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Effect of noise-perturbing intermediate defense measures in voluntary vaccination games

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ABSTRACT

Recently, a new vaccination game model was proposed, where an intermediate defense measure besides two fundamental strategies; committing vaccination that leads to a perfect immunity and not committing vaccination, was introduced as third strategy. We explore what happens if both effectiveness and cost of an intermediate defense measure stochastically perturbing on the viewpoint of whether or not the third strategy helping to improve total social payoff. We found that unlike resonance effect by adding noise to payoff matrix in case of spatial prisoner's dilemma (SPD) games, adding time-varying noise on both effectiveness and cost does not make difference from the default setting without perturbation to the third strategy. However, if the noise initially given to each agent is frozen, we found the third strategy becoming robust to survive. In particular, if the strategy updating rule allows a more advantageous third strategy can be more commonly shared among agents through copying, the total social payoff is significantly improved.

1. Introduction

Since pandemic of an infectious disease has attracted social concern very much for last couple of years, quite large number of studies have brought to the arena of medical science, theoretical biology and statistical physics (e.g. [1,2]). Besides what-is-called macroscopic model that has been well-established and regarded as a traditional approach like, for example, SIR model [3], a model of vaccination games, where epidemiology dynamics like SIR is dovetailed with evolutionary game theory that is able to emulate human decision-making process whether committing vaccination or not, is heavily concerned. The vaccination games deem a significantly powerful tool because so-called herd immunity can be thought a typical example of public goods where no-committing vaccination is best strategy for anyone to free-ride while the herd immunity would be collapsed unless certain number of people keeping cooperation. In this sense, the vaccination games can model the structure of vaccination dilemma in which an agent tries to free-ride on public goods of herd immunity in order to maximize individual payoff, which inevitably brings a situation that Nash equilibrium is inconsistent with the situation bringing social maximum payoff [4–9].

In conventional vaccination games there has been presumed two strategies; committing vaccination, meaning an agent costs a vaccination to obtain perfect immunity; and non-committing vaccination, meaning an agent does not commit vaccination to seek free-riding on herd immunity by other agents. In other words, those are determinant binary-strategies; cooperation (C) and defection (D). In real, however, there are many alternative provisions between those two extreme strategies. In fact, instead of paying high cost for vaccination for flu, some people rely on preventive OTC medicines, or take more practical preventive provisions such as masking, gargling and hand-washing. The effect of those may be not perfect, but simultaneously low cost vis-à-vis vaccination. Because of this background, we recently presented new vaccination games implementing three strategies; an intermediate defense measure as well as C and D [10]. The reported result is surprisingly interesting because the introduction of intermediate measures even with advantage than the vaccination from the viewpoint of cost—effectiveness relation does not improve social efficiency, even sometimes calls worse situation than the two-strategy system with C and D does. Incidentally, the intermediate measure as the third strategy can be thought variable amid people just because each individual may buy a different OTC medicine at a different price, or may wear a mask in a slightly different manner, which means both cost and effectiveness of the third strategy, or say the cost—effectiveness relation, stochastically deviating.

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Meanwhile, it has been well-known that adding some perturbation to a time-evolutionary system can realize a noise-driven stochastic resonance effect. For example, spatial prisoner's dilemma (SPD) games with payoff noise model [11–13], where either payoff matrix or accumulated payoff after gaming is biased by an additive noise whose average is kept zero, can significantly enhance network reciprocity.

To this end, one plausible question may occur. That is; whether or not vaccination games of three-strategy system with a third strategy that stochastically perturbs can enhance social efficiency unlike the default model of the three-strategy system does [10]. It is worthwhile to note that those two models slightly differ. The payoff noise model in SPD games presumes the game structure given by a payoff matrix perturbing, which indicates any payoffs irrespective to either C or D perturbing. Although the present model in vaccination games also presumes the game structure perturbing, the perturbed offer is only the third strategy but both C and D do not.

The paper contains four sections. Section 2 presents the model description and assumptions for numerical simulations. Section 3 reports results and discussion of the numerical simulations. Section 4 summarizes our findings.

2. Model setup

2.1. Two-strategy vaccination game on a network

As the baseline of our model, let us confirm how the conventional two-strategy vaccination game on an underlying network works [5-9]. The two strategies; committing vaccination (hereafter; V) that means a perfect immunity and no-committing vaccination (hereafter; NV) are available. In this study, we assume a seasonality of infectious diseases. For such infectious disease, an agent needs to vaccination every epidemic season because the effect of the vaccine is only temporary. Therefore, the model dynamic consists of two stages; vaccination campaign (first stage) and epidemic season (second stage).

In the first stage (vaccination campaign), each agent makes decision of whether he commits vaccination or not according to his strategy. A vaccinated agent must bear vaccination cost: C_v implying the monetary burden of a vaccination or cost for the potential risk accompanied with a vaccination. For simplicity, we assume a vaccinated agent gets perfect immunity in the season. On the other hand, no-vaccinated agent has risk of infection in the season.

