Vaccination and the theory of games

Chris T. Bauch[1,*] and David J. D. Earn[2]

revised for *Proceedings of the National Academy of Sciences*

16 July 2004

1: Department of Mathematics and Statistics
University of Guelph
Guelph, Ontario N1G 2W1, Canada

2: Department of Mathematics and Statistics
McMaster University
Hamilton, Ontario L8S 4K1, Canada

* corresponding author: Chris T. Bauch
email: cbauch@uoguelph.ca,
telephone: 519-824-4120 ext. 53079
fax: 519-837-0221

Dual Subject Classification:

Biological Sciences/Population Biology, Physical Sciences/Applied Mathematics

Approximately 4 pages of text in PNAS format; 3 Figures; 1 Table

25447 characters (incl. Figures, Tables and Equations); 128 words in abstract

Abbreviations footnote: CSNE (Convergently stable Nash equilibrium)

Voluntary vaccination policies for childhood diseases present parents with a subtle challenge: if a sufficient proportion of the population is already immune, either naturally or by vaccination, then even the slightest risk associated with vaccination will outweigh the risk from infection. As a result, individual self-interest might preclude complete eradication of a vaccine-preventable disease. We show that a formal game theoretical analysis of this problem leads to new insights that help to explain human decision-making with respect to vaccination. Increases in perceived vaccine risk will tend to induce larger declines in vaccine uptake for pathogens that cause more secondary infections (such as measles and pertussis). Following a vaccine scare, even if perceived vaccine risk is greatly reduced, it will be relatively difficult to restore pre-scare vaccine coverage levels.

The history of vaccination policy includes numerous bouts of public resistance, often in the form of vaccine scares (1–4). In the United Kingdom, for example, a pertussis vaccine scare in the 1970s caused a decline in the level of vaccine coverage, resulting in substantial increases in morbidity and mortality from whooping cough (4). Currently, measles-mumps-rubella (MMR) vaccine uptake is declining in the United Kingdom, with mounting concern that widespread outbreaks of measles may recur (5).

In deciding whether or not to vaccinate their children, parents consider the risk of morbidity from vaccination, the probability that their child will become infected, and the risk of morbidity from such an infection. The decisions of individual parents are indirectly influenced by the decisions of all other parents, because the sum of these decisions yields the vaccine coverage levels in the population and hence the course of epidemics.

Game theory (6–9) attempts to predict individual behavior in such a setting, where the payoff to strategies chosen by individuals depends upon the strategies adopted by others in the population. Here, we integrate epidemic modeling (10) into a game theoretical framework in order to analyze population behavior under voluntary vaccination policies for childhood diseases. This approach allows us to quantify how risk perception influences expected vaccine uptake and coverage levels and what role is played by the epidemiological characteristics of the pathogens.

The Vaccination Game

Description of game For simplicity, we imagine that all individuals are provided with the same information and use this information in the same way to assess risks. An individual's *strategy* is the probability P that s/he will choose to vaccinate. The *vaccine uptake* level in the population is the proportion of newborns who will be vaccinated and hence is the mean of all strategies adopted by individuals in the population. We ignore any delay between changes in vaccine uptake and corresponding changes in overall vaccine coverage in the population; consequently, if there is no disease-related or vaccine-related mortality, then the proportion of the population vaccinated, p, will be equal to the vaccine uptake level.

The payoff to an individual will be greater when morbidity risk (probability of adverse consequences) is lower. We use r_{v} and r_{i} to denote the morbidity risks from vaccination and infection, respectively, and π_p to denote the probability that an unvaccinated individual will eventually be infected if the vaccine coverage level in the population is p. With this notation, the payoff is $-r_{\mathrm{v}}$ to a vaccinated individual and $-r_{\mathrm{i}}\pi_p$ to an unvaccinated individual. Thus, the strategy of vaccinating with probability P yields expected payoff

$$E(P,p) = P(-r_{\mathrm{v}}) + (1-P)(-r_{\mathrm{i}}\pi_p)\,. \qquad \textbf{[1]}$$

