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Persistent effects of maternal parasitic infection on offspring fitness: implications for adaptive reproductive strategies when parasitized

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Summary

1. Maternal effects on offspring phenotype may represent adaptive strategies to optimize maternal or offspring fitness given the maternal environment. The effect of maternal parasitic infection on offspring phenotype has been largely ignored, despite the potential for such effects to be components of a maternal reproductive strategy. In addition, the persistence and fitness consequences of maternal effects are understudied, particularly with respect to research on maternal parasitic infection.

2. Deer mice (*Peromyscus maniculatus*) increase reproductive output by weaning heavier offspring when infected with a schistosome parasite (*Schistosomatium douthitti*). Here, I examine the persistence of maternal effects on offspring phenotype and evaluate potential consequences of maternal parasitic infection for offspring lifetime fitness.

3. Offspring of parasitized females are born heavier, and this mass advantage persists in sons until adulthood. Because adult body mass is known to influence adult reproductive success in deer mice, parasitized mothers would have produced sons of higher reproductive success.

4. Neither maternal infection nor offspring mass influenced adult son aggression. Survival was enhanced for heavier offspring post-weaning.

5. The production of heavier offspring by parasitized females, therefore, led to increased offspring fitness through enhanced survival and potentially reproductive success. The resultant increase in current maternal reproductive success in response to possible infection-induced decreases in future reproductive opportunities supports the hypothesis that infected females trade-off between current and future reproduction.

Key-words: fecundity compensation, phenotypic plasticity, rodent, terminal investment, trematode

Introduction

Maternal effects describe changes to offspring phenotype due to non-genetic maternal attributes (e.g. diet, propagule size), and can include impacts on offspring gender, development, size, behaviour, and viability (Roach & Wulff 1987; Deeming & Ferguson 1991; Mousseau & Dingle 1991; Bernardo 1996; Mousseau & Fox 1998a). Maternal effects are important for population ecology because they can impact offspring life-histories and population demography (Räsänen & Kruuk 2007). The translation of maternal phenotype or environment to offspring phenotype may be associated with costs and constraints and may be non-adaptive (e.g. Clark & Galef 1995; Uller 2003; Uller *et al*. 2004). However, it may also be an adaptive component of maternal reproduction (Mousseau & Fox 1998b; Marshall & Uller 2007). For example, females of poor condition may provide each offspring with less provision, producing offspring of reduced size or viability while maximizing maternal fitness (e.g. Shine & Downes 1999; McAdam & Boutin 2003; Gagliano & McCormick 2006). Alternatively, maternal effects may maximize offspring and maternal fitness by matching offspring phenotype to maternal or environmental conditions (Charnov 1982; Sorci & Clobert 1995; Heeb *et al.* 1998; Shine & Downes 1999; Kristan 2002, 2004). In order to understand the significance of maternal effects, the persistence of these effects and their fitness consequences for mothers and offspring must be determined.

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Variation in maternal condition frequently leads to variation in offspring size, sex, behaviour, or performance (e.g. Hewison & Gaillard 1999; Shine & Downes 1999; McAdam & Boutin 2003; Gagliano & McCormick 2006). An emerging area of research into condition-dependent reproductive strategies examines the ways in which parasitic infection and immunocompetence influence reproductive patterns (Forbes 1993; Sheldon & Verhulst 1996; Richner 1998; Agnew, Koella & Michalakis 2000; Zuk & Stoehr 2002; Stoehr & Kokko 2006). Parasites are known to have extensive direct impacts on host phenotypes, including physiology, behaviour and life-history (e.g. Schall, Bennett & Putnem 1982; Holmes & Zohar 1990; Kristan 2002; Schwanz 2006a; Lehmer *et al*. 2007; Schwanz 2008). However, the indirect effects of parasites on offspring phenotype (i.e. maternal effects) have been poorly studied, despite their potential to be important components of an adaptive host response (Sorci & Clobert 1995; Heeb *et al*. 1998; Kristan 2002, 2004; Poulin & Thomas 2008).