In the second stage (epidemic season), initial infection agents (assuming its number; $I_0 = 5$) may trigger a wide spreading of the epidemic, and are placed on the network. The infectious disease expands by obeying to SIR dynamics on the network in which we assumed Gillespie algorithm [14]. SIR model classifies agents into; susceptible (S), infectious (I) and immunes who are either recovered or vaccinated agents (R). With respect to infection rate per day per person; β [day^{-1} person^{-1}], and recovery rate per day ν [day^{-1}], we presumed $\beta = 0.5$, recovery rate $\nu = 0.3$, respectively [9]. The total population size is presumed $N = 4900$, of which topology is assumed 2-dimensional square lattice with von Neumann neighborhood of $k = 4$.

At the initial step, equal number of S and R meaning vaccinated agents are randomly placed on the underlying network.

2.2. Three-strategy vaccination game with/without perturbation

Following to ref. [10], let us introduce the intermediate strategy meaning a self-protection measure as the third strategy (hereafter; SP). The key point is the cost performance that stipulates the relation between cost ratio; $\delta \in [0, 1]$ and effectiveness; $\eta \in [0, 1]$. Note that $\delta \cdot C_v$ means cost of the presumed self-protection,

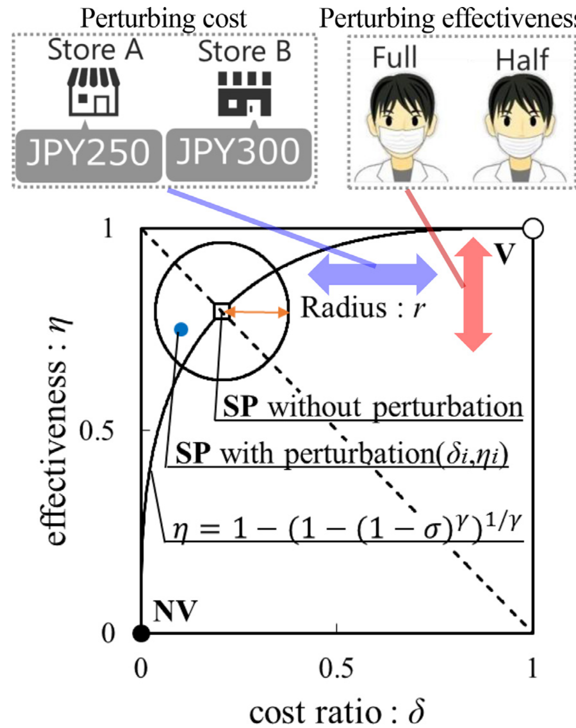

Fig. 1. Relation between cost ratio and effectiveness of self-protection measure.

and η implies how effectively the self-protection can work as compared with the perfect immunity. $\eta = \delta$ means fair relation that contains the perfect immunity $(\delta, \eta) = (1, 1)$ and the no-vaccination $(\delta, \eta) = (0, 0)$ at both ends, and implies not specifically cost-advantageous and cost-disadvantageous than the vaccination strategy. We should assume that any cost performance relation must meet with $(\delta, \eta) = (1, 1)$ and $(\delta, \eta) = (0, 0)$. In the present study, we presume the super-ellipse function;

$$\eta(\delta) = 1 - \left(1 - (1-\delta)^{\gamma}\right)^{1/\gamma} \quad (1)$$

The third strategy in the 3-strategy system without noise-driven perturbation presumes a (δ, η) at which appears as a crossing point of Eq. (1) with $\eta = 1 - \delta$ as shown in Fig. 1.

With respect to the third strategy with noise-driven perturbation, we presume that Agent i's strategy; (δ_i, η_i) is given with $(\delta \pm \Delta\delta_i, \eta \pm \Delta\eta_i)$ shown in Fig. 1, where $\pm\Delta\delta_i$ $(\pm\Delta\eta_i)$ means a spatial deviation from (δ, η), uniformly distributed within the circle of which radius is r.

We presume following three scenarios for strategy SP with perturbation.

Always: At every time step in a time evolution, each agent draws a random number to refresh $(\Delta\delta_i, \Delta\eta_i)$. It emulates that an individual buys a mask at slightly different price and wears in a slightly different way at every time step.

Initial #1: At initial time step in an episode, Agent i draws a random number to fix $(\Delta\delta_i, \Delta\eta_i)$ and keep it throughout the episode. It presumes the situation that an individual inherently determines from what store he/she buys a mask and in what way he/ she wears it. Whenever he/she takes SP as his/her strategy, this inherent $(\Delta\delta_i, \Delta\eta_i)$ is always refereed.

Initial #2: At initial time step in an episode, Agent i draws a random number to determine $(\Delta\delta_i, \Delta\eta_i)$. Unlike Initial #1, each agent does not fix $(\Delta\delta_i, \Delta\eta_i)$. In strategy updating, explained later, when Agent j copies SP from his neighbor Agent i, $(\Delta\delta_j, \Delta\eta_j)$ is overwritten by $(\Delta\delta_i, \Delta\eta_i)$. It assumes