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COEVOLUTION BETWEEN MATERNAL TRANSFER OF IMMUNITY AND OTHER RESISTANCE STRATEGIES AGAINST PATHOGENS

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Among the wide variety of resistance mechanisms to parasitism, the transgenerational transfer of immunity from mother to offspring has largely been overlooked and never included in evolutionary or coevolutionary studies of resistance mechanisms. Here we study the evolution and coevolution of various resistance mechanisms with a special focus on maternal transfer of immunity. In particular we show that maternal transfer of immunity is only expected to evolve when cross immunity is high and when the pathogens have an intermediate virulence. We also show that the outcome of the coevolution between various resistance mechanisms depends critically on the life span of the host. We predict that short-lived species should invest in avoidance strategies, whereas long-lived species should invest in acquired resistance mechanisms. These results may help understanding the diversity of resistance strategies that have evolved in vertebrate species. Our framework also provides a general basis for the study of the evolution of other transgenerational resistance mechanisms.

KEY WORDS: **Evolutionary epidemiology, host–parasite interactions, maternal effect, recovery, transfer of maternal antibodies.**

Parasites can impose important fitness costs on their hosts (Grenfell and Dobson 1995) and, in response, hosts have evolved different costly defense strategies that aim at reducing the deleterious effects of parasites (Sheldon and Verhulst 1996; Sandland and Minchella 2003). Defense strategies can include avoidance mechanisms that prevent infection by a parasite (e.g., Hart 1990) or different mechanisms that directly reduce the impact of a parasite when it has successfully infected the host. In particular, the immune system has evolved as a way to fight infection inside hosts, and in many cases eradicating the parasite. In vertebrates, the efficiency of the immune system relies on a combination of innate and acquired responses and on the ability of recovered hosts to remain protected for an extended period of time (Frank 2002). Moreover, an important arm of the acquired immune response of vertebrates induces the production of parasite specific immune compounds, the antibodies, which can be transferred by mothers to their offspring through the transfer of maternal antibodies (Carlier and Truyens 1995). Although decaying after birth, these antibodies have the potential to provide newborns with a protection early in life, a critical time at which their own immune system may not be fully mature (Grindstaff et al. 2003; Boulinier and Staszewski 2008; Hasselquist and Nilsson 2009).

It is thus apparent that defense against parasites relies on a combination of different resistance mechanisms (Schulenburg et al. 2009; Schmid-Hempel 2011). The generation and coexistence of such a large range of defense strategies has been the focus of several theoretical studies (see Boots et al. (2009) for a review). Overall, these studies show that the evolution and coevolution of resistance mechanisms depend critically on (1) the fitness costs imposed by the infection, (2) the epidemiological feedbacks, and

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(3) the shape of the trade-off between defense strategies and various fitness components of the host.

The evolution of resistance to parasites has indeed been extensively studied from a theoretical point of view using various methods ranging from population genetics to adaptive dynamics models (Gillespie 1975). Adaptive dynamics has been used to explore the evolution of a variety of resistance mechanisms including avoidance (Antonovics and Thrall 1994; Bowers et al. 1994; Boots and Haraguchi 1999), tolerance (Boots and Bowers 1999; Roy and Kirchner 2000), recovery (van Baalen 1998), and acquired immunity (Boots and Bowers 2004; Miller et al. 2007). Some of the studies focused on the coevolution of different resistance mechanisms (e.g., Boots and Bowers 1999, 2004; Carval and Ferriere 2010), whereas some others explicitly tackled the importance of other characteristics of either the host (Gandon et al. 2002; Zuk and Stoehr 2002; Miller et al. 2007) or the parasite (van Baalen 1998; Alizon and van Baalen 2008). Yet, and in spite of its impact on the fitness of juveniles and its potential influence on epidemiological dynamics, the evolution of the transgenerational transfer of immunity has been largely overlooked in previous studies.

In an attempt to fill this gap, we study here the evolution and the coevolution between different resistance mechanisms using a classical epidemiological model modified to include the transgenerational transfer of immunity. Resistance can thus be achieved at different steps of the interaction between the host and the parasite: (1) avoidance before the infection by the parasite, (2) recovery, and (3) transgenerational transfer of immunity. Each of these resistance mechanisms has implications on the epidemiology which in turns feeds back on the intensity of the selection for resistance to the parasite. We derive a general invasion condition using the Next Generation Theorem (van den Driessche and Watmough 2002; Hurford et al. 2010) and use this host fitness function to study the evolution of the transfer of maternal immunity. We first consider the force of infection as a constant in a model with one or two strains of parasite. Then, focusing on the one strain model, we add epidemiological feedbacks to study the effect of host and parasite traits on the evolution of the maternal transfer of immunity. We also study the coevolution between the transfer of maternal immunity and recovery rate, and finally add avoidance as another coevolving resistance mechanism. We discuss how particular traits of the host life cycle may mold theallocation between different resistance strategies.

Epidemiological Model

We model a population of asexually reproducing hosts exposed to several parasites, each of which being characterized by its force of infection, h, and itsvirulence, α (i.e., additional mortality). We assume no vertical transmission and no effect of parasites on host fecundity. Four different types of hosts are considered: susceptible, infected, recovered, and protected by maternal immunity. The density of hosts in these four different compartments is noted S, I, R, and M, respectively. The following system of differential equations (the dot notation refers to differentiation with respect to time) describes the change inthese different compartments when a single parasite is considered (see also Fig. 1):

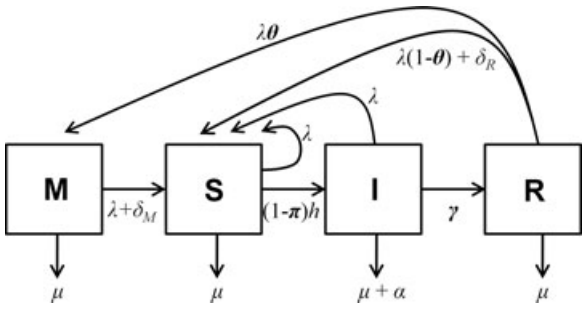

Figure 1. Flow diagram of the epidemiological model including the maternal transfer of antibodies to offspring. The model distinguishes four categories of individuals: maternally protected (*M*), susceptible (*S*), infected (*I*), and recovered and immune (*R*). The ability of immune individuals to transfer antibodies to their newborns is described by the parameter θ. Other parameters: λ, birth rate; δ_R, rate of loss of immune protection; δ_M, rate of loss of the maternal protection; h, force of infection (equates to βI when epidemiological feedbacks are considered); γ, recovery rate; α, virulence of the parasite (resulting in an increase in the mortality of infected individuals); μ, natural mortality rate.

$$\begin{aligned}
\dot{M} &= \lambda\theta R - (\mu + \delta M)M,\\
\dot{S} &= \lambda\,(M + S + I + (1-\theta)\,R) + \delta_M M + \delta_R R\\
&\quad -(\mu + (1-\pi)\,h)\,S,\\
\dot{I} &= (1-\pi)\,hS - (\mu + \alpha + \gamma)\,I,\\
\dot{R} &= \gamma I - (\mu + \delta_R)\,R. \qquad (1)
\end{aligned}$$

We assume that all hosts can reproduce with a rate $\lambda = r - \kappa N$ which depends on host fecundity, r, the total host density, $N = M + S + I + R$, and a crowding parameter κ (which is related to the carrying capacity by the relation $K = r/\kappa$). Newly produced offspring are all susceptible except a fraction θ of the offspring of recovered hosts which are assumed to be fully protected by maternal immunity. The protection of those individuals is temporary and depends on δ_M, the rate of loss of maternal immunity. Susceptible hosts can become infected with a rate that depends on the force of infection of the parasite, h, and the ability, π, of the host to reduce the probability of infection by avoiding infection. The

natural mortality rate of the host is μ, but infected individuals suffer an additional mortality due to parasite virulence, α. Infected individuals can recover with a rate, γ, and they remain in the recovered compartment until they lose immunity, which occurs with a rate δ_R. In the absence of the parasite, the host population reaches a stable equilibrium with a density $\hat{S}$ of only susceptible hosts. The parasite will invade this fully naïve host population if its basic reproductive ratio is higher than one (see Appendix): $R_0 = \frac{(1-\pi)h}{\mu+\alpha+\gamma}\hat{S} > 1$. After this invasion, the system reaches a new stable endemic equilibrium where all the four different types of hosts coexist.

