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Review

Peromyscus as a model system for understanding the regulation of maternal behavior

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ABSTRACT

The genus *Peromyscus* has been used as a model system for understanding maternal behavior because of the diversity of reproductive strategies within this genus. This review will describe the ecological factors that determine litter size and litter quality in polygynous species such as *Peromyscus leucopus* and *Peromyscus maniculatus*. We will also outline the physiological and social factors regulating maternal care in *Peromyscus californicus*, a monogamous and biparental species. Because biparental care is relatively rare in mammals, most research in *P. californicus* has focused on understanding the biology of paternal care while less research has focused on understanding maternal care. As a result, the social, sensory, and hormonal cues used to coordinate parental care between male and female *P. californicus* have been relatively well-studied. However, less is known about the physiology of maternal care in *P. californicus* and in other *Peromyscus* species. The diversity of the genus *Peromyscus* provides the potential for future research to continue to examine how variation in social systems has shaped the mechanisms that underlie maternal care.

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1. Introduction

The genus *Peromyscus* contains more than 50 species of mice and has been used as a model system for understanding social behavior [1,2]. However, most research related to maternal behavior has focused on five species: *Peromyscus californicus*, *Peromyscus eremicus, Peromyscus leucopus*, *Peromyscus maniculatus*, and *Peromyscus polionotus*. These five species represent a wide spectrum of mating and other social behaviors with variation in their mating systems being attributed to differences in female density, spacing, and other environmental factors [3,4]. Tendencies toward monogamy and paternal care have generally been observed in *Peromyscus*, although males of the commonly studied species, *P. leucopus* and *P. maniculatus,* lean more strongly toward polygyny. In contrast, *P. eremicus, P. polionotus,* and *P. californicus* possess many of the physiological characteristics that are associated with monogamy [4]. Field studies using DNA fingerprinting verified that *P. californicus,* in contrast to many other monogamous animals, is not only socially monogamous, but is genetically monogamous [5].

This diversity in mating systems among *Peromyscus* species has been associated with considerable variation in the amount of time and energy that females devote to parental care. Some polygynous species such as *P. maniculatus* rely on females to provide all of the care for large litters of small pups, and few of these pups survive until weaning age. In r-selected species such as these polygynous species of *Peromyscus,* organisms possess physiological traits that maximize an individual's reproductive output and encourage a rapid population growth rate (r). In K-selected species, population size is more stable and remains at or near its carrying capacity (K) because organisms tend to produce fewer, high-quality offspring. Monogamous species of *Peromyscus* tend to exhibit features of K-selected species, including smaller litter sizes with high pup survival due to extensive biparental care [4]. Cooperative care of young by multiple generations has also been identified in certain *Peromyscus* species. In *P. polionotus,* females often provide assistance to their mothers in caring for their younger siblings. Females who have had the opportunity to practice caring for young before raising their first litter show a higher quality of care toward their own pups; these females spend more time building nests and their offspring are more likely to survive [6].

Regardless of the mating system, parental care in *Peromyscus* provides thermoregulatory, energetic, and other benefits that increase pup survival [*e.g.* [7–11]]. The frequency of specific forms of parental behavior (*e.g.* pup retrievals) also shapes hormone levels in pups during development and influences the adult phenotype of offspring [12–16]. This review will address the social, ecological, and physiological factors that underlie variation in maternal care in the most extensively studied *Peromyscus* species.

2. Ecology of maternal behavior

Because of large variations in maternal life history, the genus *Peromyscus* has been used as a model system for understanding how ecology shapes maternal behavior. Large-scale field studies in *P. leucopus* and *P. maniculatus* determined that maternal characteristics interact with the ecology of a female's home range or territory to determine pup survival. Maternal size, age, and parity all contribute to the number of offspring produced by a female and to the likelihood that these offspring will survive until adulthood.

2.1. Maternal body size and litter size

A robust relationship between maternal size and litter size exists in *P. leucopus* and *P. maniculatus*. One complication for identifying the effect of female body size on litter size is that measurements of female size are often inconsistent between observers [17]. In addition, the size of the pregnancy itself may confound the measurements. For example, a female carrying a large litter of pups may be measured as being much larger than a female carrying a smaller litter [18]. Despite these methodological issues, several studies have demonstrated that as a female *P. leucopus* ages, she grows larger and produces more pups in each subsequent litter until senescence [17,19]. As a result, seasonal variation in litter sizes in *P. leucopus* often results from seasonal variation in the age-related sizes of breeding females [19]. Mathematical models that take into account the decline in fertility when female *P. leucopus* approach senescence tend to show age-related increases in litter size [19,20]. Populations with no age-related increases in fertility (such as [21]) tend to have very high mortality and/or have not been analyzed using quadratic regression or other statistics to account for declining fertility at senescence.

The pattern of increased litter size from the onset of breeding until senescence, however, does not hold for all *Peromyscus* species. A comparative study of litter size in five *Peromyscus* species found that although litter size decreased in older females from all five species, litter size did not consistently increase with age in younger females from other *Peromyscus* species [4]. Therefore, results from using *P. leucopus* as a model system for understanding age-related increases in litter size in young mice may not be generalizable to all other *Peromyscus* species.

2.2. Environmental conditions underlying age-related changes in litter size and composition

Although the physiological mechanisms regulating age-related changes in reproduction in *Peromyscus* are not well understood, nutrient deficiencies in females may prevent very young and very old females from reproducing. Young female *P. leucopus and P. maniculatus* cannot reproduce when protein is scarce in the environment [22–24]. Older female *P. leucopus* that suffer from calcium deprivation do not completely cease reproduction, but show skeletal changes related to bone loss and tend to produce smaller litters that are biased toward female offspring [25,26].

Under harsh environmental conditions, sex ratios of *Peromyscus* litters tend to shift from being male-biased toward being female-biased, providing further support for the idea that nutritional deficiencies may underlie changes in litter size and offspring sex ratio at senescence [22,27]. Sex allocation theory suggests that in times of hardship, a female can increase her reproductive success by producing more daughters than sons [28]. Although most females find mates, low-quality males are less likely to be chosen by highly selective females. A high degree of resource competition, which may lead to nutrient depletion, also shifts the sex ratio of a litter in a female-biased direction in *P. maniculatus* [29]. *Peromyscus* with smaller litter sizes appear less likely to show any alterations in litter sex ratios. Female *Peromyscus mexicanus* typically produce only three pups per litter and show no evidence of shifting sex ratios even with food supplementation [30]. Although the physiological mechanisms used for prenatal sex allocation have yet to be identified in *Peromyscus*, studies in other mammals have identified a role for maternal hormones. In other mammals, females undergoing stressful situations and other females with elevated glucocorticoid levels tend to produce more female offspring, whereas dominant females and other females with higher testosterone tend to produce more male offspring (reviewed in [31]). Females in species of *Peromyscus* that have larger litter sizes may have the capacity to use similar endocrine mechanisms to increase their fitness by manipulating offspring sex ratios.