In the context of vaccination, parents act according to *perceived* morbidity risks, which may differ significantly from actual morbidity risks (3, 11). Consequently, we interpret r_{i} and r_{v} as the perceived morbidity risks from infection and vaccination, and $E(P,p)$ as the perceived payoff. The game is unchanged if we scale the payoff function by a constant. Therefore, we can eliminate one of the parameters, leaving only the *relative risk*, $r = r_{\mathrm{v}}/r_{\mathrm{i}}$. Thus, we can write

$$E(P,p) = -rP - \pi_p(1-P)\,. \qquad \textbf{[2]}$$

Characterization of Nash equilibria We now seek to identify which strategies are likely to be adopted. If most of the population adopts strategy P, and individuals that adopt any other strategy Q always obtain a lower payoff than those adopting P, then P is said to be a *Nash equilibrium*. In contrast, if most individuals adopt strategy Q, but individuals adopting a strategy that is closer than Q to P obtain a higher payoff than those adopting Q (and those adopting a strategy further from P obtain a lower payoff), and if this is true for any $Q \neq P$, then P is said to be *convergently stable*. If P is a Nash equilibrium, and everyone is currently playing P, then no one should change strategy. If P is convergently stable, then regardless of what strategy is most common in the population, individuals should start to play strategies closer to P, and ultimately adopt P. It is generally expected that a strategy observed in a real population (12) must be a *convergently stable Nash equilibrium* (CSNE).

Suppose that a proportion ε of the population vaccinates with probability P and the remainder vaccinate with probability Q. Since we ignore any difference between vaccine uptake, $\varepsilon P + (1-\varepsilon)Q$, and overall vaccine coverage in the population, p, we can always write

$$p = \varepsilon P + (1-\varepsilon)Q\,. \qquad \textbf{[3]}$$

The payoff to individuals playing P is, therefore,

$$E_P(P,Q,\varepsilon) = E(P, \varepsilon P + (1-\varepsilon)Q)\,, \qquad \textbf{[4]}$$

while the payoff to individuals playing Q is

$$E_Q(P,Q,\varepsilon) = E(Q, \varepsilon P + (1-\varepsilon)Q)\,, \qquad \textbf{[5]}$$

The *payoff gain* to an individual playing P in such a population is

$$\Delta E = E_P - E_Q = [\pi_{\varepsilon P+(1-\varepsilon)Q} - r](P-Q)\,. \qquad \textbf{[6]}$$

The payoff gain ΔE is a measure of the incentive for an individual to change strategies from Q to P. For any given relative risk r there is a unique strategy $P = P^*$ such that ΔE

is strictly positive for all strategies $Q \neq P^*$ and all proportions ε, where $0 \leq \varepsilon < 1$ (see the Appendix for a proof). The special case of this fact for small proportions playing Q (ε near 1) implies that P^* is a Nash equilibrium. We also show in the Appendix that if neither P nor Q is equal to the Nash equilibrium P^*, but P is closer than Q to P^*, then $\Delta E > 0$, implying that P^* is convergently stable and hence a CSNE.

The unique CSNE in this vaccination game is easily found (see the Appendix). If the vaccine is perceived to be sufficiently risky ($r \geq \pi_0$) then the CSNE is “never vaccinate” ($P^* = 0$). In contrast, if $r < \pi_0$ then the CSNE is “vaccinate with non-zero probability P^*” ($0 < P^* < 1$). In the latter case, the CSNE is said to be *mixed* (as opposed to the *pure* strategies $P = 0$ and $P = 1$).

Incorporation of an epidemic model

To make more precise predictions we must specify the infection probability π_p. For this, we need an epidemiological model. We use a standard three-compartment model in which individuals are either susceptible to the disease (S), infectious (I) or recovered to a state of lifelong immunity (R). This *SIR model*, and variants thereof, are widely used in modeling childhood diseases (10, 13). The model is specified by the rates of change of the proportions of the population in each compartment,

$$\frac{dS}{dt} = \mu(1-p) - \beta SI - \mu S\,, \qquad \textbf{[7]}$$

$$\frac{dI}{dt} = \beta SI - \gamma I - \mu I\,, \qquad \textbf{[8]}$$

$$\frac{dR}{dt} = \mu p + \gamma I - \mu R\,. \qquad \textbf{[9]}$$

Here, μ is the mean birth and death rate, β is the mean transmission rate, $1/\gamma$ is the mean infectious period, and p is the vaccine uptake level (assuming, for simplicity, that individuals are never infected before being vaccinated). Once a dynamical steady state is reached, the vaccine coverage level in the population will equal the uptake level. Since we shall focus on the steady state solution of the model, our notation p for vaccine uptake is consistent with our notation in the game-theoretical analysis (cf. Eq. **3**).