In the deer mouse (*Peromyscus maniculatus*), infection with the blood fluke *Schistosomatium douthitti* (Trematoda) is chronic and leads to reduced liver function and altered thermoregulation (Schwanz 2006a, 2008). In addition, exposure to high doses of the parasite reduces host survival. In response to parasitism, female deer mice alter their reproductive investment, producing heavier offspring at weaning, although an equal number of offspring per litter (Schwanz 2008). An increase in reproductive investment in response to a chronic infection that reduces survival may be a facultative reproductive strategy of infected females to compensate for reduced future reproductive opportunities (i.e. terminal investment or fecundity compensation, Minchella & LoVerde 1981; Clutton-Brock 1984; Schwanz 2006b). Under this hypothesis, increased investment in current reproduction must lead to an increase in current reproductive success. Therefore, for the deer mouse – *S. douthitti* system, producing heavier offspring should increase the fitness of offspring, thus increasing current maternal reproductive success, presumably at the expense of maternal survival or future reproduction (Millar, Derrickson & Sharpe 1992; Millar 1994; Schwanz 2008). It is important to note that *S. douthitti* is an indirect parasite, requiring an intermediate host (freshwater snail) to complete its life cycle (Price 1931; Malek 1977). Therefore, infected mice cannot pass infection to offspring and any effects of maternal parasitism on offspring phenotype are indirect.

Here, I examine potential adaptive explanations for maternal effects in this system. Because infected females produce heavier offspring, I first determine whether the increased investment in offspring occurs during gestation or during lactation in order to gain insight into the nature of the maternal effect. I then explore how offspring mass influences offspring fitness by examining: (i) how mass affects survival throughout the life-history stages of offspring; and (ii) whether mass differences at weaning are maintained until adulthood. Adult mass in deer mice is known to influence female fecundity and male territoriality and fertility, so maternal effects on offspring adult mass would influence offspring reproductive success (Fairbairn 1977, 1978; Dewsbury 1979; Millar 1983; Myers & Master 1983; Schwanz 2008). If production of offspring of a greater size is an adaptive reproductive strategy by infected mothers to increase current reproductive success, I predict that heavier offspring will have greater survival or that they will remain heavier in adulthood, where this mass advantage will translate to reproductive benefits. In addition, I examine whether maternal parasitism has indirect effects on offspring survival and behaviour independent of mass effects. Finally, male aggression is examined and is predicted to increase with body mass (Fairbairn 1978; Dewsbury 1979).

Methods

EXPERIMENTAL DESIGN

Adult deer mice (*P. maniculatus rufinus*) were 5th–9th generation laboratory-reared animals from New Mexico (Botten, Ricci & Hjelle 2001). Mice were maintained in standard rodent cages on a 12 : 12 light:dark cycle and provided food (Formulab Diet 5008) and water *ad libitum* (Schwanz 2006a, 2008). The experiment was initiated with infection or sham-infection of females with *S. douthitti.* Details on the parasite life cycle and the infection procedure can be found in Schwanz (2006a, 2008). Briefly, the aquatic stage of the parasite life cycle that is infective to rodents (cercaria) was collected from patent snails (snails that are shedding parasites) under a dissecting microscope and fed to the experimental mice. Use of a dissecting microscope allowed approximate counts of the parasites fed to each mouse. Fifty-one virgin, mature female mice (70–159 days old) were divided into three treatments. Mice in the low dose (LD) treatment ($N = 20$) received 30–50 parasites, those in the high dose (HD) treatment ($N = 10$) received 100–150 parasites, and those in the control treatment ($N = 21$) were sham-infected by providing uncontaminated water to the mice.

At 30 days after infection (DAI), when eggs typically begin being released from the host, females were randomly paired with uninfected, mature males (100–346 days old). Pairs were housed together continuously for 150 days, during which time all breeding events were recorded (see below). For pairs that bred, first litters were typically born 30–60 days after pairing (*c.* 60–90 DAI), and post-partum estrus was typical (Schwanz 2008). At 180 DAI, females were euthanized with CO_2 and dissected to confirm infection status via examination of liver homogenate for *S. douthitti* eggs or larvae (see Schwanz 2006a). Parasite load was not estimated. Final sample sizes of number of offspring by female treatment were determined by confirmation of maternal treatment status and the rate of reproduction of pairs (12 control, 11 LD and 3 HD females produced at least one litter; Schwanz 2008).

