ELSEVIER

Commentary

The true cost of host manipulation by parasites

Robert Poulin*, Brian L. Fredensborg, Ellen Hansen, Tommy L.F. Leung

Department of Zoology, University of Otago, P.O. Box 56, Dunedin, New Zealand

If there is one thing that the past three decades of research in behavioural and evolutionary ecology have taught us, it is that there are no free lunches. Adaptive traits provide net fitness benefits to the animals bearing them, but the gains would be even greater if there were no concurrent costs associated with the expression of those traits. The ability of many parasites to enhance their transmission success by manipulating the behaviour of their hosts is one such trait (see Moore, 2002). In their excellent synthesis of past and current research on this phenomenon, Thomas et al. (2005) cast a doubt on the importance of the cost incurred by manipulating parasites. They argue that the existence and magnitude of such costs are dependent upon the type of mechanism used by a parasite to alter host behaviour. Thomas et al. (2005) focus exclusively on physiological, or proximate, costs such as the energetic costs necessary for the production of neuroactive substances in parasite species that use them to modify host behaviour. In a broader evolutionary context, however, one must consider costs at the ultimate level, in terms of fitness. Fitness is usually defined as the average number of surviving offspring produced by individuals with a certain genotype relative to that produced by other genotypes, or as an individual's relative contribution of genes to future generations (Ridley, 1996; Freeman and Herron, 2001), Energy is not the best currency to measure loss of fitness, because other fitness components, such as mortality risk, cannot readily be quantified in units of energy. Elsewhere in their review, in their discussion of mafia-like strategies, Thomas et al. (2005) consider fitness costs, but a similar perspective is needed to assess the cost of manipulation itself.

Here, we wish to re-visit the issue of costs associated with manipulation. Even if the energetic expenses necessary to alter host behaviour are nil, a manipulative parasite may still incur a cost resulting, for instance, from a higher probability of being killed. This is a probabilistic cost, only paid in the event that the parasite dies, but it is a cost nonetheless. The net fitness outcome of manipulation must be positive, of course, otherwise it would not have been selected; it is the quantity subtracted from the gross benefits that we are dealing with here. Ideally, one would need to compare the fitness costs paid by a manipulative parasite with the costs, if any, incurred by a conspecific parasite that benefits from manipulation without itself inducing it. We found three examples of manipulative trematode

* Corresponding author. Fax: +64 3 479 7584.
  E-mail address: robert.poulin@stonebow.otago.ac.nz
(R. Poulin).

species where such a contrast is possible. Thomas et al. (2005) question whether there is a cost associated with encystment in a particular site within the host as opposed to another site. Specifically, they ask whether it is costly for a parasite to encyst in the eye of a fish, referring to the well-studied trematodes such as *Diplostomum spathaceum* that encyst in the eye lenses of fish, altering the latter's behaviour and making them more susceptible to predation by avian definitive hosts (e.g., Crowden and Broom, 1980; Seppälä et al., 2004). The fact that a significant proportion of *D. spathaceum* cercariae die en route to the eyes after penetrating the fish through the gills or the skin (Ratanarat-Brockelman, 1974; Whyte et al., 1991) suggests that encysting in the eyes is costly. This is true even if the eye is a prime location for avoiding host immunity (the eye lens lacks blood vessels and circulating antibodies) and manipulating the host. Because all *D. spathaceum* cercariae migrate to the eyes of their fish host, it is not possible to compare them to conspecifics that encyst elsewhere. The three examples we chose allow such a comparison, and demonstrate that the site of encystment can relate to both the success of manipulation and its cost.

Our first example is the trematode *Dicrocoelium dendriticum* (and related species), the classical textbook example of a manipulative parasite. Infected ants, which serve as intermediate hosts for this trematode, attach to the tips of grass blades where they are presumably more susceptible to ingestion by grazing sheep, the parasite's definitive host (see Carney, 1969; Romig et al., 1980). Following their arrival in an ant, only one cercaria (the "brainworm") migrates to the ant's suboesophageal ganglion and induces the behavioural change; the others remain within the host's haemocoel. When an infected ant is eaten by a sheep, the brainworm invariably dies whereas the other parasites establish within the definitive host (Wickler, 1976). It appears that while it is inducing a change in host behaviour, the brainworm does not develop as do other metacercariae, and does not become infective for its next host. Thus, the manipulative individual dies whereas the non-manipulative individuals have a good chance of surviving and reproducing. Does that represent a cost of manipulation? We say it does.

It is possible that this cost in *D. dendriticum* is mitigated by kin selection. Based on the mode of transmission of this parasite, all cercariae ingested by a given ant may come from the same snail first intermediate host,

i.e., they may all be derived from a single parasite egg. Cercariae shed from a snail occur as batches in slime balls exuded from the snail's mantle cavity. If a given ant feeds on a single slime ball containing several genetically identical cercariae, then the brainworm's sacrifice would ensure the transmission of its clones, and could be favoured by selection (Wickler, 1976; Wilson, 1977). In this scenario, manipulation would remain directly costly for the manipulative individual, but would be indirectly compensated by the increased success of the manipulator's kin. There is no confirmation, however, that *D. dendriticum* individuals inside the same ant are indeed clones; this is purely speculative at this point. In fact, there have been no studies on the genetic structure of groups of metacercariae sharing the same hosts in any of the many trematode species known to induce changes in the behaviour of intermediate hosts. In any event, the following two examples are set in aquatic habitats, where the dispersal of cercariae makes it extremely unlikely that clones regularly co-occur in the same intermediate host.

Our second example is the trematode *Microphallus papillorobustus*, another well-known manipulator. Metacercariae of this species that encyst in the cerebral region of the second intermediate host, the amphipod *Gammarus aequicauda*, induce a strong positive phototaxis and aberrant evasive responses in the host (Helluy, 1983). This manipulation of host behaviour results in infected amphipods being more susceptible to predation by aquatic birds, which serve as definitive hosts for the parasite (Helluy, 1984). However, not all metacercariae of *M. papillorobustus* encyst in the cerebral region of amphipods, some also encyst in the abdomen. Amphipods are capable of mounting an immune response against invading parasites, involving both encapsulation and melanization, and they use this cellular defense reaction against metacercariae. Thomas et al. (2000) have found that approximately 17% of cerebral metacercariae of *M. papillorobustus* are killed by encapsulation and melanization, whereas less than 1% of abdominal metacercariae suffer this fate. Three other trematode species, belonging to the same family (Microphallidae) as *M. papillorobustus*, also parasitize the amphipod *G. aequicauda*; they all encyst in the amphipod's abdomen, and none of them is attacked by the host immune system (Thomas et al., 2000). The host's defenses are apparently targeted specifically at those metacercariae most likely to cause it harm. The end