In this model, the host may thus defend itself through three different, yet not mutually exclusive, ways. First, it may try to limit early on the risk of being infected (avoidance, host defense trait π). Second, upon infection, it may recover from the infection (recovery rate, host defense trait γ), and transmit this protection via maternal immunity (transfer of maternal immunity, host defense trait θ). In the following, we study the evolution of the maternal transfer of immunity and its coevolution with other resistance mechanisms.

Evolutionary Model

To study host evolution we derive a general invasion criteria for a rare mutant host that could affect any of the host resistance traits (see Appendix). This invasion condition depends on the costs of resistance on both fecundity and survival. In the following, however, we will restrict our study to a simple cost function that will be assumed to affect only fecundity (see Appendix for the full definition of the trade-off). There is empirical evidence to support the idea of a cost of resistance to parasites in terms of reduced birth rate (e.g., through an increase of developmental period; Boots and Begon 1993). Maternal transfer of antibodies in particular is likely to be a costly mechanism for the mother given the amount of antibodies transferred (Kowalczyk et al. 1985; Coe et al. 1994) and the set up and maintenance of the specific receptors required for the transfer (West et al. 2004; Roopenian and Akilesh 2007). We further assume a slightly accelerating trade-off shape which can prevent evolutionary branching (Boots and Haraguchi 1999; but see Hoyle et al. 2008) because it simplifies the evaluation of the optimal investment in the different resistance strategies.

The general invasion condition we derive in the Appendix can be understood as a quantity that relates to the average number of offspring produced in one generation by a mutant host in a resident host population (see Appendix and Fig. A1):

$$R_m = \frac{\left(\tau^m_{S\to S} + \sqrt{4\tau^m_{M\to S}\tau^m_{S\to M} + \tau^{m2}_{S\to S}}\right)}{2}, \qquad (2)$$

where $\tau^m_{S\to S}$, $\tau^m_{M\to S}$, and $\tau^m_{S\to M}$ refer to the different transitions leading to the production of two types of newborns mutants: the ones that are susceptible, S, and the ones that are protected by maternal antibodies, M. Under the hypothesis of adaptive dynamics (i.e., rare mutations), this invasion condition can be used to find singular points and to characterize their evolutionary properties to determine the optimal investment in the different resistance traits. In all the scenarios we study below, the evolutionary equilibria we found are both convergence and evolutionary stable and thus correspond to continuously stable strategies (Geritz et al. 1998). Note that, although the present analysis is based on the assumption that the host reproduces asexually, previous studies showed that the adaptive dynamics can also be carried out for sexual species (Kisdi and Geritz 1999). The results discussed below may thus be relevant under a broad range of reproductive systems.

Evolution of Maternal Transfer of Immunity with a Constant Force of Infection

The evolutionary stable investment in the maternal transfer of immunity is an increasing and saturating function of the force of infection, h (see Fig. S1A). It means that, not surprisingly, higher levels of resistance are evolving when the rate of acquisition of a new infection is increasing. In other words, when the force of infection increases, the mean age at infection decreases which in turn favors higher levels of maternal protection. Perhaps more surprisingly we find that an increase of pathogen virulence has a nonmonotonous effect on the evolution of maternal transfer (see Fig. S1B). This is because when virulence becomes very high it is not worth investing in a resistance mechanism that will never be expressed as most individuals die from the infection and never recover (recall that only recovered individuals can transfer immunity). In addition, we also find a nonmonotonous effect of recovery on the evolution of maternal transfer of immunity (see Fig. S1C). Indeed when recovery becomes very high, the best strategy is to let the offspring encounter the parasite as they will recover very fast from the infection anyway. We will come back to these effects in the following section where we will allow the force of infection to be a dynamical variable that depends on parasite density and transmission rate.

The model with a constant force of infection can also be used to illustrate the potential effects of being exposed to multiple parasites on the evolution of maternal transfer of immunity. We explain in the Appendix how to modify the above model to account for the circulation of two different strains (described by their force of infection h_1 and h_2). We assume that a host that has recovered from an infection by one strain can transfer immunity to this strain, but the cross immunity against the other strain is imperfect and measured by the parameter χ. When

$\chi = 0$ there is no cross immunity and, in contrast, when $\chi = 1$ cross immunity is perfect and the two parasites model reduces to the previously described model with $h = h_1 + h_2$. We further introduce a parameter η describing the potential bias toward the transmission of one strain over the other. More precisely, holding the total force of infection constant and equal to $h = h_1 + h_2$, we assume the force of infection of each strain to be equal to $h_1 = \eta h$ and $h_2 = (1 - \eta)h$. A value of η of 0.5 maximizes the symmetry of the force of infection ($h_1 = h_2$), whereas any deviation from 0.5 increases the bias toward one strain.

Figure 2 shows that lower levels of cross immunity select for decreased levels of maternal transfer of immunity. When cross immunity is high, the own protection of mothers is a good predictor of the efficiency of the protection they can provide to their newborns and they are thus expected to transfer their immune protection. A bias in the force of infection toward one strain increases also the predictability of the environment and always selects for higher levels of maternal transfer of immunity.

As outlined by Boots et al. (2009), one important force driving the evolution of resistance mechanisms is how epidemiology feeds back on the selection gradients. In the following section, we investigate how such epidemiological feedbacks will affect the evolution of the transfer of maternal immunity.

Evolution of Maternal Transfer of Immunity with Epidemiological Feedbacks

Here, we focus on the evolution of the ability to transfer maternal immunity when the force of infection includes the effects of epidemiology, $h = \beta I$. For the sake of simplicity, we will restrict our analysis to the one strain model. The duration of transgenerational protection and the life span of the host have monotonous effects on the evolutionary stable ability to transfer immunity to offspring. The optimal transfer of immunity is an increasing function of the host life span (Fig. 3A) because, as outlined by Miller et al. (2007), increasing host life span modifies the prevalence of the parasite and increases the force of infection. Thus, it increasingly pays off to invest in transgenerational protection with longer life expectancy. In contrast, the evolutionary stable level of transfer is a decreasing function of the rate of loss of maternal protection (Fig. 3B): the longer the maternal protection, the higher the benefits of this mechanism. Ultimately, when maternal protection is lost sufficiently quickly, there is no more investment in maternal transfer of immunity and the model reduces to a classical Susceptible - Infected - Recovered - Susceptible (SIRS) model.

Increasing the virulence of the parasite has a nonmonotonous effect on the evolution of the maternal transfer of immunity (Fig. 3C). At first, the investment in the transfer of maternal immunity increases toward a maximum and then decreases until eventually reaching a point when there is no more investment in the transgenerational transfer. This drop is due to two effects. First, as mentioned earlier (see above section "Evolution of maternal transfer of immunity with a constant force of infection"), higher virulence reduces the number of recovered individuals, and thus the efficacy of the transfer of immunity. Second, when virulence reaches high values, infected hosts die rapidly which causes a rapid drop in the force of infection. As a consequence, the transfer of maternal immunity is only expected to evolve for intermediate levels of parasite virulence.