OFFSPRING GROWTH MEASUREMENTS

The experiment was conducted in 2004 (control and LD treatments) and 2005 (all treatments). Maternal mass was measured weekly following pairing. Cages were checked daily (for pregnant females, based on weekly mass gain) or every other day (for other females) for the presence of new litters. In 2005 only, offspring and parental mass were recorded on the day of birth and every three days thereafter until weaning (20–22 days after birth, normal age of independence, Millar & Innes 1983; Millar & Threadgill 1987). During lactation, offspring were individually-marked with unique numbers of bands

on their tails, drawn with a marker. This marking only persisted following day 3, so individual identity was established from day 3. At weaning for both years of study, offspring were given numbered, metal ear tags (National Band and Tag Company, Newport, KY, model 1005–1), and their mass and sex was recorded. Offspring were then removed from the natal cage and maintained in a cage until 45-days-old in one of two ways: (i) with only littermates (Isolated), or (ii) with a mixture of littermate and non-littermate offspring within ±2 days of age (Mixed). Cages contained both sexes and two to six offspring. The mixed caging was intended to more-closely resemble natural competitive environments that offspring would encounter in the wild. During this time, isolated and mixed cages were not provided with rodent chow, but were given scattered, mixed seed that was limited in quantity. One to two handfuls of seed were provided every other day, depending on the number of offspring per cage, and whether leftover seed was visible in the cage. This amount of food was, therefore, a variable percentage of each mouse's daily requirement. Offspring grew during this stage (see results), suggesting that the diet did not represent a substantial dietary restriction. Because offspring of the different treatments were mixed together in cages, the variability of the seed diet was unlikely to introduce artificial treatment effects.

At day 45 (43–47 days), the typical age of sexual maturation (Millar & Threadgill 1987), offspring body mass was recorded again. A subset of offspring was maintained and weighed at day 90 (85–97 days), when body mass plateaus for deer mice (Linzey 1970; Millar 1983). Between 45 and 90 days, male mice were housed alone or with male littermates to minimize agonistic interactions. Females were housed with other female littermates or non-littermates (up to six mice per cage). Daily growth rates were calculated for each offspring for three stages: (i) lactation (day 3–day 21), (ii) juvenile (day 21–day 45), and (iii) adult (day 45–day 90). Daily growth values were calculated as (*mass at the end of the period – mass at the beginning of the period*)/(*days between two measurements*).

BEHAVIOUR TRIALS

Agonistic behaviour trials were performed in the dark during the active phase of the deer mouse daily cycle (21:00–24:00 h). Each trial paired a son of a control female and a son of an infected female (LD only; all males were adults, ≥ 90 days old). Males were weighed prior to the trial and marked on their tail with a black pen for visual identification. Males were then placed into a circular arena (*c.* 19-L bucket, 28-cm diameter) on separate sides of an opaque partition. Following a 5-min acclimatization period, the partition was removed and the arena was recorded for 20 min using the Nightshot Plus feature on a Sony camcorder (CCD-TRV328 Hi8 NTSC Handycam, Sony Electronics Inc.). No humans were present during the trial. Each male was used only once in a behaviour trial. Tail markings and side of acclimatization were randomized with respect to maternal treatment.

Recordings of trials were scored for standard deer mouse behaviours, including acts of aggression (wrestling on top, lunging, boxing, rearing) and submission (wrestling on bottom, retreat; Eisenberg 1968). Dominance scores were calculated for each mouse as the proportion of scored behaviours that were aggressive (lunging) rather than submissive (retreating from boxes or lunges). Dominance in each trial was decided separately for (i) dominance scores (dominant mouse had at least twice the dominance score) and (ii) wrestling bouts (dominant mouse was on top during a wrestle for at least twice as many wrestling bouts as the submissive mouse). A mouse was declared as the winner of the trial if he was more dominant in both dominance measures, or if he had higher dominance according to one measure while the other measure was unclear or provided insufficient data.

