Social and economic influences on human behavioural response in an emerging epidemic

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Abstract. The human behavioural changes have been recognized as an important key in shaping the disease spreading and determining the success of control measures in the course of epidemic outbreaks. However, apart from cost-benefit considerations, in reality, people are heterogeneous in their preferences towards adopting certain protective actions to reduce their risk of infection, and social norms have a function in individuals’ decision making. Here, we studied the interplay between the epidemic dynamics, imitation dynamics and the heterogeneity of individual protective behavioural response under the considerations of both economic and social factors, with a simple mathematical compartmental model and multi-population game dynamical replicator equations. We assume that susceptibles in different subpopulations have different preferences in adopting either normal or altered behaviour. By incorporating both intra- and inter-group social pressure, the outcome of the strategy distribution depends on the initial proportion of susceptible with normal and altered strategies in both subpopulations. The increase of additional cost to susceptible with altered behaviour will discourage people to take up protective actions and hence results in higher epidemic final size. For a specific cost of altered behaviour, the social group pressure could be a “double edge sword”, though. We conclude that the interplays between individual protective behaviour adoption, imitation and epidemic dynamics are necessarily complex if both economic and social factors act on populations with existing preferences.

1. Introduction

The role of human behaviour in the spread and control of infectious diseases has received significant attention [1]. Various behavioural changes, including vaccination, taking antiviral drugs, health protective actions such as social distancing, wearing masks, reducing travels, practicing better hygiene and avoiding crowded places, have been incorporated into epidemic models. Without including behavioural changes, the disease spreading model will predict the worst possible scenario [2]. In the course of epidemic outbreak, individuals are not passive, they weigh up the costs and risks associated with certain protective actions with the benefit of reducing the infection risk, and then choose the best strategy that maximizes their own benefit. This individual-level decision making can be concisely described in the language of game theory.

In biology, strategies are inherited, but the underlying mechanism for the evolution of strategy adoption in epidemiology is imitation process. Imitation dynamics can be coupled into one-population susceptible-infective-recovered (SIR) compartmental model via the replicator...
dynamical equation. For instance, Bauch [3] used cost-benefit analysis to study the decision making by parents in vaccinating their children for childhood diseases. Bauch’s model was extended in [4] by introducing social norm into it. In [5], the spontaneous behavioural changes in an emerging epidemic were modelled based on Bauch’s framework for both natural selection and imitation process. With these simple well-mixed one-population models, rich epidemic dynamics, including oscillations and simulation results fitted with real disease incidence data, can be achieved.

In homogeneous population models, every individual has the same kind of contact pattern and strategy interactions. However, entities are heterogeneous and there also exists heterogeneity between groups. People that belong to certain group may be more inclined to certain behaviour or perceive the risk of disease in a specific way. These give rise to the development of multi-group epidemic and game-dynamical models. Among them, most of the studies are related to vaccination behaviour with specific investigations on different age groups [6], countries [7] and risk perceptions [8-9]. Also, multi-population model was used in [10] to study health protective behaviour during epidemic. However, all these studies assumed that individuals only make economic cost-benefit considerations without considering other social factors in their decision making. Hence, we focus on the health protective actions adopted by susceptibles in an emerging epidemic in which the imitation dynamics are constructed by taking into account of a combination of economic and social points of view in two subpopulations setting.

In two subpopulations (or groups), a player could be randomly paired with one of other players either from the same or different subpopulation. This leads to intra- and inter-subpopulation strategy interactions. Bi-matrix games are suitable for the situation whereby there are only inter-subpopulation interactions [11]. This specification rules out own subpopulation effects. However, since we are living in a modern society with people from different backgrounds, beliefs and cultural, both intra- and inter-subpopulation strategy interactions are important in shaping our decision making. Therefore, we chose the multi-population game-dynamical modelling framework proposed in [12-13] which allows strategy interactions within and across groups with different preferences in constructing our game-dynamical model.