Optimal investment in the transfer of maternal immunity is also a nonmonotonous function of the recovery rate (Fig. 3D). Because only recovered individuals can transfer immunity, low recovery rates do not offer the possibility for an efficient transfer of immunity. Evolutionary stable maternal transfer increases with the rate of recovery and reaches a maximum for intermediate recovery rates. Beyond this point, larger recovery rates reduce the fitness cost of infection (see above section "Evolution of maternal transfer of immunity with a constant force of infection") and select for lower levels of transfer. This effect is amplified by the epidemiological feedback as higher recovery rates decrease the force of infection. Increasing the rate of loss of immunity in adults decreases the maximal level of transfer but allows the selection for this mechanism on a wider and higher range of recovery rates.

Relaxing some assumptions in the life cycle of the host does not qualitatively modify these results (see Supporting Information). In particular, when newborns (either maternally protected or susceptible) are not allowed to reproduce or when the decay of immune protection in resistant individuals is taken into account (so that resistant hosts can be protected without transferring protection), all the qualitative results mentioned above remain unchanged.

Coevolution Between Maternal Transfer of Immunity and Other Traits

The invasion criteria derived in the Appendix can be used to determine the coevolutionary stable set of strategies (CoESS, see also van Baalen 1998). We first consider the coevolutionary dynamics between maternal transfer of immunity and recovery. The CoESS of both traits is an increasing saturating function of the baseline duration of the life span (Fig. 4A) with maternal transfer of immunity (black curve) starting to increase after recovery rate (gray curve) and reaching lower coevolutionary stable levels. These levels are maximized for intermediate values of the rate of loss of immunity (Fig. 4B). When immunity decays quickly enough, there is no more transfer of maternal immunity and acquired resistance only relies on recovery. Similarly, virulence has a nonmonotonous effect on the coevolutionary outcome. First,

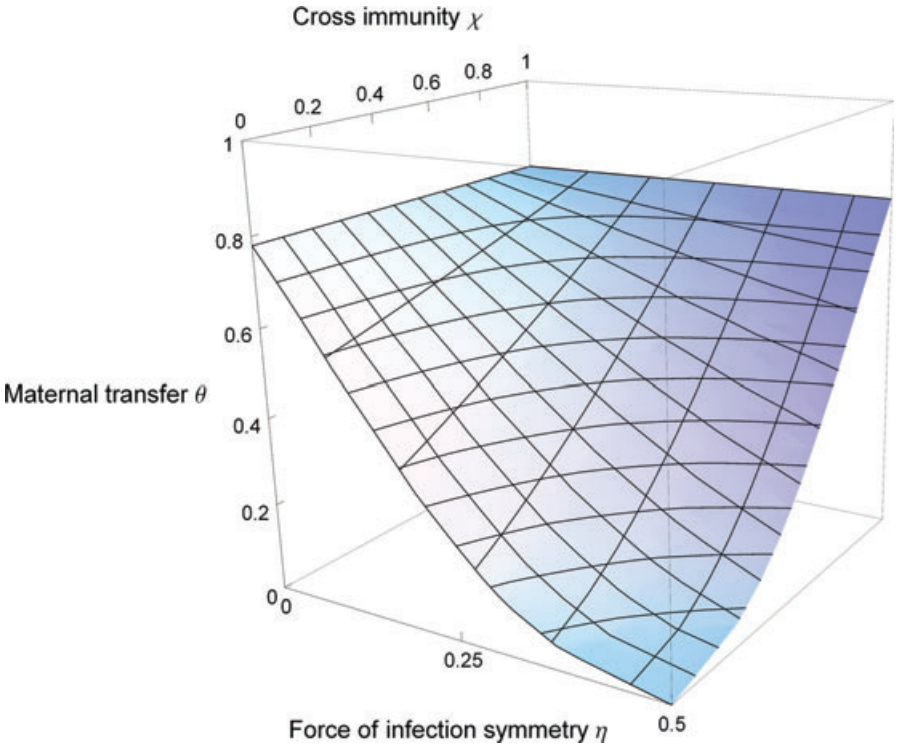

Figure 2. **Evolutionary stable investment in the ability to transfer maternal immunity (θ) as a function of the level of cross immunity of such maternal protection (χ) and of the symmetry of the force of infection (η) in a model with two strains of parasites described by their force of infection, respectively, h_1 and h_2. Increased cross protection and less symmetric forces of infection select for a higher investment in maternal immunity as the environment of mothers becomes a better predictor of the environment of their offspring. Other parameter values: $r_0 = 1.5$, $\mu = 0.05$, $\kappa = 0.1$, $c_{r,\theta} = 0.075$, $k_\theta = 1/0.9$, $\alpha = 5$, $\pi = 0$, $\gamma = 0.8$, $h = 2$, $\delta_R = 1$, $\delta_M = 1$.**

an increase in virulence selects for higher investment in both recovery rate and maternal transfer of immunity (Fig. 4C). Second, for higher virulence levels, both recovery and maternal transfer decrease with virulence. As outlined earlier, the effects of all those parameters are mediated by different epidemiological feedbacks acting on the prevalence of the parasite. Finally, it is interesting to note that the transfer of immunity is consistently selected for on a smaller range of parameter values than recovery rate. This is because the evolution of the transfer of maternal immunity is constrained by the requirement of a prior evolution of recovery (only recovered individuals can transmit).

Recovery and maternal transfer of immunity are both acquired responses to parasites that represent only part of possible responses to parasites. Avoidance is another resistance mechanism relying on an ability of the host to directly reduce the infection probability. Not surprisingly, we find that an increase in the ability to avoid infection by the parasite results in decreased coevolutionary levels of both recovery and maternal transfer of immunity (Fig. 4D). When avoidance is sufficiently high, there is no more investment in acquired resistance mechanisms. Yet, these results rely on the assumption that avoidance mechanisms are fixed quantities. This alternative resistance mechanism may, however, coevolve with the other strategies.

When we allow the three different resistance mechanisms to evolve jointly, we find that the coevolutionary outcome is very sensitive to the host life span (Fig. 5). When the life span is short, evolution leads to investment into the ability to avoid the infection by the parasite. When the life span increases above a threshold value, a bistability emerges where two coevolutionary outcomes may occur. Depending on the initial investment in the different resistance traits, the host may continue to invest only in avoidance or may invest only in a combination of recovery and maternal transfer of immunity. This is because increasing the host life span increases the probability of encountering the parasite again and thus increases the benefits of developing an acquired resistance. To summarize, short-lived individuals are expected to invest in innate (i.e., avoidance) rather than acquired (i.e., recovery rate and maternal transfer of immunity) defense mechanisms, whereas longer lived individuals are expected to display the opposite pattern.

Discussion

In spite of an abundant literature on the evolution of various host defense mechanisms against parasites (van Baalen 1998; Miller et al. 2007; Boots et al. 2009), the evolution of the