DATA ANALYSIS

Previous analysis of the reproductive data from this experiment (Schwanz 2008) indicated that the two infection treatments (LD and HD) did not differ significantly from each other in reproductive variables (litter size, offspring size at weaning, etc), so they are combined here for statistical analysis into a single 'infected' treatment group. Because few mice reared more than four litters and for the sake of clear comparison to previous analyses (Schwanz 2008), only offspring from the first four litters (parities) were included in statistical analysis. Offspring mass during lactation (days 3–21) and the juvenile stage (days 45–90) were analysed for treatment effects using a repeated measures, nested ANCOVA with parental pair of each offspring as a factor nested within treatment. Offspring identity, nested within parental pair and treatment, was entered in the models as a random effect to account for repeated measures across individual offspring. Offspring mass at day 0 and offspring growth rates were examined for treatment differences with a nested ANCOVA. One control litter (three offspring) was excluded from all lactation analyses because the offspring were not weighed during lactation. Other predictors entered into the ANCOVA models included sex (factor), litter size (covariate), maternal parity (order of litter; factor), offspring age (covariate), caging (isolated or mixed; factor), parity × treatment, sex × treatment and age × treatment. Because sex was unknown at birth and individual identity was not established until day 3, sex was not available as a predictor of birth mass. Predictors (other than treatment) with $P > 0{\cdot}15$ were unlikely to provide any predictive ability and were removed from the model.

Survival during lactation was assessed using only 2005 data because litter sizes at birth are uncertain for 2004. A χ^2-test was used to analyse maternal treatment effects on survival mice from day 0 to weaning. Logistic regression was used to test for effects of maternal treatment and offspring body mass (mass at the beginning of the time interval) on survival during the following intervals: days 3–21, 21–45 and 45–90. For post-weaning intervals, offspring caging and sex were included as predictors. Parental pair, nested within treatment, was included in logistic models to account for parental effects.

For behaviour trials, competitiveness of sons from mothers of the different treatments was examined using χ^2-analyses. Percent mass difference of 'infected' sons and 'control' sons [100 × (*mass of 'infected' son – mass of 'control' son*)/*mass of lighter son*] was also used as a predictor of the likelihood of an 'infected' son winning a trial (logistic regression). All statistics were performed with JMP version 6·0. Significance was assessed at $P = 0{\cdot}05$, while $0{\cdot}05 < P < 0{\cdot}10$ was considered as statistical trend.

Results

MASS

At birth, offspring from infected mothers were significantly heavier than offspring of control mothers, and mass was negatively correlated with litter size (Nested ANCOVA, with birth litter size: treatment $P = 0{\cdot}004$, pair (treatment) $P < 0{\cdot}0001$, birth litter size $P < 0{\cdot}0001$; or with weaned litter size: treatment $P < 0{\cdot}0001$, pair (treatment) $P < 0{\cdot}0001$, litter size $P < 0{\cdot}0001$; $N_{obs} = 103$). Mass during lactation (days 3–21) remained

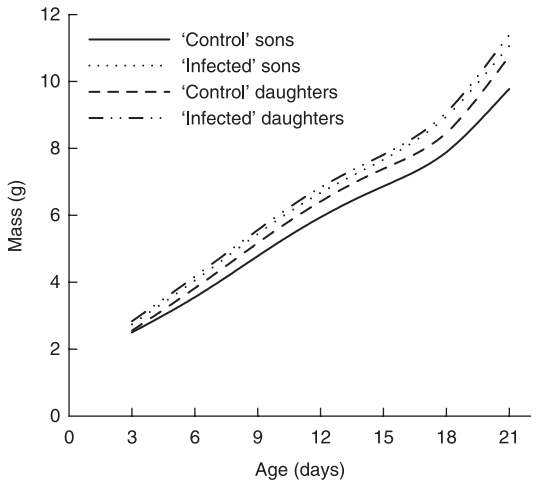

Fig. 1. Average body mass during lactation of male and female offspring from control and infected mothers (days 3–21, averaged across all parities). Sample sizes are as follows: 'infected' sons (35), 'infected' daughters (30), 'control' sons (18), and 'control' daughters (25).