2. The Model

Our proposed natural selection and imitation dynamics model with economic and social factors is given below.

\[
\begin{align*}
\frac{dS}{dt} &= -\beta XSI \\
\frac{dI}{dt} &= \beta XSI - \gamma I \\
\frac{dR}{dt} &= \gamma I \\
\frac{dp}{dt} &= \beta p (X-1) I + p (1-p) \rho \left\{ f \left[ k(1-mI) + \Omega_n + \delta (2p-1) \right] + (1-f) \left[ k(1-mI) + \Omega_n + \delta (p(1-q)^2 - (1-p)q^2) \right] \right\} \\
\frac{dq}{dt} &= \beta q (X-\alpha) I + q (1-q) \rho \left\{ (1-f) \left[ -k(1-mI) + \Omega_a + \delta (2q-1) \right] + f \left[ -k(1-mI) + \Omega_a + \delta (q(1-p)^2 - (1-q)p^2) \right] \right\}
\end{align*}
\]

where \( X = fp + af(1-p) + (1-f)(1-q) + a(1-f)q \). \( S, I, R, p, q \) and hence \( X \) are time-dependent variables. Equations (1a)-(c) are the rate equations for individuals with disease state susceptible (\( S \)), infective (\( I \)) and recovered (\( R \)), which govern the epidemic dynamics.
Susceptible individuals are subdivided into two subclasses, namely individuals adopting normal behaviour (or strategy) \((S_a)\) and individuals adopting altered behaviour \((S_b)\). \(\beta\) is the disease transmission rate, \(1/\gamma\) is the average duration of infectivity and \(\alpha \in (0,1)\) is the reduction of the force of infection performed by \(S_a\).

Equations (1d) and (1e) govern the evolution of strategy frequencies in two subpopulations, respectively. Following [12-13], we assume that the preferred strategy in subpopulation 1 is normal behaviour and subpopulation 2 is altered behaviour. Hence, \(p\) (resp. \(q\)) is the proportion of susceptibles in subpopulation 1 (resp. 2) who adopt subpopulation 1’s (resp. 2’s) preferred behaviour, i.e. normal (resp. altered) behaviour. We have \(S \equiv p S^{[1]} + (1-q) S^{[2]} + (1-p) S^{[1]} + q S^{[2]}\), where \(S\) with superscript \([1]\) and \([2]\) are the fraction of susceptible in two respective subpopulations at any time. We assume that the subpopulation of susceptibles does not change throughout the simulation, i.e. no migration between subpopulations.

The parameter \(\rho\) gives the speed of the imitation process with respect to the disease transmission process as well as a measure of how willing the players are to switch to new strategy based on the payoff difference. If \(\rho = 0\), individuals do not include cost-benefit analysis in changing their strategy, and system (1) is reduced to the natural selection model. In two-subpopulation game dynamics, \(f\) (resp. \(1-f\)) can be interpreted as the relative power of subpopulation 1 (resp. 2), which reflects how much influence a subpopulation has on the strategy adoption of susceptible individuals [13] and essentially the sizes of both subpopulations evolve in a constant ratio [11]. Hence, \(X\) in (1) reflects the population average reduction of force of infection which is determined by strategy frequencies and the relative power of both subpopulations.

The parameter \(k\) represents the additional cost of adopting altered behaviour as compared to doing nothing in the course of epidemic outbreak, and \(m\) weighs the perceived disease prevalence [5]. As the direct consequences of following [12-13], the \(\pm\) sign in \(+k(1-mI)\) and \(-k(1-mI)\) reflects that the evolution of strategies frequency under cost-benefit analysis in one subpopulation is the opposite of the outcome on another subpopulation. In this way, this model the common belief that the increase (resp. decrease) of the cost of adopting altered behaviour will drive more susceptible in subpopulation 1 (resp. 2) adopting normal (resp. altered) behaviour. We assume that the susceptibles have full knowledge on disease prevalence which is certainly not realistic but unavoidable so as to use minimal number of equations in the model.