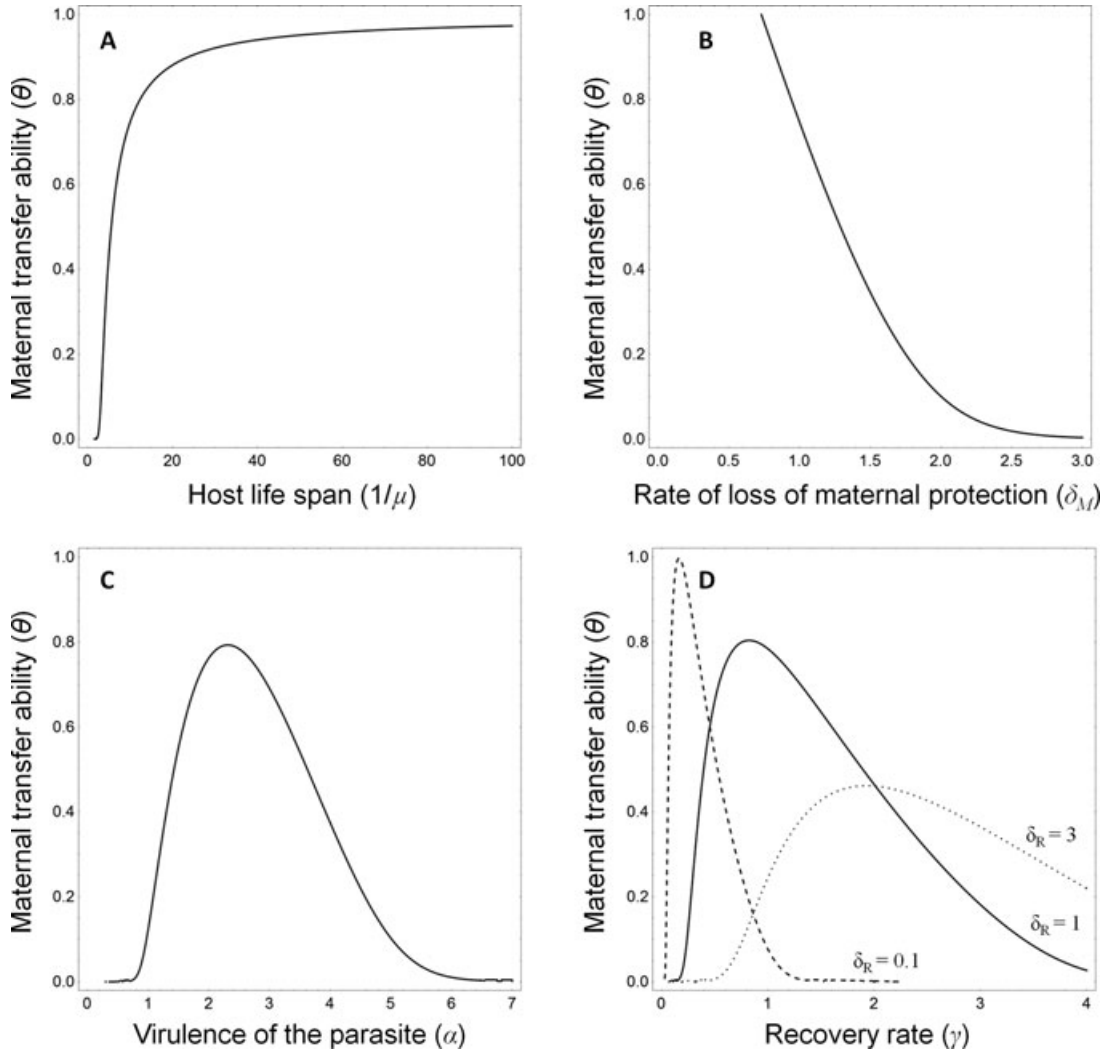

Figure 3. **Evolutionary stable investment in transgenerational transfer of immunity ability (θ) as a function of different parameters. (A) Effect of the host life span (1/μ). (B) Effect of the rate of loss of maternal protection (δ_M). (C) Effect of the virulence of the parasite (α). (D) Effect of the recovery rate (γ) for different rates of loss of immune protection (δ_R). Default parameter values used in the figures: $r_0 = 1.5$, $\mu = 0.1$, $\kappa = 0.1$, $c_{r,\theta} = 0.075$, $k_\theta = 1/0.9$, $\alpha = 2.75$, $\beta = 2$, $\delta_R = 1$, $\delta_M = 1$, $\gamma = 0.6$.**

transgenerational transfer of immunity has been largely overlooked in previous studies. This is probably due to the intrinsic complexity which arises when one wants to model this effect as it becomes necessary to add a class of individuals which are temporary protected by a vertically transmitted immunity. Here we provide a general theoretical framework to study the evolution of this trait, as well as more classical resistance mechanisms against parasites (i.e., avoidance of infection and recovery).

We first analyze the evolution of the transgenerational transfer of immunity when the other traits remain fixed. This allows us to show that several parameters like parasite virulence and host recovery rates have a nonmonotonous effect on the evolution of this trait. This effect is partly mediated by the feedback of epidemiology on this evolution via the force of infection (see Boots et al. 2009 for a general discussion of these feedbacks on other resistance mechanisms). Another important result of our study is that, when two strains of parasite are circulating, the evolutionary outcome depends on the level of cross immunity provided by the protection acquired vertically. Less cross immunity hinders the evolution of this resistance mechanism. This result illustrates that what matters for the evolution of the transfer of immunity is the correlation between the environment of the mother and the environment of the offspring (see also Mousseau and Fox 1998 for a discussion of the importance of these correlations for the evolution of maternal effects). Considering the variations in time and space of the distribution of parasites and their hosts could bring more insight into our understanding of the evolution of passive protection by transfer of maternal immunity.

We also studied the coevolution between maternal transfer of immunity and other resistance mechanisms. In particular, our

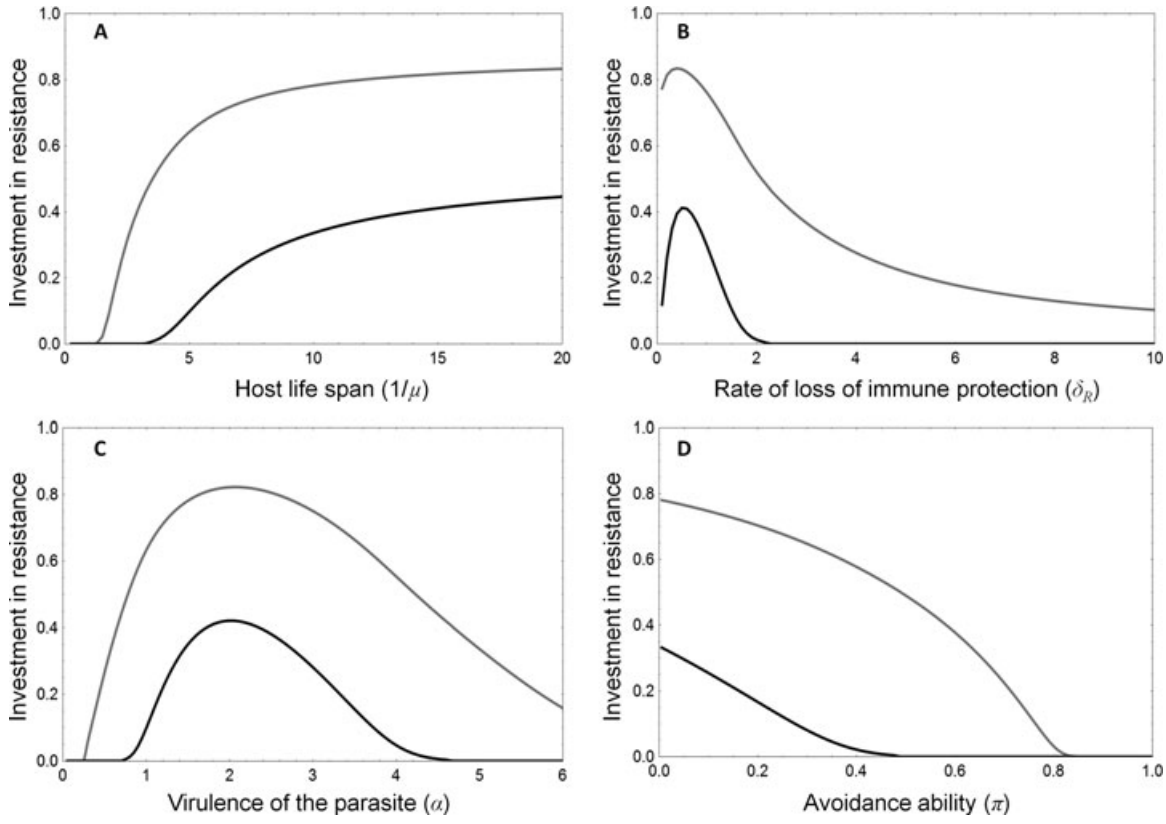

Figure 4. Coevolution between recovery rate (γ, gray line) and transgenerational transfer of immunity ability (θ, black line). (A) Effect of the host life span (1/μ). (B) Effect of the rate of loss of immunity (δ_R). (C) Effect of the virulence of the parasite (α). (D) Effect of the avoidance ability (π). Default parameter values used in the figures: $r_0 = 1.5$, $\mu = 0.1$, $\kappa = 0.1$, $c_{r,\theta} = 0.075$, $c_{r,\gamma} = 0.2$, $k_\theta = 1/0.9$, $k_\gamma = 1/0.9$, $\alpha = 2.75$, $\beta = 2$, $\pi = 0$, $\delta_R = 1$, $\delta_M = 1$.