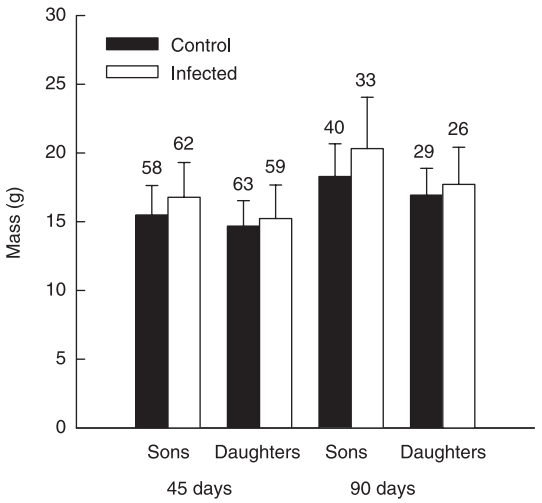

Fig. 2. Average body mass of male and female offspring from control and infected mothers at sexual maturity (45 days) and asymptotic adult mass (90 days). Error bars are 1 SD. Numbers above bars are offspring sample sizes.

significantly greater for offspring of infected females compared to those of uninfected females (Fig. 1, Table 1). Offspring sex did not influence offspring mass during lactation, but parity had a significant effect (LS means ± SE, parity 1: 6·8 ± 0·1; parity 2: 5·9 ± 0·1; parity 3: 6·0 ± 0·2; parity 4: 6·4 ± 0·2).

Individual offspring mass at sexual maturity (45 days) was correlated with mass at weaning ($N = 240$, $r^2 = 0{\cdot}338$, $P < 0{\cdot}0001$). The mass of offspring at 90 days was correlated with mass at maturity ($N = 126$, $r^2 = 0{\cdot}321$, $P < 0{\cdot}0001$) and at weaning ($N = 127$, $r^2 = 0{\cdot}382$, $P < 0{\cdot}0001$). Females and offspring from larger litters were at a size disadvantage in adulthood (Table 1). Average adult mass of male and female offspring combined did not differ significantly between maternal treatments, although a statistical trend was apparent (Fig. 2, Table 1). However, based on the nearly-significant sex × treatment interaction, *post hoc* Tukey HSD tests were evaluated (significance was assessed by JMP at $\alpha = 0{\cdot}05$) and revealed that adult sons of infected females remained larger than sons of control females ($P < 0{\cdot}05$), but no treatment effects on the mass of daughters persisted in adulthood ($P > 0{\cdot}05$).

Table 1. Nested, repeated measures ANCOVA models reporting the effect of predictors on mass of offspring during lactation (2005 only) and in adulthood

Model	d.f.	d.f. denom	*F*	*P*
Lactation mass, days 3–21 $N_{obs} = 757$				
Maternal treatment	1	88·07	6·66	0·0115
Pair (treatment)	12	88·09	15·06	< 0·0001
Parity	3	89·08	8·44	< 0·0001
Parity × Treatment	3	89·2	7·25	0·0002
Litter size	1	87·63	29·31	< 0·0001
Offspring age	1	648·2	11 660	< 0·0001
Offspring age × Treatment	1	648·2	22·90	< 0·0001
Adult mass, days 45–90 $N_{obs} = 370$				
Maternal treatment	1	225·2	3·19	0·0752
Pair (treatment)	23	221	2·74	< 0·0001
LS	1	220·2	17·76	< 0·0001
Offspring age	1	171·5	203·27	< 0·0001
Offspring age × Treatment	1	171·1	3·43	0·0656
Sex	1	218·6	29·03	< 0·0001
Sex × Treatment	1	218·5	3·82	0·0519

Offspring ID, nested in pair and treatment was entered as a random effect to account for repeated measures. Caging was not used as a predictor of mass during lactation because the caging effect was only established after weaning. Predictors were removed from the model if $P > 0{\cdot}15$.