The third equation in the SIR model above is superfluous because $S+I+R=1$. The remaining two equations can be written in a convenient, dimensionless form,

$$\frac{dS}{d\tau} = f(1-p) - \mathcal{R}_0(1+f)SI - fS\,, \qquad \textbf{[10]}$$

$$\frac{dI}{d\tau} = \mathcal{R}_0(1+f)SI - (1+f)I\,, \qquad \textbf{[11]}$$

where $\tau = t/\gamma$ is time measured in units of the mean infectious period, $f = \mu/\gamma$ is the infectious period as a fraction of mean lifetime, and $\mathcal{R}_0 = \beta/(\gamma+\mu)$ is the basic reproductive ratio (the average number of secondary cases produced by a typical primary case in a fully susceptible population). For childhood diseases, $f < 0.001$ and $\mathcal{R}_0 \sim$ 5–20 (e.g., Ref. 10).

The predictions of the SIR model depend on the critical coverage level that eliminates the disease from the population (10), p_{crit}, which itself is a function of $\mathcal{R}_0$,

$$p_{\text{crit}} = \begin{cases} 0 & \text{if } \mathcal{R}_0 \leq 1, \\ 1 - \frac{1}{\mathcal{R}_0} & \text{if } \mathcal{R}_0 > 1. \end{cases} \qquad \textbf{[12]}$$

If $p \geq p_{\text{crit}}$ then the system converges to the *disease-free* state $(\hat{S},\hat{I}) = (1-p,0)$, whereas if $p < p_{\text{crit}}$, it converges to a stable *endemic* state given by

$$\hat{S} = 1 - p_{\text{crit}}\,, \qquad \textbf{[13]}$$

$$\hat{I} = \frac{f}{1+f}(p_{\text{crit}} - p)\,. \qquad \textbf{[14]}$$

Since S and I are constant in this situation, the probability that an unvaccinated individual eventually becomes infected can be expressed, using Eqs. **10-14**, as the proportion of susceptible individuals becoming infected versus dying in any unit time,

$$\pi_p = \frac{\mathcal{R}_0(1+f)\hat{S}\hat{I}}{\mathcal{R}_0(1+f)\hat{S}\hat{I} + f\hat{S}} = 1 - \frac{1}{\mathcal{R}_0(1-p)}\,. \qquad \textbf{[15]}$$

(Note that the parameter f does not appear in this expression for π_p, so the CSNE will not depend on the birth rate or the infectious period of the disease.) The condition $r < \pi_0$, which yields a mixed CSNE, can therefore be written

$$\mathcal{R}_0(1-r) > 1\,. \qquad \textbf{[16]}$$

The value of the mixed CSNE P^*, obtained by solving the equation $r = \pi_{P^*}$ for P^*, is

$$P^* = 1 - \frac{1}{\mathcal{R}_0(1-r)}\,. \qquad \textbf{[17]}$$

Results and Discussion

For any perceived relative risk $r > 0$, the expected vaccine uptake is less than the eradication threshold, i.e., $P^* < p_{\text{crit}}$ (Figure 1). This formalizes an argument that has previously been made qualitatively (8, 14); namely, it is impossible to eradicate a disease through voluntary vaccination when individuals act according to their own interests. In situations where vaccination is perceived to be more risky than contracting the disease ($r > 1$), one would expect—even without the aid of a model—that no parents would vaccinate their children. Our game theoretical analysis shows that, in fact, the threshold in perceived relative risk beyond which all parents should cease vaccinating depends upon $\mathcal{R}_0$. In particular, parents can be expected to play a pure nonvaccinator strategy if $r > \pi_0$, i.e., if

$$r > 1 - \frac{1}{\mathcal{R}_0}\,. \qquad \textbf{[18]}$$

For childhood diseases this *relative risk threshold* is close to 1, but for diseases with relatively small $\mathcal{R}_0$, the threshold could be substantially smaller.