model shows that parasite virulence can mould the investment in both recovery and transfer of immunity, with maternal transfer of immunity being selected for on a more restricted range of values. We also show that the host life span has a massive impact on the allocation between avoidance and acquired resistance strategies like recovery and maternal transfer of immunity: short-lived hosts always invest in avoidance, whereas long-lived hosts display a bistability between an investment in innate or acquired immunity. Life span has indeed been suggested as one of the life-history traits that could modify the evolution of physiological processes such as resistance to parasites (Ricklefs and Wikelski 2002). Because they are more likely to encounter the same parasites on multiple occasions during their lifetime, long-lived species are expected to favor investment in acquired responses (Lee 2006). The results of our theoretical analyses support this hypothesis and highlight the need for more empirical studies of the variability of (maternal) immunity in species with contrasted life histories.

PERSPECTIVES

In our model, transgenerational immune protection fully protects newborns with maternal antibodies (M) from an infection by a parasite their mother encountered. Such protective transgenerational immunity is notably used in the poultry industry to protect chickens against some pathogens (Davison et al. 2008) and it likely occurs in natural host–parasite systems, although little evidence exists yet (Boulinier and Staszewski 2008; Garnier et al. 2012). High maternal antibody levels early after birth have been shown to prevent newborns from mounting a potentially costly immune response (Staszewski et al. 2007; Garnier et al. 2012). Later in early life, decaying levels of maternal antibodies could provide a partial protection resulting in an activation of the newborns immune system at reduced costs (Zinkernagel 2003; Navarini et al. 2010). This would increase the infectious period and the prevalence of the parasite, and the effect on the CoESS would be very similar to a reduction in the virulence of the parasite (see Fig. 4C). Even after complete disappearance of the passive protection, newborns having received antibodies could benefit from higher recovery rates when later exposed to the parasite (Lemke et al. 2003; Grindstaff et al. 2006). Accounting for that sort of effect would add a direct link between maternal transfer of immunity and recovery rate and would certainly modify the CoESS between those acquired resistance traits. Our modeling framework could be readily modified to explore the quantitative consequences of this new scenario.

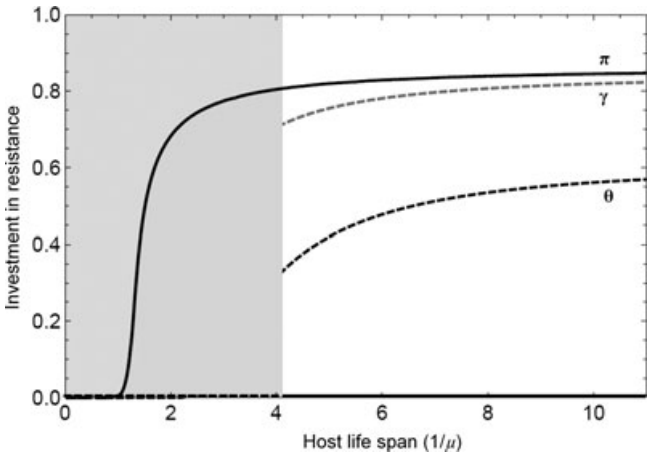

Figure 5. **Effect of the host life span ($1/\mu$) on the coevolutionary stable investment in recovery rate (γ, light gray lines), maternal transfer ability (θ, dark gray lines), and avoidance ability (π, black lines) depending on initial conditions (plain curves: $\pi_{start} = 0.7$; $\gamma_{start} = 0.01$; $\theta_{start} = 0.01$; dashed curves: $\pi_{start} = 0.01$; $\gamma_{start} = 0.7$; $\theta_{start} = 0.7$). When life span is short (gray background), selection favors investment in avoidance ability only. When life span increases (white background), however, the coevolutionary outcome depends on the initial conditions. Two endpoints are possible where the host could either invest solely into avoidance (top black line) or solely into recovery and maternal transfer of immunity (dashed line and lower black line). Default parameter values: $r_0 = 1.5$, $\mu = 0.1$, $\kappa = 0.1$, $c_{r,\pi} = 0.3$, $c_{r,\gamma} = 0.2$, $c_{r,\theta} = 0.08$, $k_{r,\pi} = 0.5$, $k_{r,\gamma} = 1/0.9$, $k_{r,\theta} = 1/0.9$, $\alpha = 2.75$, $\beta = 2$, $\delta_R = 0.5$, $\delta_M = 0.75$.**

Our model does not account for the age structure of the host population. Age structure may indeed modify the evolution of the transgenerational transfer of immunity as newborns may face less virulent parasites. Several disease agents indeed show a strong age dependent virulence. For instance, varicella zoster virus leads more often to complications and death in adults than in children (Preblud 1981; Guess et al. 1986). Moreover, as mentioned above, the immune system requires time to achieve its full efficiency and newborns only display part of their future adult ability to recover from the infection. Accounting for age structure in our framework may thus give interesting insights on how the occurrence of such variable patterns of virulence and ability to recover may modify the evolution of acquired resistance mechanisms. In particular, accounting for both the dynamics of passive protection and the dynamics of the development of the immune system in the newborn could bring insight on key periods for early life infectious risk such as the "window of susceptibility" (e.g., Day and Schultz 2011).

Our model focused on the evolution of host defense strategies but host resistance feeds back on the evolution of the parasite. In particular, increase in recovery rate has been shown to result in an increase in parasite virulence (van Baalen 1998). As maternal transfer of immunity is associated with recovery and results in the protection of another part of the population, accounting for this mechanism should thus lead to decreased levels of virulence. We also showed that considering several strains of parasite modified the evolution of the transfer of maternal immunity. How maternal transfer of immunity would affect the coexistence and the characteristics of different parasite strains remains to be determined. Our theoretical framework, in particular when accounting for two strains, could be readily modified to provide insight on that question.

CONCLUDING REMARK

Although we primarily built this framework with vertebrate models in mind as the transfer of maternal antibodies is a mechanism specific to this group, there is no reason to exclude the possibility of specific acquired resistance mechanisms in invertebrates (Schmid-Hempel 2005). There is also increasing evidence for specific transgenerational immune priming in invertebrates (Little and Kraaijeveld 2004; Sadd and Schmid-Hempel 2007; Tidbury et al. 2011) and our approach could be easily extended to understand the evolution of those biological systems. The analysis of a modified version of our model to fit the general assumptions of insect–pathogen interactions led to qualitatively similar results (see the description of the MSI model in Supporting Information). It could also be developed to explore the evolution of genetic resistance mechanisms such as CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) in bacteria (Sorek et al. 2008) or epigenetic resistance mechanisms like herbivory in plants (Agrawal 2002). By inserting some more specific biological features and including yet other resistance mechanisms, the general modeling framework we develop here could thus contribute to a better understanding of the evolution and coevolution of transgenerational resistance mechanisms.