GROWTH

Growth from day 3 until weaning did not differ between treatments (Table 2). Growth during lactation was negatively related to litter size, varied according to parity (LS means ± SE, parity 1: 0·51 ± 0·01; parity 2: 0·39 ± 0·01; parity 3: 0·39 ± 0·01; parity 4: 0·43 ± 0·02), but was not related to offspring sex. From weaning until sexual maturity, juvenile daily growth rate was higher for males than females, but was not related to maternal infection treatment (Table 2). Daily adult growth rate (days 45–90) was greater for male offspring than female offspring, but did not differ according to maternal treatment (Table 2).

SURVIVAL

From day 0 to weaning, survival of offspring of control mothers (66·2%, 43 of 65) and of infected mothers (61·3%, 65 or 106) did not differ significantly ($\chi^2 = 0{\cdot}41$, $P = 0{\cdot}52$). Most mortality for control offspring occurred during the first 3 days (only four offspring died after day 3), whereas 28 of 41

Table 2. Results (*P*-values of predictors) of nested ANCOVA models examining daily growth rates of offspring during lactation (2005 only), juvenile and adult stages

	Lactation daily growth rate, 3–21 days	Juvenile daily growth rate, 21–45 days	Adult daily growth rate, 45–90 days
N_{obs}	108	240	127
N_{pairs} (control, infected)	5, 9	11, 14	11, 12
Maternal treatment	0·170	0·229	0·279
Pair (treatment)	< 0·0001	< 0·0001	0·0002
Sex	–	< 0·0001	0·009
Sex × Treatment	–	0·031	–
Litter size	< 0·0001	–	0·082
Parity	< 0·0001	–	–
Parity × Treatment	0·0002	–	–
Juvenile caging	NA	–	–

Caging was not used as a predictor of lactation growth rate because the caging effect was only established after weaning. Predictors were removed from the model if $P > 0{\cdot}15$.

Table 3. Influence of predictors (*P*-values) on offspring survival during lactation (2005 only), juvenile and adult intervals

	Lactation survival, days 3–21	Juvenile survival, days 21–45	Adult survival, days 45–90
Pair (treatment)	< 0·0001	0·481	0·013
Maternal treatment	0·995	0·998	0·995
Offspring mass (direction of effect)	0·780	0·022 (+)	0.265
Sex [Female (F) vs. Male (M)]	–	0·941	0·014 (F < M)
Caging [Isolated (I) vs. Mixed (M)]	–	0·094 (I > M)	0·039 (I > M)

Offspring mass at the beginning of each interval was used as the covariate. Caging and sex were not entered as factors in the model of lactation survival because caging treatments had not been established by weaning, and sex was not known for offspring that did not survive lactation.

offspring of infected mothers that did not survive until weaning, died after day 3. Survival from day 3 until weaning (when individual identity can be tracked) was not influenced by maternal infection or offspring mass (Table 3).

Survival of offspring after weaning was high in the laboratory. Only 7 of 249 offspring suffered mortality between days 21 and 45, and juvenile survival was positively influenced by offspring mass at day 21 (Table 3). Of the 154 offspring maintained from days 45 to 90, 26 died. Survival from maturation until 90-days-old was not influenced by offspring mass when offspring sex was taken into account. Adult survival was reduced for offspring that were housed in mixed cages during the juvenile phase.

BEHAVIOUR TRIALS

In 22 of 26 behaviour trials, winners could be assigned. Three of the remaining trials yielded insufficient behavioural data, while one trial had conflicting results from wrestling and dominance scores and was declared undecided. Sons of parasitized mothers were not more or less likely to win a trial when considering all trials (14 of 22 won, $\chi^2 = 1{\cdot}59$, $P = 0{\cdot}21$) or only trials with a percent mass difference of ≤ 10% (7 of 10 won, $\chi^2 = 1{\cdot}51$, $P = 0{\cdot}22$). Lighter males won 73% of fights, but effects of offspring mass on outcome of fights was not significant ($N = 22$, $P = 0{\cdot}07$; Fig. 3).