To reflect the incompatible preferences, we assume that one of the two strategies in a particular subpopulation is more attractive than the other. For each individual, if one strategy is more attractive, he/she would be better paid if choosing that strategy [14]. Unlike [12-13], the incompatible preferences in our model are reflected by adding an extra benefit \(\Omega\), as in [14], for susceptibles choosing the preferred strategy in their respective subpopulation. We incorporated social factor by assuming that individuals can apply two types of group pressure \(\delta\) to support conformity and discourage dis-coordinated behaviour. First, similar to [4], \(\delta(2p-1)\) and \(\delta(2q-1)\) are the intra-subpopulation pressure imposed on subpopulation 1 and 2, respectively. Second, the appearance of \(\delta(p(1-q)^2-(1-p)q^2)\) and \(\delta(q(1-p)^2-(1-q)p^2)\) are the result of inter-subpopulation strategy interactions.

### 3. Results and Discussion

Figure 1 gives the vector fields which represent the direction and size of temporal change of strategy distribution. The initial conditions \((p(0), q(0))\) can be regarded as the previous history of proportion of normal and altered strategies in both subpopulations, which is indeed the existing preferences of particular subpopulation. By setting \(\rho = 0\) (figure 1(a)), the strategy switching is only driven by natural selection and consequently the temporal change of strategy distribution in both subpopulations is minimal. If the imitation process is incorporated into the model by setting \(\rho > 0\), then when the magnitude of social group pressure \(\delta\) is small (figure
The fixed points and their associated eigenvalues obtained from the local stability analysis.

| l  | Fixed point $(p_l, q_l)$ | Associated eigenvalues, $\lambda_l$ and $v_l$ |
|----|--------------------------|-----------------------------------------------|
| 1  | (0, 0)                   | $\lambda_1 : -\rho(f\delta - k)$              |
|    |                           | $v_1 : -\rho(k + (1 - f)\delta)$              |
| 2  | (1, 0)                   | $\lambda_2 : -\rho(k + \delta)$              |
|    |                           | $v_2 : -\rho(k + \delta)$                    |
| 3  | (0, 1)                   | $\lambda_3 : \rho(k - \delta)$              |
|    |                           | $v_3 : \rho(k - \delta)$                    |
| 4  | (1, 1)                   | $\lambda_4 : -\rho(f\delta + k)$             |
|    |                           | $v_4 : -\rho(-k + (1 - f)\delta)$             |
| 5  | $(p_5 = \frac{f\delta - k}{\delta f + \delta}, 0)$ | $\lambda_5 : p_5(1 - p_5)\rho(\delta f + \delta)$ |
|    |                           | $v_5 : \rho((1 - f)(-k - \delta) + f(-k - \delta p_5^2))$ |
| 6  | $(p_6 = \frac{\delta - k}{\delta f + \delta}, 1)$ | $\lambda_6 : p_6(1 - p_6)\rho(\delta f + \delta)$ |
|    |                           | $v_6 : -\rho((1 - f)(-k - \delta) + f(-k - \delta(1 - p_6)^2))$ |
| 7  | $(1, q_7 = \frac{k + \delta}{2\delta - \delta f})$ | $\lambda_7 : -\rho(f(k + \delta) + (1 - f)(k + \delta(1 - q_7)))$ |
|    |                           | $v_7 : q_7(1 - q_7)\rho(2(1 - f)\delta + \delta f)$ |
| 8  | $(0, q_8 = \frac{k + \delta(1 - f)}{2\delta - \delta f})$ | $\lambda_8 : \rho(f(-k - \delta) + (1 - f)(k - \delta q_8^2))$ |
|    |                           | $v_8 : q_8(1 - q_8)\rho(2(1 - f)\delta + \delta f)$ |

1(b)), all trajectories tend towards the fixed point (1, 0) which means all susceptibles finally adopt normal behaviour as the epidemic is over. However, if $\delta$ is large (figure 1(c)), there exist four basins of attraction leading to four fixed points located at four respective corners of the $pq$-plane. The social group pressure could be balanced by extra benefit $\Omega$ given to individuals adopting preferred strategy in their respective subpopulation. In figure 1(d), both subpopulations end up with subpopulation-specific norms (fixed point (1, 1) which is defined as coexisting “subcultures” [13]) whenever $p(0)$ and $q(0)$ are almost the same.