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Appendix

EPIDEMIOLOGY

In the absence of the parasite the dynamics of the host is determined by the balance between density-dependent reproduction and mortality of susceptible individuals in the following way:

$$\dot{S} = (r - \kappa S - \mu)\, S \tag{A1}$$

with κ being a crowding parameter, related to the carrying capacity for the host population by the relation $K = r/\kappa$. At the parasite-free equilibrium the host density is thus: $\hat{S} = (r - \mu)/\kappa$. The ability of a few parasites to invade the host population can be determined from the dynamics of the parasite when it is rare. The parasite will invade when its basic reproductive ratio, R_0, is above 1:

$$R_0 = \frac{(1-\pi)\, h \hat{S}}{\alpha + \gamma + \mu} > 1. \tag{A2}$$

When the above condition is fulfilled, the system (see equation (1)in the main text) reaches a new endemic equilibrium with different types of hosts coexisting ($\bar{M}$, $\bar{S}$,$\bar{I}$, and $\bar{R}$). The overbar refers to the endemic equilibrium. In particular, the endemic density of susceptible hosts is:

$$\bar{S} = \frac{\alpha + \gamma + \mu}{(1-\pi)\, h}. \tag{A3}$$

For the other types of hosts there is no simple analytical expression but they can easily be obtained numerically.

EVOLUTION OF THE HOST WITH A SINGLE PARASITE

Let us now assume that the above system has reached an endemic equilibrium and that a new mutant host appears (i.e., its frequency is initially rare). Will this mutant invade the host population? Because we assume that the resident system has reached an endemic equilibrium and that the mutant is initially rare, the invasion condition can be derived from the linearization of the system (equation (1)in the main text) near the endemic equilibrium of the resident (the superscript m refers to the mutant):

$$H^m = A^m \cdot H^m, \tag{A4}$$

where $H^m = (M^m\, S^m\, I^m\, R^m)^T$ is the vector of the densities of the mutant in the different states of the hosts, and A^m describes the growth of the mutant in these different states:

$$\mathrm{A}^m = \begin{pmatrix} -(\mu^m + \delta_M) & 0 & 0 & \theta^m \lambda^m \\ \lambda^m + \delta_M & \lambda^m - (\mu^m + (1-\pi^m)h) & \lambda^m & (1-\theta^m)\,\lambda^m + \delta_R \\ 0 & (1-\pi^m)\, h & -(\mu^m + \gamma^m + \alpha) & 0 \\ 0 & 0 & \gamma^m & -\mu^m - \delta_R \end{pmatrix}. \tag{A5}$$

We assume that the mutation may act on various host defense traits and that this mutation is supposed to be associated with costs on reproduction or survival. More specifically we assume:

$\lambda^m = r_0(1 - C_r)(1 - \bar{N}/K)$ and $\mu^m = \mu_0(1 + C_s)$, where $\bar{N} = \bar{M} + \bar{S} + \bar{I} + \bar{R}$ is the equilibrium density of the total host population, r_0 and μ_0 are the intrinsic birth and death rates of the host, respectively. The parameters C_r and C_s refer to the costs on reproduction and on survival, respectively; and are of the form:

$$C_r = \sum_x c_{r,x} x^{k_x},$$

$$C_s = \sum_x c_{s,x} x^{k_x}.$$

The coefficients $c_{r,x}$ and $c_{s,x}$ measure how an increase in host trait x affects reproduction and survival, and the coefficients k_x measure the shape of the relationship between the trait and the cost. In the present article, we consider the evolution of three different host defense strategies: $x \in \{\pi^m, \gamma^m, \theta^m\}$. Moreover, for the sake of simplicity, we only assume host defense affects fecundity (a cost on survival does not modify qualitatively the results). In other words we assume throughout the article that $C_s = 0$ and $\mu^m = \mu = \mu_0$.

The above matrix can be written as $A^m = F^m - V^m$, where F^m refers to fecundity (how many mutant hosts are created in each of the four different types) and V^m refers to the transition

between the different types:

$$F^m = \begin{pmatrix} 0 & 0 & 0 & \theta^m \lambda^m \\ \lambda^m + \delta_M & \lambda^m & \lambda^m & (1-\theta^m)\lambda^m + \delta_R \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \quad \text{(A6)}$$

$$V^m = \begin{pmatrix} \mu + \delta_M & 0 & 0 & 0 \\ 0 & \mu + (1-\pi^m)h & 0 & 0 \\ 0 & -(1-\pi^m)h & \mu + \gamma^m + \alpha & 0 \\ 0 & 0 & -\gamma^m & \mu + \delta_R \end{pmatrix}, \quad \text{(A7)}$$

Note, however, that the gain of S individuals through the loss of immunity endured by M and R individuals described by the parameters $\delta_M$and $\delta_R$are included in the F^m matrix. Although they do not correspond to reproduction events, including those transitions in F^m greatly simplifies the expression of V^{m-1} which in turn allows for the derivation of a simpler invasion condition for the mutant (see below). It can be readily shown that, as the parameters of our model are all positive quantities, the conditions required to satisfy the Next Generation Theorem are all fulfilled (van den Driessche & Watmough 2002; Hurford et al. 2010). In other words, the spectral bound of $-V^m$ is negative and all the elements of F^m and V^{m-1} are greater than or equal to zero.

The mutant host will invade the resident equilibrium when the dominant eigenvalue of A^m is positive or, equivalently, when the dominant eigenvalue of $B^m = F^m \cdot V^{m^{-1}}$ is higher than one (Diekmann, O., J. A. P. Heesterbeek, and J. A. J. Metz. 1990. On the definition and computation of the basic reproduction ratio R0 in models for infectious diseases in heterogeneous populations. J Math Biol 28:365-382. Hurford et al. 2010). We focus on the latter criteria because it yields a pergeneration measure of parasite population growth rate. This matrix B^m is of the form:

$$B^m = \begin{pmatrix} 0 & \tau^m_{S\to M} & \tau^m_{I\to M} & \tau^m_{R\to M} \\ \tau^m_{M\to S} & \tau^m_{S\to S} & \tau^m_{I\to S} & \tau^m_{R\to S} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \quad \text{(A8)}$$

where the coefficients $\tau^m_{i\to j}$ are the rates of production of host type j by a host type i. The dominant eigenvalue of this matrix is as follows:

$$R_m = \frac{\left(\tau^m_{S\to S} + \sqrt{4\tau^m_{M\to S}\tau^m_{S\to M} + \tau^{m2}_{S\to S}}\right)}{2}. \quad \text{(A9)}$$

Hence, this expression depends only on three elements of B^m.

$$\tau^m_{S\to M} = \frac{(1-\pi^m)h}{((1-\pi^m)h+\mu)} \frac{\gamma^m}{(\alpha^m+\gamma^m+\mu)} \frac{\theta^m\lambda^m}{(\mu+\delta_R)}, \quad \text{(A10)}$$

$$\tau^m_{M\to S} = \frac{\lambda^m + \delta_M}{\mu + \delta_M}, \quad \text{(A11)}$$

$$\tau^m_{S\to S} = \frac{\lambda^m}{(1-\pi^m)h+\mu} + \frac{\lambda^m(1-\pi^m)h}{((1-\pi^m)h+\mu)(\alpha^m+\gamma^m+\mu)} + \frac{(1-\pi^m)h((1-\theta^*)\lambda^m+\delta_R)\gamma^m}{((1-\pi^m)h+\mu)(\alpha^m+\gamma^m+\mu)(\mu+\delta_R)}. \quad \text{(A12)}$$

These three coefficients correspond to the different transitions between M and S hosts (see Fig. S1). For instance, focusing on the expression of $\tau^m_{S\to M}$, there are three steps for a susceptible individual to produce maternally protected newborns: the individual has first to get infected (S to I), then to recover to become resistant (I to R) and finally to reproduce depending on its immunity transfer strategy (R to M). Equation (A10) is the product of these three terms. The same reasoning applies to the expression of $\tau^m_{M\to S}$, which includes both reproduction of M individuals and loss of immunity. Finally, in $\tau^m_{S\to S}$, each term of the sum describes three different ways in which a susceptible individual can produce new susceptible individuals (see Fig. S1).