With knowledge of the perceived relative risk, r, we can thus predict vaccine coverage levels under voluntary policies. However, risk perception (and hence the value of r) can change over time in response to a variety of factors, such as media coverage and the activities of anti-vaccination groups (3, 11, 15–17). Under normal circumstances the relative risk is perceived to be very low (typically much lower than the relative risk threshold, $r \ll \pi_0 < 1$). During a vaccine scare, the perceived risk of vaccination will rise (by definition) and hence relative risk will increase to some new level $r' > r$. Note that a reduction in the perceived risk of morbidity from disease has the same effect. In either case, the qualitative nature of our predictions depends on whether the new risk ratio exceeds the relative risk threshold; if $r < r' \ll \pi_0$ then behavioural changes will be relatively minor during a scare, whereas if $r \ll \pi_0 < r'$ then dramatic changes in vaccine uptake can occur (see Table 1 and Figure 2).

Several lines of evidence suggest that it is likely that $r' > \pi_0$ during a vaccine scare. Many parents currently have concerns about the safety of the MMR vaccine (18, 19) (and other vaccines (20)), and many parents (in developed countries) believe that diseases such as measles and whooping cough are essentially harmless (21) (together these observations indicate that $r' > 1$ for measles, mumps and rubella at present in the UK). Targetted surveys show that among subscribers to a parenting magazine (22) and among inhabitants of specific areas in the UK (23), a significant proportion of parents believe vaccines entail more risk than the diseases against which they protect ($r' > 1$) and this perception is correlated with not vaccinating (22).

When $r \ll \pi_0 < r'$, the degree to which a vaccine scare is likely to impact vaccination behaviour depends sensitively on the value of $\mathcal{R}_0$. The payoff gain ΔE that measures the incentive to switch from the previous CSNE P (associated with $r \ll \pi_0$) to the new CSNE P' (associated with $r' > \pi_0$) is always larger for diseases with larger $\mathcal{R}_0$. Consequently, we would expect individuals to be convinced more rapidly to change their vaccination behaviour in the face of a vaccine scare for measles or whooping cough (for which $\mathcal{R}_0 > 10$) than for less transmissible infections. In general, for a given increase in risk perception, we expect precipitous reductions in vaccine uptake to be more common for diseases with higher $\mathcal{R}_0$.

If $\mathcal{R}_0$ is large, individuals are also likely to be more responsive to any reductions in the perceived relative risk of vaccination that occur after a vaccine scare (Figure 3 and Table 1). Such reductions in r might result from media coverage of a few severe cases of disease (which are more likely as vaccine uptake drops and disease incidence rises). More importantly, education programmes that aim to increase public confidence in vaccines following a scare are likely to be most effective for precisely the vaccines for which scares have the greatest impact.

Unfortunately, the effectiveness of education programmes is constrained in a way that vaccine scares are not. During a vaccine scare, the payoff gain ΔE is given by the expression in the second row of Table 1; this expression is bounded below by a positive number for all ε (even for $\varepsilon = 1$), so the incentive not to vaccinate remains substantial even as the vaccine coverage approaches zero. In contrast, during successful education programmes to combat a vaccine scare, there will be a shift in risk perception from $r > \pi_0$ to $r' < \pi_0$, and the proportion of the population vaccinated will climb to the new CSNE level as more and more individuals are vaccinated. In this case, the payoff gain for adopting the new CSNE is given by the third row of Table 1, which implies (regardless of $\mathcal{R}_0$) that $\Delta E \to 0$ as $\varepsilon \to 1$; this means that the incentive to vaccinate diminishes as the vaccine coverage approaches the new CSNE level. We conclude that, generally, it will be relatively easy to induce a drop in vaccine uptake during a scare, but relatively difficult to restore uptake levels afterwards. This prediction is consistent with the history of the pertussis vaccination scare during the 1970s in Britain (24), for which vaccine uptake dropped much more quickly than it later recovered after the scare. All else being equal, we anticipate that when the current MMR scare in Britain is over, vaccine uptake will rise more slowly than it declined.

We have demonstrated previously that game theory can be a useful tool for evaluating schemes to prepare for the potential reintroduction of a pathogen that has been eradicated globally through mass vaccination (9). Here we have investigated the feedback between individual vaccination decisions and population-level processes that determine vaccine uptake and herd immunity for an endemic disease, bearing in mind that vaccination decisions are strongly influenced by incorrect risk perception (11, 15). Since our goal has been to elucidate the most fundamental issues, we have focussed on the simplest possible epidemiological model appropriate for childhood diseases and have assumed implicitly that transient dynamics (13), seasonal forcing (13, 25) and stochasticity (13, 26) all have negligible effects. We have also ignored variance in risk perception and any effects of risk perception spreading non-homogeneously through social networks. All of these features of real systems merit further investigation.