Following [12], we carried out local stability analysis for subsystem (1d) and (1e) without...
Figure 2: The epidemic final size for all initial conditions \((p(0), q(0))\) with different relative powers (or strengths) of subpopulation, \(f\). (a) \(f = 0.5\), both subpopulations are equally strong. (b) \(f = 0.2\), subpopulation 2 is more powerful than subpopulation 1. (c) \(f = 0.7\), subpopulation 1 is more powerful than subpopulation 2. (d) \(f = 0.99\), subpopulation 1 is extremely strong such that the preference of subpopulation 2 is negligible.

Table 2: The fixed points and their associated eigenvalues for figures 1(b) and 1(c).

| \(l\) | Fixed point \((p_l, q_l)\) | Figure 1(b) | Figure 1(c) |
|------|-----------------|-------------|-------------|
| 1    | \((0, 0)\)      | \(\lambda_l = 0.0374\) | \(\lambda_l = -0.2625\) |
|      |                  | \(v_l = -0.0375\) | \(v_l = -0.3375\) |
| 2    | \((1, 0)\)      | \(\lambda_l = -0.0376\) | \(\lambda_l = -0.6375\) |
|      |                  | \(v_l = -0.0376\) | \(v_l = -0.6375\) |
| 3    | \((0, 1)\)      | \(\lambda_l = 0.0373\) | \(\lambda_l = -0.5625\) |
|      |                  | \(v_l = 0.0373\) | \(v_l = -0.5625\) |
| 4    | \((1, 1)\)      | \(\lambda_l = -0.0375\) | \(\lambda_l = -0.3375\) |
|      |                  | \(v_l = 0.0374\) | \(v_l = -0.2625\) |
| 5    | \((p_5, 0) = (0.2916, 0)\) | Note: All \(p_5\), \(p_6\), \(q_7\) and \(q_8\) are \(0.1859\) | \(\lambda_l = 0.1859\) |
|      |                  | \(v_l = -0.3630\) | \(v_l = -0.3047\) |
| 6    | \((p_6, 1) = (0.625, 1)\) | out of range \([0, 1]\). Therefore, no fixed points lie on the boundary of the \(pq\)-plane. | \(\lambda_l = 0.2109\) |
|      |                  | \(v_l = 0.1859\) | \(v_l = 0.2109\) |

We explored the epidemic dynamics in parameter space \(\delta-k\) for four different initial proportions of strategies in figure 3. All panels show the increase of additional cost to those...
Figure 3: (Color online) The contour plots of epidemic final size in the parameter space δ-k, where δ ∈ (0.05, 0.4) and k ∈ (0.025, 0.2), with different initial conditions (p(0), q(0)). (a) p(0) = 0.2, q(0) = 0.8, the initial proportion of S are high in both subpopulations. (b) p(0) = q(0) = 0.8 (or p(0) = q(0) = 0.2). (c) p(0) = 0.8, q(0) = 0.2, the initial proportion of S are high in both subpopulations.

adoption the altered behaviour k will discourage people take up protective actions and hence results in higher epidemic final size. For a specific k, the epidemic final size will be reduced if the intensity of group pressure δ is increased (figures 3(a)-(b)). However, interestingly, the group pressure could be a “double edged sword” if the initial proportions of S are already majority in both subpopulations. The increase of δ acting on S gives rise to higher epidemic final size (figure 3(c)). This finding aligns with that of [4] who claimed that social norms can either support or hinder immunization goals.

4. Conclusion
We conclude that the interplays between individuals protective behaviour, imitation and epidemic dynamics are necessarily complex if both economic and social factors act on population with existing preferences.

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