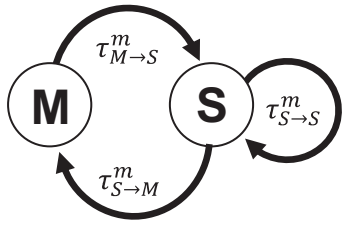

Figure A1. Diagram showing the transitions represented by $\tau^m_{M\to S}$, $\tau^m_{S\to M}$, and $\tau^m_{S\to S}$.

EVOLUTION OF THE HOST WITH TWO PARASITES

Here we expand the previous model to a situation where two strains of parasites (1 and 2) are circulating in the host population. With regard to each parasite, individuals can thus be sensitive (S), infected by either strain 1 (I_1) or strain 2 (I_2), recovered from infection (R_1 or R_2), and protected by maternal immunity (M_1 or M_2). For the sake of simplicity, we consider that when individuals have recovered from an infection by a given strain (R individuals), they cannot be infected by the other strain. Individuals can thus only develop their immunity against one of the strains. Maternally protected (M) individuals for a given strain may, in contrast, be infected by the other strain. How maternal transfer of immunity against one strain efficiently prevents infection by the other strain is described by an additional parameter, χ, which measures the level of cross immunity of the maternal transfer.

As for the one strain model, the invasion of a mutant host requires a description of the dynamics of the system near the endemic equilibrium of the resident (the superscript m refers to the mutant) using equation (A4) with

$H^m = (M_1^m\ M_2^m\ S^m\ I_1^m\ I_2^m\ R_1^m\ R_2^m)^T$ and where A^m can be decomposed as $A^m = F^m - V^m$ with F^m and V^m:

$$F^m = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & \theta^m\lambda^m & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \theta^m\lambda^m \\ \lambda^m+\delta_M & \lambda^m+\delta_M & \lambda^m & \lambda^m & \lambda^m & (1-\theta^m)\lambda^m+\delta_R & (1-\theta^m)\lambda^m+\delta_R \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \gamma & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \gamma & 0 & 0 \end{pmatrix}$$

$$V^m = \begin{pmatrix} \mu+\delta_M+(1-\chi)h_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \mu+\delta_M+(1-\chi)h_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \mu+(1-\pi^m)(h_1+h_2) & 0 & 0 & 0 & 0 \\ 0 & -(1-\chi)h_1 & -(1-\pi^m)h_1 & \mu+\gamma^m+\alpha & 0 & 0 & 0 \\ -(1-\chi)h_2 & 0 & -(1-\pi^m)h_2 & 0 & \mu+\gamma^m+\alpha & 0 & 0 \\ 0 & 0 & 0 & -\gamma^m & 0 & \mu+\delta_R & 0 \\ 0 & 0 & 0 & 0 & -\gamma^m & 0 & \mu+\delta_R \end{pmatrix}.$$

The same calculation using the Next Generation Theorem can be applied to obtain an expression of the invasion criterion R_m that determines whether a mutant can invade the resident host population. This expression, however, is a bit more complicated and we only use it to derive the evolutionary stable level of maternal transfer of immunity in Fig. 2.

Supporting Information

The following supporting information isavailable for this article:

Figure S1. Evolutionary stable investment in transgenerational transfer of immunity ability (θ) as a function of different parameters.
Supporting Information may be found in the online version of this article.

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Supporting information

Alternative life cycles

In the following we relax some simplifying assumptions of the model analysed in the main text and we discuss 3 alternative life cycles.

1. A model without recovered individuals (MSI life cycle)

We first consider a scenario where infected hosts can reproduce and transfer immune protection with a probability θ, but cannot recover from the infection. This life cycle may fit the interaction between many insects and their pathogens. The matrices $\boldsymbol{F^m}$ and $\boldsymbol{V^m}$ can be rewritten in the following way to describe this model:

$$F^m = \begin{pmatrix} 0 & 0 & \theta^m\lambda^m \\ \lambda^m + \delta_M & \lambda^m & (1-\theta^m)\lambda^m \\ 0 & 0 & 0 \end{pmatrix} \quad \text{(S1)}$$

$$V^m = \begin{pmatrix} \mu + \delta_M & 0 & 0 \\ 0 & \mu + (1-\pi^m)h & 0 \\ 0 & -(1-\pi^m)h & \mu + \alpha \end{pmatrix} \quad \text{(S2)}$$

In that case, the invasion criterion for a mutant host corresponds to the dominant eigenvalue of the $\boldsymbol{B^m}$ matrix of the form:

$$B^m = \begin{pmatrix} 0 & \tau^m_{S\to M} & \tau^m_{I\to M} \\ \tau^m_{M\to S} & \tau^m_{S\to S} & \tau^m_{I\to S} \\ 0 & 0 & 0 \end{pmatrix} \quad \text{(S3)}$$

where the coefficients $\tau^m_{i\to j}$ are the rates of production of host type *j* by a host type i. The dominant eigenvalue of this matrix reduces to the dominant eigenvalue of the upper 2x2 matrix and thus the invasion criteria is of the same form for the *MSI* and the *MSIRS* models

(see equation A9 in the appendix). However, as the terms in $\boldsymbol{F^m}$ and $\boldsymbol{V^m}$ are different, the resulting $\tau_{i\to j}^{m}$ in $\boldsymbol{B^m}$ are also different:

$$\tau_{S\to M}^{m} = \frac{(1-\pi^m)h}{((1-\pi^m)h+\mu)}\frac{\theta^m\lambda^m}{(\mu+\alpha)} \quad \text{(S4)}$$

$$\tau_{M\to S}^{m} = \frac{\lambda^m+\delta_M}{\mu+\delta_M} \quad \text{(S5)}$$

$$\tau_{S\to S}^{m} = \frac{\lambda^m}{(1-\pi^m)h+\mu} + \frac{\lambda^m(1-\pi^m)h}{\left((1-\pi^m)h+\mu\right)(\alpha^m+\mu)} \quad \text{(S6)}$$

2. A model with two classes of recovered individuals ($MSIR_1R_2S$ life cycle)

Next we will consider a scenario where recovered individuals can lose their ability to maternally protect newborns before losing their own protection against the pathogen. To model this case we split the compartment of recovered individuals in two types of immune hosts:

- R_1 are produced by the recovery of infected individuals. They have the ability to transfer their protection to their newborns at a rate θ, and become R_2 individuals at a rate δ_{R1}.
- R_2 individuals are still immune but their immunity has decayed so that they only produce susceptible individuals when they reproduce. They also lose their remaining protection to become susceptible at a rate δ_{R2}.

This model can be described by the following set of matrices $\boldsymbol{F^m}$ and $\boldsymbol{V^m}$:

$$\boldsymbol{F}^m = \begin{pmatrix} 0 & 0 & 0 & \theta^m\lambda^m & 0 \\ \lambda^m+\delta_M & \lambda^m & \lambda^m & (1-\theta^m)\lambda^m & \lambda^m+\delta_{R2} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad \text{(S7)}$$

$$\boldsymbol{V}^m = \begin{pmatrix} \mu + \delta_M & 0 & 0 & 0 & 0 \\ 0 & \mu + (1-\pi^m)h & 0 & 0 & 0 \\ 0 & -(1-\pi^m)h & \mu + \gamma^m + \alpha & 0 & 0 \\ 0 & 0 & -\gamma^m & \mu + \delta_{R1} & 0 \\ 0 & 0 & 0 & -\delta_{R1} & \mu + \delta_{R2} \end{pmatrix} \quad \text{(S8)}$$

