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Can memory and conformism resolve the vaccination dilemma?

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HIGHLIGHTS

- A novel vaccination dilemma model is proposed by entangling the spreading dynamics with an evolutionary framework.
- Tie strength between agents is taken into account.
- The results indicate that memory or conformism may lead to the decrease of the density of vaccination.
- The total payoffs of the individuals in the ER network are bigger than in the BA network.

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ABSTRACT

Considering that memory and conformity could affect the agent's decision, in this paper, we propose a novel model to describe the vaccination dilemma by entangling the spreading dynamics with an evolutionary framework. Our results indicate that if the individuals make decision mostly depending on their own payoffs and do not believe too much in the celebrity, the final infected number will be significantly reduced. Comparing with the individuals in the BA network, people in the ER network escape from contagion much more easily and could get bigger payoffs. For the countries, strengthening the medical security system and reducing the cost of immunity can curb the spread of viruses effectively. From an individual's viewpoint, people just remember their own last season's payoffs can urge them to vaccinate.

1. Introduction

Infectious diseases, such as the smallpox and human immunodeficiency virus, continue to significantly impact morbidity, mortality, and economic outcomes in many populations [1–4]. The primary intervention method for preventing the transmission of infectious diseases is vaccination. However, under the complexity of human mobility and interaction, the individual's decision whether or not to vaccinate mainly results from a tradeoff between their cost and the potential risk. The decisions of an individual can evolve in time depending on the epidemic incidence observed in the population. Therefore, the game theoretical approach could be suitable for describing the decision-making processes.

There is plenty of research going on this topic. Alessio [5] et al. analyze the evolution of voluntary vaccination in scale-free networks and random networks. The results show that if the vaccine is perfect, scale-free networks enhance the

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vaccination behavior relative to homogeneous networks, however, when vaccine is imperfect the homogeneous networks outperform scale-free ones. Zhang [6] et al. investigate Braess's Paradox in the epidemic game; the results verify that improvement of the successful rate of self-protection does not necessarily downsize the epidemic or increase the whole society's payoff. Eunha Shim [7] et al. study the game dynamic model of the vaccine skeptics and vaccine believers; they demonstrate that the pursuit of vaccine skeptics-interest among vaccine skeptics often leads to vaccination levels that are suboptimal for a population, even if complete coverage is achieved among vaccine believers. Zhang [8] et al. give two models to report the impact of the rational decision-making of individuals on voluntary vaccination. Results indicate that the rational behavior of individuals may increase an individual's utility but decrease the total utility of society. By using probabilistic cellular automaton, Schimit [9] et al. propose a vaccination game according to public health actions and personal decisions in which the players are the government and the susceptible newborns. The results supported show that the disease is not fully eliminated and the government implements quasi-periodic vaccination campaigns. Chen [10] et al. study the decision of individuals during epidemics; it reveals that if the contact ratio is increasing with the number of people out in public then there exists a unique Nash equilibrium, but if the contact ratio is decreasing with the number of people out in public, then there can be multiple Nash equilibria, none of which is in general socially optimal.

In the real world, tie strength, as the strength of the interaction represented by networks, is believed to be an important variable in networks [11]. Individuals with higher degree are considered as celebrities and other individuals would preferentially consider imitating their strategies. On the other hand, a man has different relationships with his various friends, and the relationships are asymmetric. For example, when A regards B as a close friend, B does not necessarily regard A as the same. So the mutual effects are different when individuals make decision. Xu [12] et al. investigate the effect of tie strength on the dynamics of evolutionary prisoner's dilemma games according to online social network datasets. The results indicate that the fraction of cooperators has a non-trivial dependence on tie strength. Pierre [13] et al. present the influence of tie strength on evolutionary games on networks; results show that taking the tie strength into account does not change in a radical manner the long-run steady-state behavior of the studied games.

Most research works about evolutionary games on networks assume that individuals have no memory [14,15]. Yet, in the real world, past things can affect an agent's decision. In general, people may not remember the entire historical thing, that is to say there exists the memory decay. The existence of long memory has a significant effect on decision-making. If the memory decay is very small, the previous events have strong influence on the current behavior. On the other hand, one may have short memory, which means that the memory decay is very large and the agents only remember their latest thing, but events long ago have less impact on their present behavior. However, memory of the history may not always urge individuals to overcome the dilemma or increase cooperation [16]. Meanwhile, agents' decision may rely on the behaviors of their neighbors as well. The case could be observed in the evolution of biological species or the economic society. Some researchers have dealt with that kind of questions, where the evaluation of agents' payoff not only according to themselves but their fellows [17–20]. Those investigations include the prisoner's dilemma [21–23] and the public goods game etc. [24].

The imitation behavior of an agent depends on the current payoff difference between a selected pair [25,26]. That is to say, after each epidemic season, the agent will select one neighbor randomly to determine whether or not to adopt the selected neighbor's strategy. Normally, if the selected neighbor's strategy could gain her or his payoff, in the next season the neighbor's strategy will be adopted with a higher probability. In reality, individuals can also adjust the probability of taking vaccination according to the prevalence of the epidemic. Alberto [27] et al. study an SIR transmission model with dynamic vaccine demand by using an imitation mechanism. Their results indicate that in order to achieve high coverage the huge disproportion between the perceived risk of disease and vaccination is necessary. Zhang [28] et al. present a spatial vaccination game model by considering the impact of other-regarding tendencies. The results suggest that when the vaccination cost is small, the variance of vaccination coverage and the epidemic size is monotonically based on the other-regarding effect. But if the vaccine price is high, a moderate deviation from being entirely self-centered results in poor communal vaccination profits.

Motivated by the above discussion, in this paper, we propose a novel model of epidemic spreading by considering the memory decay and crowd psychology. The tie strength is taken into account when we model the connection relationship. Our results suggest that if individuals depend on their own fitness mostly, they may incline to immune, and the final infected number will be reduced. Additionally, if people have a herd mentality, they would better not believe too much in the celebrity. Comparing with agents in the BA network, people could get more payoffs in the ER network. Meanwhile, the memory decay factor has impact on people's decisions. Once the individuals have a good memory, they do not incline to take vaccination and the total number of infected would be increased. Based on the results of our study, we conclude that for the countries, it is an effective way to make people be willing to take vaccination by strengthening the medical security system and reducing the cost of immunity. At a personal level, it is better for individuals to forget their earlier payoffs.

The remainder of this paper is organized as follows: in Section 2, the model is introduced in detail. Section 3 presents the simulation results and the relevant discussions. Section 4 provides the conclusions we drew.