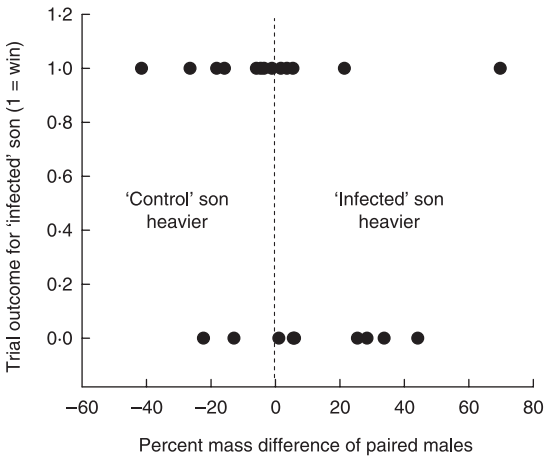

Fig. 3. Wins (= 1) and losses (= 0) of behavioural trials by sons of infected females when paired with sons of control females. The percent mass difference between males in each trial was calculated as [100 × ('infected' son's mass – 'control' son's mass)/lighter male's mass].

Discussion

Maternal effects are widespread in animals and may represent adaptive strategies to increase maternal fitness (Mousseau & Fox 1998b; Marshall & Uller 2007). Effects of maternal parasitic infection on offspring phenotype may have

consequences for offspring and maternal fitness and may be part of an adaptive plastic response by parasitized females to ameliorate the fitness costs of parasitism. Despite this potential importance for maternal effects in disease ecology, we know little about the persistence of these maternal effects, or the consequences for multiple components of offspring and maternal fitness (Sorci & Clobert 1995; Heeb *et al*. 1998; Kristan 2002, 2004; Poulin & Thomas 2008).

INDIRECT EFFECTS OF PARASITIC INFECTION

In the deer mouse, maternal parasitic infection with *S. douthitti* had lasting effects on offspring mass. Infected mothers birthed and weaned offspring of greater mass, and produced larger adult sons. The persistence of mass effects was reflected by equivalent daily growth rates. Smaller offspring did not show compensatory growth following weaning, as is often observed in rodents (Sikes 1998; Oksanen, Koskela & Mappes 2002). Only two previous studies in rodents have demonstrated a positive effect of maternal infection on offspring size (Kristan 2002, 2004).

Producing offspring of greater mass had many fitness benefits for the offspring through improved reproductive success and survival. In deer mice, greater mass in females often leads to greater fecundity (Millar 1983; Myers & Master 1983). Heavier adult male *Peromyscus* are more likely to win agonistic encounters and appear to have an advantage in maintaining territories (Fairbairn 1977, 1978; Dewsbury 1979). During this experiment, female fecundity was positively related to maternal mass at parturition (Schwanz 2008), but daughters of infected females did not remain larger as adults to gain the reproductive benefits of greater adult mass. Although this study found no evidence that larger mass benefited males in agonistic trials, the persistent mass advantage of sons of infected females in adulthood may still indicate that being born heavier provides improved reproductive success of sons.

Larger offspring also had enhanced survival as juveniles. Although post-weaning survival for deer mice in the field is typically high (*c.* 0·8 survival for 2 weeks, Millar & Innes 1983), it is lower than the survival recorded in this laboratory-based study, raising questions as to whether this study provides an adequate test of post-weaning survival. Large body mass may be more important for offspring survival in natural settings than in the laboratory, suggesting that the results recorded in this laboratory study may be enhanced and pertinent for wild mouse populations. Because offspring lifetime fitness is determined by survival and reproductive success, this study demonstrates that the production of larger offspring by infected mothers clearly enhances multiple components of offspring lifetime fitness.

Additional indirect effects of maternal parasitic infection were limited. Although research in mammals has demonstrated effects of maternal condition on a son's aggression (Meikle & Westberg 2001), maternal infection status here had no effect on the dominance of sons. In addition, survival was not influenced by maternal infection. However, the analysis of lactation survival combining offspring mass and maternal treatment could only assess survival from day 3. Therefore, it may not provide an adequate test of the importance of these factors for survival during lactation due to the disparity between treatments in the timing of offspring mortality (largely before day 3 for control offspring). Additional effects of maternal infection have been recorded in laboratory mice, where offspring of mothers infected with nematodes are more likely to recover from direct infection (Kristan 2002, 2004). Schistosome resistance as a maternal effect in deer mice was not examined here, and is an interesting future avenue of research.