In that case, the invasion criterion for a mutant host corresponds to the dominant eigenvalue of the $\boldsymbol{B^m}$ matrix of the form:

$$\boldsymbol{B}^m = \begin{pmatrix} 0 & \tau^m_{S\to M} & \tau^m_{I\to M} & \tau^m_{R_1\to M} & 0 \\ \tau^m_{M\to S} & \tau^m_{S\to S} & \tau^m_{I\to S} & \tau^m_{R_1\to S} & \tau^m_{R_2\to S} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad \text{(S9)}$$

where the coefficients $\tau^m_{i\to j}$ are the rates of production of host type *j* by a host type i. The dominant eigenvalue of this matrix reduces again to the dominant eigenvalue of the upper 2x2 matrix and thus the invasion criteria is of the same form for the *MSIR₁R₂S* and the *MSIRS* models (see equation A9 in the appendix). However, the separation of the immune individuals into R_1 and R_2 that differently produce *M* individuals induces modifications in the transitions $\tau^m_{S\to M}$ and $\tau^m_{S\to S}$:

$$\tau^m_{S\to M} = \frac{(1-\pi^m)h}{((1-\pi^m)h+\mu)} \frac{\gamma^m}{(\alpha^m+\gamma^m+\mu)} \frac{\theta^m\lambda^m}{(\mu+\delta_{R_1})} \quad \text{(S10)}$$

$$\tau^m_{S\to S} = \frac{\lambda^m}{(1-\pi^m)h+\mu} + \frac{\lambda^m(1-\pi^m)h}{((1-\pi^m)h+\mu)(\alpha^m+\gamma^m+\mu)} + \frac{(1-\pi^m)h\gamma^m(1-\theta^*)\lambda^m}{((1-\pi^m)h+\mu)(\alpha^m+\gamma^m+\mu)(\mu+\delta_{R_1})} + \frac{(1-\pi^m)h\gamma^m\delta_{R_1}(\lambda^m+\delta_{R_2})}{((1-\pi^m)h+\mu)(\alpha^m+\gamma^m+\mu)(\mu+\delta_{R_1})(\mu+\delta_{R_2})} \quad \text{(S11)}$$

3. A model where juveniles do not reproduce (MS_JS_AIRS life cycle)

One important assumption of the MSIRS model is that all individuals are able to reproduce. However, the transmission of maternal protection implies some sort of age structure as maternally protected *M* individuals are supposed to be newborns and should not be able to reproduce. The same reasoning applies to the susceptible *S* individuals as this category is a mix of adults and newborns. To take this hidden age structure into account, we consider two categories of newborns: maternally protected juveniles (*M)* and susceptible juveniles (S_J), both of them unable to reproduce. Maternally protected juveniles lose their protection at a rate δ_M and then become susceptible adults (S_A) able to reproduce. Susceptible juveniles can be infected depending on the force of infection of the parasite and become susceptible adults at a rate δ_M similar to the one of *M* individuals. This modifies the $\boldsymbol{F^m}$ and $\boldsymbol{V^m}$ matrices in the following way:

$$\boldsymbol{F}^m = \begin{pmatrix} 0 & 0 & 0 & 0 & \theta^m\lambda^m \\ 0 & 0 & \lambda^m & \lambda^m & (1-\theta^m)\lambda^m \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad \text{(S12)}$$

$$\boldsymbol{V}^m = \begin{pmatrix} \mu+\delta_M & 0 & 0 & 0 & 0 \\ 0 & \mu+\delta_M+(1-\pi^m)h & 0 & 0 & 0 \\ -\delta_M & -\delta_M & \mu+(1-\pi^m)h & 0 & -\delta_R \\ 0 & -(1-\pi^m)h & -(1-\pi^m)h & \mu+\gamma^m+\alpha & 0 \\ 0 & 0 & 0 & -\gamma^m & \mu+\delta_R \end{pmatrix} \quad \text{(S13)}$$

Note that the gain of S_A individuals through the loss of immunity endured by *M* and *R* individuals, or through aging of S_J individuals (i.e. the parameters δ_M and δ_R) is no longer included in the $\boldsymbol{F}^m$ matrix. Here, contrary to the previous analyses, including those transitions in $\boldsymbol{V}^m$ greatly simplifies the expression of $\boldsymbol{B}^m$and thus allows for the derivation of a simpler invasion condition for the mutant. This $\boldsymbol{B}^m$ matrix is of the form:

$$\boldsymbol{B}^m = \begin{pmatrix} \tau^m_{M\to M} & \tau^m_{S_J\to M} & \tau^m_{S\to M} & \tau^m_{I\to M} & \tau^m_{R\to M} \\ \tau^m_{M\to S_J} & \tau^m_{S_J\to S_J} & \tau^m_{S\to S_J} & \tau^m_{I\to S_J} & \tau^m_{R\to S_J} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad \text{(S14)}$$

where the coefficients $\tau^m_{i\to j}$ are the rates of production of host type *j* by a host type i. The dominant eigenvalue of this matrix reduces again to the dominant eigenvalue of the upper 2x2 matrix:

$$R_m = \left(\tau^m_{M\to M} + \tau^m_{S_J\to S_J} + \sqrt{4\tau^m_{M\to S_J}\tau^m_{S_J\to M} + (\tau^m_{M\to M} - \tau^m_{S_J\to S_J})^2}\right)/2 \quad \text{(S15)}$$

In this expression, the main transitions involve the production of juveniles, either maternally protected (*M*) or susceptible (S_J). The four different transitions required in S15 are the following:

$$\tau^m_{M\to M} = \frac{\delta_M}{\mu+\delta_M}\frac{(1-\pi^m)h\,\gamma^m\theta^m\lambda^m}{((1-\pi^m)h+\mu)(\alpha^m+\gamma^m+\mu)(\mu+\delta_R)-(1-\pi^m)h\gamma^m\delta_R} \quad \text{(S16)}$$

$$\tau^m_{S_J\to M} = \frac{(1-\pi^m)h\,\gamma^m\theta^m\lambda^m}{(\mu+\delta_R)\big(\mu(\alpha^m+\gamma^m+\mu)+(1-\pi^m)h(\mu+\alpha)\big)+(1-\pi^m)h\mu\,\gamma^m} \quad \text{(S17)}$$

$$\tau^m_{M\to S_J} = \frac{\delta_M}{(\delta_M+\mu)}\frac{((\alpha+\gamma^m+\mu)(\delta_R+\mu)+(1-\pi^m)h(\gamma^m(1-\theta^m)+\delta_R+\mu))\lambda^m}{(\mu(\alpha+\gamma^m+\mu)(\delta_R+\mu)+(1-\pi^m)h(\alpha(\delta_R+\mu)+\mu(\gamma^m+\delta_R+\mu)))} \quad \text{(S18)}$$

$$\tau^m_{S_J\to S_J} = \frac{((1-\pi^m)h\,\gamma^m(\delta_R+(1-\theta^m)\big((1-\pi^m)h+\delta_M+\mu\big))+\delta_M(\alpha+\gamma^m+\mu)(\delta_R+\mu)+(1-\pi^m)h((1-\pi^m)h+\delta_M+\mu)(\delta_R+\mu))\lambda^m}{((1-\pi^m)h+\delta_M+\mu)(-(1-\pi^m)h\,\gamma^m\delta_R+((1-\pi^m)h+\mu)(\alpha+\gamma^m+\mu)(\delta_R+\mu))} \quad \text{(S19)}$$

Supplementary Figure

Figure S1: Evolutionary stable investment in transgenerational transfer of immunity ability (θ) as a function of different parameters. (A) Effect of the force of infection (h). (B) Effect of the virulence of the parasite (α). (C) Effect of the recovery rate (γ). Default parameter values used in the figures: $r_0 = 1.5$, $\mu = 0.1$, $\kappa = 0.1$, $c_{r,\theta} = 0.25$, $k_\theta = 1/0.9$, $\alpha = 5$, $h = 10$, $\delta_R = 1$, $\delta_M = 1$, $\gamma = 0.6$.