Acknowledgments We thank Sigal Balshine, Junling Ma and two anonymous refereees for helpful comments. CTB is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC). DJDE is supported by NSERC, the Canadian Institutes of Health Research (CIHR), the Canada Foundation for Innovation (CFI), the Ontario Innovation Trust (OIT) and an Ontario Premier's Research Exellence Award.

References

[1] Durbach, N. (2000) *Soc. Hist. Med.* **13(1)**, 45–62.

[2] Albert, M. R, Ostheimer, K. G, & Breman, J. G. (2001) *N. Engl. J. Med.* **344**, 375–379.

[3] Streefland, P. H. (2001) *Health Policy* **55**, 159–172.

[4] Baker, J. P. (2003) *Vaccine* **21**, 4003–4010.

[5] Jansen, V. A, Stollenwerk, N, Jensen, H. J, Ramsay, M. E, Edmunds, W. J, & Rhodes, C. J. (2003) *Science* **301**, 804.

[6] von Neumann, J & Morgenstern, O. (1944) *Theory of Games and Economic Behavior*. (Princeton University Press, Princeton).

[7] Maynard-Smith, J. (1982) *Evolution and the Theory of Games*. (Cambridge University Press, Cambridge).

[8] May, R. M. (2000) *Science* **287**, 601–602.

[9] Bauch, C. T, Galvani, A. P, & Earn, D. J. D. (2003) *Proc. Natl. Acad. Sci.* **100**, 10564–10567.

[10] Anderson, R. M & May, R. M. (1991) *Infectious Diseases of Humans*. (Oxford University Press, Oxford).

[11] Bellaby, P. (2003) *Brit. Med. J.* **327**, 725–728.

[12] Eshel, I. (1996) *J. Math. Biol.* **34**, 485–510.

[13] Bauch, C. T & Earn, D. J. D. (2003) *Proc. R. Soc. Lond. B* **270**, 1573–1578.

[14] Geoffard, P & Philipson, T. (1997) *Am. Econ. Rev.* **87**, 222–230.

[15] Science Media Centre. (2002) MMR: learning lessons, www.sciencemediacentre.org/aboutus/mmrreport.html.

[16] Taylor, B, Miller, E, Lingam, R, Andrews, N, Simmons, A, & Stowe, J. (2002) *Brit. Med. J.* **324**, 393–396.

[17] Gangarosa, E. J, Galazka, A. M, Wolfe, C. R, Phillips, L. M, Gangarosa, R. E, Miller, E, & Chen, R. T. (1998) *The Lancet* **351**, 356–361.

[18] Roberts, R. J, Sandifer, Q. D, Evans, M. R, Nolan-Farrell, M. Z, & Davis, P. M. (1995) *Brit. Med. J.* **310**, 1629–1639.

[19] Evans, M, Stoddart, H, Condon, L, Freeman, E, Grizzell, M, & Mullen, R. (2001) *Brit. J. Gen. Prac.* **51**, 904–910.

[20] Lashuay, N, Tjoa, T, de Nuncio, M. L. Z, Franklin, M, Elder, J, & Jones, M. (2000) *Prev. Med.* **31**, 522–528.

[21] Schmitt, H. J. (2002) *Vaccine* **20**, S2–S4.

[22] Asch, D. A, Baron, J, Hershey, J. C, Kunreuther, H, Meszaros, J, Ritov, I, & Spranca, M. (1994) *Medical decision making* **14**, 118–123.

[23] Smailbegovic, M. S, Laing, G. J, & Bedford, H. (2003) *Child: Care, Health and Development* **29**, 303–311.

[24] Miller, E & Gay, N. J. (1997) *Dev. Biol. Stand.* **89**, 15–23.

[25] Earn, D. J. D, Rohani, P, Bolker, B. M, & Grenfell, B. T. (2000) *Science* **287**, 667–670.

[26] Bartlett, M. S. (1960) *Stochastic population models in ecology and epidemiology.* (Methuen, London).

Appendix

The probability π_p that an individual eventually becomes infected must decrease strictly with the proportion p of the population that is vaccinated, until p reaches the eradication threshold, $p_{\text{crit}} = 1 - 1/\mathcal{R}_0$. Thus the maximum of π_p occurs for $p = 0$, and for $p \geq p_{\text{crit}}$, $\pi_p = 0$.

