Nat. Mem.*, 7:30-43.
- NETER, J., AND N. WASSERMAN. 1974. Applied linear statistical models. Richard D. Irwin, Inc., Homewood, Illinois, 842 pp.
- NIE, N. H. ET AL. 1975. Statistical package for the social sciences. Second ed. McGraw-Hill Book Co., New York, 675 pp.

- NIKOLAI, J. C., AND D. M. BRAMBLE. 1983. Morphological structure and function of desert heteromyid rodents. *Great Basin Nat. Mem.*, 7:44-64.
- ROSENZWEIG, M. L. 1973. Habitat selection experiments with a pair of coexisting heteromyid rodent species. *Ecology*, 54:111-117.
- ROSENZWEIG, M. L., AND J. WINAKUR. 1969. Population ecology of desert communities: habitats and environmental complexity. *Ecology*, 50:558-572.
- SOKAL, R. R., AND F. J. ROHLF. 1981. *Biometry*. W. H. Freeman and Co., San Francisco, 859 pp.
- SPSS, INC. 1985. *SPSS^X users guide*. Second ed. McGraw-Hill Book Co., New York, 988 pp.
- TAYLOR, C. R., N. HEGLUND, AND G. M. O. MALOY. 1982. Energetics and mechanics of terrestrial locomotion. I. Metabolic energy consumption as a function of speed and body size in birds and mammals. *J. Exp. Biol.*, 97:1-21.
- THOMPSON, S. D. 1980. Microhabitat use, foraging behavior, energetics and community structure of heteromyid rodents. Unpubl. Ph.D. dissert., Univ. California, Irvine, 156 pp.
- . 1982a. Microhabitat utilization and foraging behavior of bipedal and quadrupedal heteromyid rodents. *Ecology*, 63:1303-1312.
- . 1982b. Structure and species composition of desert heteromyid rodent species assemblages: effects of a simple habitat manipulation. *Ecology*, 63:1313-1321.
- . 1985. Bipedal hopping and seed-dispersion selection by heteromyid rodents: the role of locomotion energetics. *Ecology*, 66:220-229.
- VAN BERKUM, F. H., R. B. HUEY, AND B. A. ADAMS. 1986. Physiological consequences of thermoregulation in a tropical lizard (*Ameiva festiva*). *Physiol. Zool.*, 59:464-472.
- VAN BERKUM, F. H., AND J. S. TSUJI. 1987. Interfamilial differences in sprint speed of hatchling *Sceloporus occidentalis* (Reptilia: Iguanidae). *J. Zool.*, 212:511-519.

Submitted 8 July 1987. Accepted 9 December 1987.