PERSISTENCE OF MATERNAL EFFECTS

Maternal effects on offspring phenotype were persistent in this study of deer mice. In addition to effects of treatment on offspring mass and resultant survival, litter size and parental identity had persistent effects on offspring phenotype. Litter size had a strong, negative effect on offspring mass that persisted through the asymptotic mass of offspring. Because maternal mass was positively correlated with litter size in this experiment (Schwanz 2008), females of higher mass produced larger litters with offspring that remained small in body mass throughout their lives, producing a negative association between maternal and offspring mass (Millar 1983). Whereas maternal effects are often demonstrated at a single stage (typically early) in offspring life or for a single performance measure, the persistence of maternal effects and their consequences for multiple components of fitness often remain unexamined (Fox & Savalli 1998; Kerr *et al*. 2007; Marshall & Uller 2007). The results from this study demonstrate that maternal effects can be quite persistent and have a strong impact on offspring lifetime fitness (Clark & Galef 1995; Kerr *et al*. 2007).

INFECTION AND MATERNAL REPRODUCTIVE STRATEGIES

While it is clear that the production of heavier offspring benefits offspring fitness, the fitness consequences for mothers of producing larger offspring remain less clear. Producing heavier offspring with higher fitness increases a mother's current reproductive success (anticipatory maternal effects, Marshall & Uller 2007). In this respect, maternal effects in the deer mouse–*S. douthitti* system appear to be part of an adaptive maternal strategy to increase current reproductive success when faced with decreased residual reproductive value caused by infection (Schwanz 2008). Therefore, the response of female deer mice to *S. douthitti* infection supports hypotheses of adaptive host plasticity in life-history (i.e. fecundity compensation and terminal investment hypotheses, Minchella & LoVerde 1981; Clutton-Brock 1984; Forbes 1993; Schwanz 2006b).

Some insight into maternal reproductive strategies may be gained from considering the nature of the maternal effects. That offspring of infected mothers were larger at birth suggests

that there are benefits during lactation that were not demonstrated here (e.g. in lactation survival). The persistence of a mass difference to weaning suggests that post-weaning effects of offspring mass are also important aspects of maternal reproduction. This is because energetic investment in offspring by deer mice increases dramatically during lactation and is greater for heavier litters (Stebbins 1977; Millar & Innes 1983; L.E. Schwanz, unpublished data), indicating that parasitized females could have reduced energetic demands by reducing milk production and weaning offspring of equivalent size as those of control mothers. Greater reproductive competitiveness and juvenile survival in sons would be fitness benefits of weaning heavier sons. Adult survival is a large determinant of lifetime reproductive success in female deer mice (Millar *et al*. 1992); however, the lack of a mass advantage in adult daughters of infected mothers suggests that mothers do not benefit from weaning larger daughters.

Parasitized females appear to have produced heavier weanings without an increase in energetic costs. This is because: (i) energetic demands of gestation in laboratory deer mice are minor compared to lactation and are not much higher than non-breeding females (Stebbins 1977), and (ii) mothers in the two treatments had equivalent investments during lactation based on offspring growth rates and food consumption (infected deer mice have equivalent food consumption and digestive efficiencies as control mice, Schwanz 2006a, 2008). If larger offspring have higher fitness and can be produced without increased energetic demands, the 'restraint' in offspring birth size shown by control deer mice suggests that birthing larger offspring comes at a cost not apparent in laboratory settings. For example, a larger litter mass may reduce maternal mobility during pregnancy, impeding foraging or increasing predation risk (Brodie 1989; Lee *et al*. 1996; McLean & Speakman 2000; Shine 2003; Ghalambor, Reznick & Walker 2006). Similarly, the birthing process itself may be riskier to embryo or mother when the embryo is larger. Indeed, one infected female died during parturition in this study. Production of larger offspring at birth may also lead to reduced future fecundity or survival of mothers. In order to confirm the importance of larger offspring size for adaptive reproductive investment by parasitized mothers, additional data are needed on the impact on maternal survival of heavier offspring during gestation, parturition and lactation.

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