Nash equilibrium If $r \geq \pi_0$ then $r > \pi_p$ for all $p > 0$, so for any $\varepsilon \in [0,1)$ in Eq. **6**, $\Delta E > 0$ for all $Q \neq P$ if and only if $P = 0$. Thus, $P^* = 0$ is the unique Nash equilibrium. If $r < \pi_0$ then there exists a unique $p^* \in (0, p_{\text{crit}})$ such that $\pi_p - r > 0$ if $p < p^*$, $\pi_{p^*} = r$ and $\pi_p - r < 0$ if $p > p^*$. For any $Q < P$, we have $p = \varepsilon P + (1-\varepsilon)Q < P$ for all $\varepsilon \in [0,1)$ and, similarly, for any $Q > P$ we have $p > P$ for all $\varepsilon \in [0,1)$. Therefore, in this case where $r < \pi_0$, for any $\varepsilon \in [0,1)$ in Eq. **6**, $\Delta E > 0$ for all $Q \neq P$ if and only if $P = p^*$. Thus, the Nash equilibrium P^* is the unique solution of the equation $\pi_{P^*} = r$.

Convergent stability Given relative risk r, let P^* denote the associated Nash equilibrium. Suppose a proportion ε of the population play a strategy P (not necessarily equal to P^*) while the remainder play $Q \neq P$. We must show, for $\varepsilon \ll 1$, that if $Q < P \leq P^*$ or $P^* \leq P < Q$ then individuals playing P obtain a higher payoff than those playing Q, i.e., $\Delta E > 0$ in Eq. **6**. In fact, this is true for any $\varepsilon \in [0,1)$ and follows immediately because π_p decreases with p and $\pi_{P^*} = r$. If $Q < P \leq P^*$ then $\pi_{\varepsilon P + (1-\varepsilon)Q} - r > 0$, whereas if $P^* \leq P < Q$ then $\pi_{\varepsilon P + (1-\varepsilon)Q} - r < 0$. Hence, in either case, $\Delta E > 0$ in Eq. **6**.

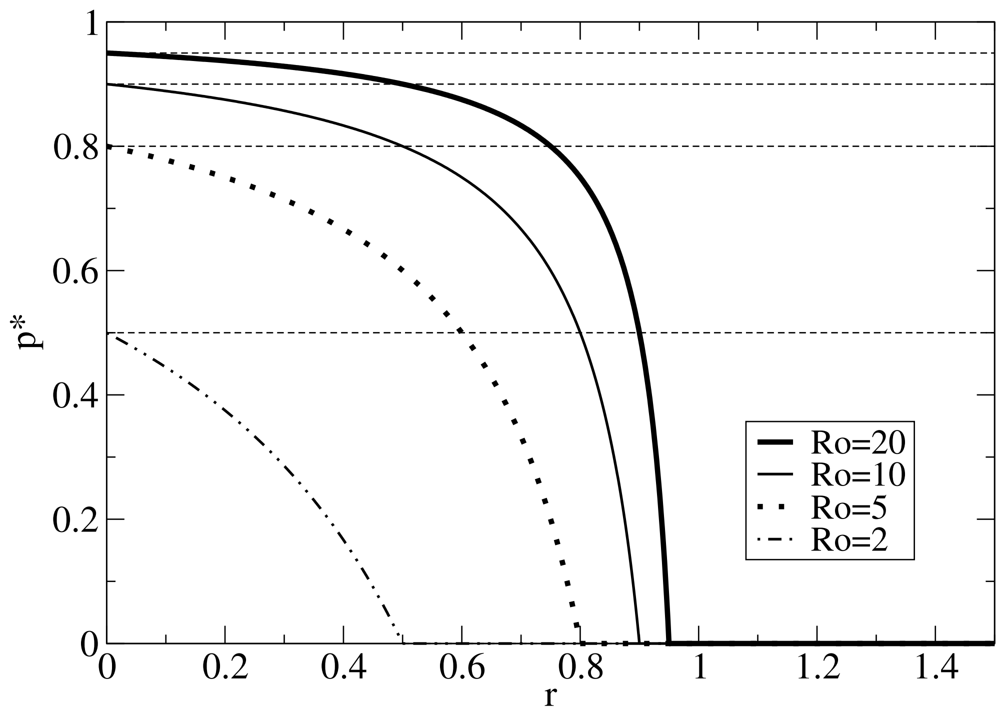

Figure 1: Vaccine coverage p^* at the CSNE versus relative risk r, from Eq. **17**, for various values of $\mathcal{R}_0$. Dashed horizontal lines demarcate the critical coverage level p_{crit} that eliminates the disease from the population (Eq. **12**). In the limit of very large $\mathcal{R}_0$, the plot of p^* versus r approaches a step function with a step at $r = 1$ (Eq. **17**).

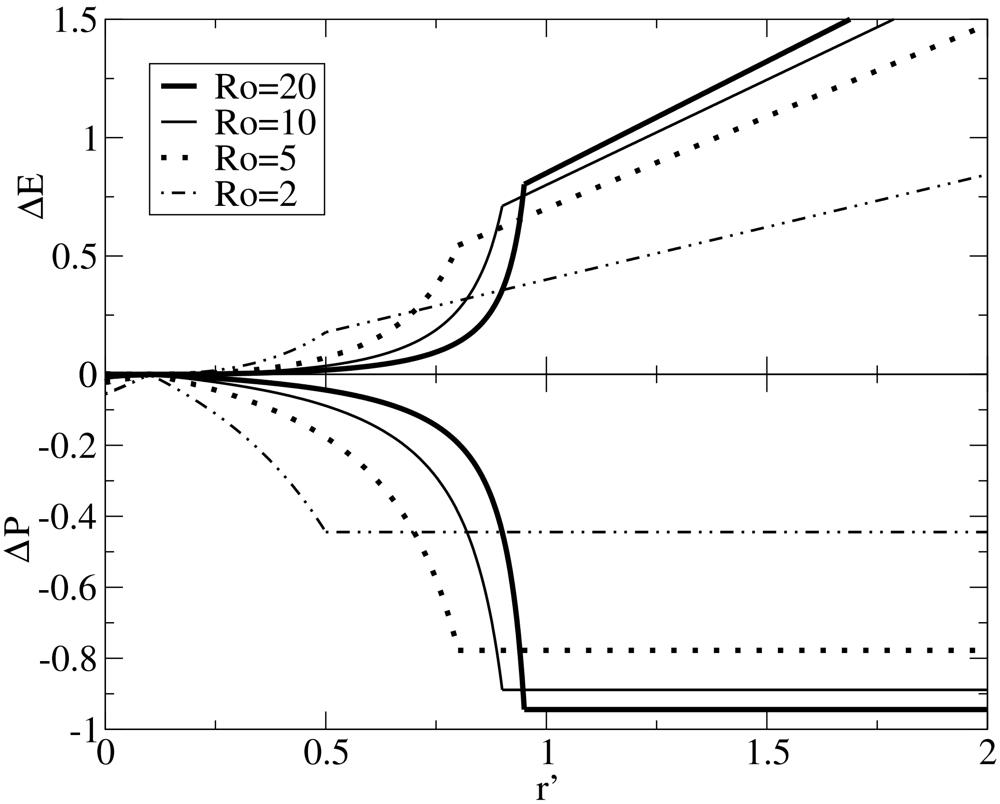

Figure 2: Analysis of vaccine scares: Payoff gain, ΔE, and change in vaccine uptake, ΔP, after a shift in risk perception from $r < \pi_0$ to r' (see Table 1). For this figure, $r = 0.1$ and the proportion of individuals currently adopting the new CSNE is $\varepsilon = 0$ (corresponding to the start of a vaccine scare); the shapes of the curves are qualitatively similar for other values of r and ε.

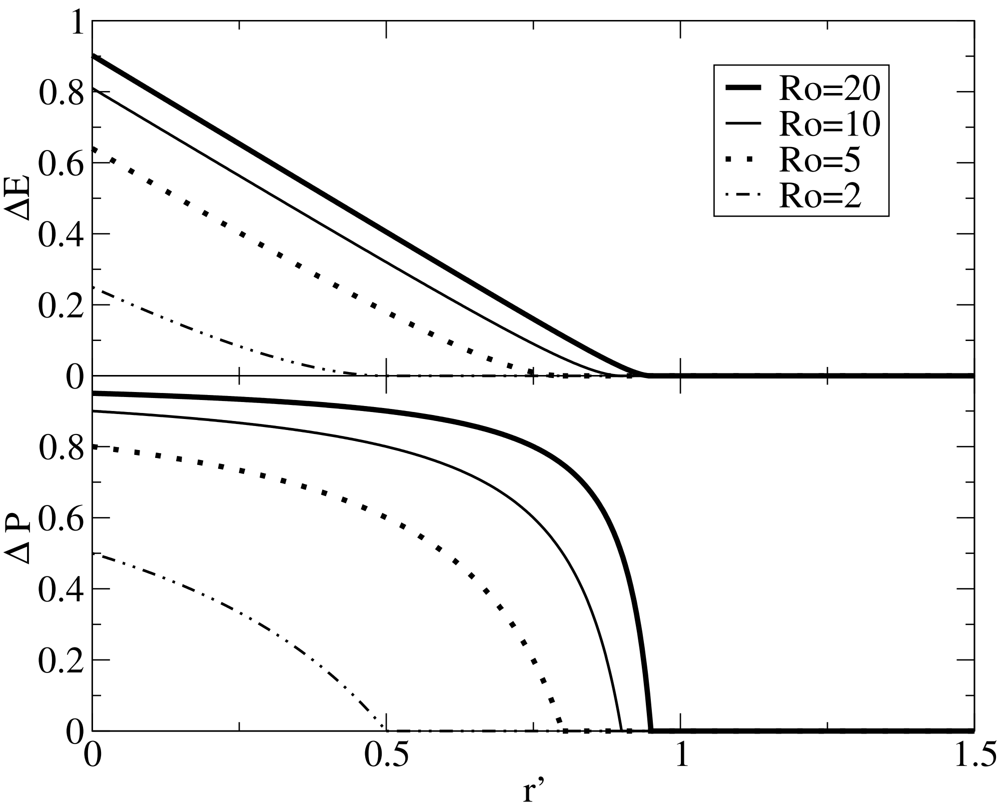

Figure 3: Analysis of public education programmes to counteract vaccine scares: Payoff gain, ΔE, and change in vaccine uptake, ΔP, after a shift in risk perception from $r > \pi_0$ to r'. As in Figure 2, $\varepsilon = 0$ here. The results are independent of r (because the CSNE is always $P = 0$ when $r > \pi_0$). The shapes of the curves are qualitatively similar for other values of ε, but the maximum of ΔE goes to zero as ε increases to 1.

Case	Payoff gain, ΔE	ΔP
$r < \pi_0, \quad r' < \pi_0$	$\frac{(1-\varepsilon)(r'-r)^2}{\mathcal{R}_0(1-r)\{1-[(1-\varepsilon)r'+\varepsilon r]\}}$	$\frac{1}{R_0}\frac{r-r'}{(1-r)(1-r')}$
$r < \pi_0, \quad r' > \pi_0$	$\left[1-\frac{1}{\mathcal{R}_0(1-r)}\right]\left[r'-\pi_0+\frac{1-\varepsilon}{\mathcal{R}_0}\left(\frac{\mathcal{R}_0(1-r)-1}{1+\varepsilon[\mathcal{R}_0(1-r)-1]}\right)\right]$	$-\left(1-\frac{1}{\mathcal{R}_0(1-r)}\right)$
$r > \pi_0, \quad r' < \pi_0$	$\frac{1-\varepsilon}{\mathcal{R}_0}\left(\frac{[\mathcal{R}_0(1-r')-1]^2}{\varepsilon+(1-\varepsilon)\mathcal{R}_0(1-r')}\right)$	$1-\frac{1}{\mathcal{R}_0(1-r')}$
$r > \pi_0, \quad r' > \pi_0$	0	0

Table 1: Payoff gain ΔE (Eq. **6**) to an individual adopting the new CSNE P' (associated with perceived relative risk r') when a proportion ε of the population does the same, and the remainder play the strategy P (which is the CSNE associated with relative risk r). π_0 is the probability that an individual will eventually become infected if nobody is vaccinated (cf. Eq. **15**). To see that ΔE is always strictly positive if $0 \leq \varepsilon < 1$, note that $r < \pi_0$ if and only if $\mathcal{R}_0(1-r) > 1$. The third column of the table shows $\Delta P = P' - P$, the change in the population's vaccine uptake after the change in risk perception. When both r and r' exceed π_0, the CSNE is the same before and after the change in risk perception ($P' = P = 0$).