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Exploring voluntary vaccination with bounded rationality through reinforcement learning

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HIGHLIGHTS

- We study human voluntary vaccinating behaviors with bounded rationality.
- We present a reinforcement learning-based decision-making mechanism.
- We consider the effects of both rationality and social influence.
- We simulate the RL-based mechanism in scale-free social networks.

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ABSTRACT

Evidence shows that there exists a complex interaction between human vaccinating behaviors and disease prevalence during an epidemic. Usually, rational individuals make vaccinating decisions by strategically evaluating the cost of vaccination and the risk of infection. While in reality, individuals' decisions can also be influenced by their social acquaintances. In this paper, we present a reinforcement learning-based mechanism to characterize human decision-making process with bounded rationality, which takes into consideration both individuals' rational decisions and social influence from their neighbors. Specifically, we investigate human voluntary vaccinating behaviors in the face of flu-like seasonal diseases in locally-mixed social networks, where each individual together with his/her neighbors forms a well-mixed environment. Through carrying out simulations, we evaluate the performance of decision-making mechanisms with/without reinforcement learning in terms of vaccine coverage, final epidemic size, average payoff and vaccine effectiveness under different settings of relative cost of vaccination and infection. Simulation results show that reinforcement learning can improve the vaccine effectiveness through balancing individuals' rationality and social influence. This emphasizes the importance of appropriately utilizing human bounded rationality in preventing disease epidemics through voluntary vaccination policies.

1. Introduction

The design of effective vaccination policies is one of the common means to prevent and eliminate vaccine-preventable diseases [1–3]. No matter what vaccination policies are suggested, a certain level of vaccine coverage for the population as a

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whole must be achieved to prevent disease spread [4–8]. Along this line, many existing studies have focused on investigating whether and under what conditions the critical level of vaccine coverage can be reached through voluntary vaccination among individuals with self-interest [9,10]. Usually, rational individuals are assumed to make vaccinating decisions by strategically evaluating the cost of vaccination and the risk of infection. However, in reality, individuals' vaccinating decisions can also be affected by their social neighbors, such as colleagues and family members. In this paper, we focus on investigating human voluntary vaccinating behaviors in the face of flu-like seasonal diseases in social networks. Specifically, we present a reinforcement learning-based (i.e., RL-based) mechanism to characterize human vaccinating behaviors with bounded rationality, which takes into consideration both individuals' rational evaluations and influence from their social neighbors.

For many years, the game-theoretical approach has been widely adopted to explore human decision-making with respect to voluntary vaccination, where individuals are assume to be rational and self-interested [11–14]. For example, Bauch et al. show that vaccine-preventable diseases (e.g., smallpox), are unlikely to be eradicated under voluntary vaccination policy unless a risk-free vaccine is used [11]. They further present a vaccine game and reveal that there exists a conflict between self-interest and group interest [12]. In these studies, populations are assumed to be homogeneously-mixing, where individuals have complete information about each other and make vaccinating decisions only once. However, in reality, diseases often spread in structured populations, where individuals interact with each other in the form of social contact networks. In this case, it is impossible for any individual to have complete information about the population structure, as well as all other individuals' response to the epidemics [15–17].

For flu-like seasonal diseases, individuals make annual decisions and can adaptively adjust their vaccinating behaviors based on not only the outcome of their historical vaccination decisions, but also the level of vaccine coverage at previous season. By presenting an individual-level adaptive decision-making model, Vardavas et al. have found that voluntary vaccination fails to eradicate a flu-like seasonal disease even though a risk-free vaccination is used [9]. In their model, the authors use a parameter ϵ ($0 < \epsilon < 1$) to describe an individual's adaptability to seasonal epidemic dynamics based on their past experiences with vaccination. The problem is that all individuals have the same adaptability parameter ϵ, which cannot reflect the structural diversity of individuals (e.g., hub nodes) in social networks.

In structured populations, the reaction–diffusion dynamics between disease spreading and human vaccination is very complex and intractable to be theoretically analyzed [18,19]. Accordingly, various numerical simulation models have been proposed to characterize such disease–behavior dynamics [20–23]. Except for simulating pairwise interactions between individuals in structured populations, many studies have also focused on modeling the disease–behavior dynamics on metapopulation networks [24–26], as well as locally-mixed social networks [27,28]. Accordingly in this paper, we assume that each individual together with his/her neighbors in a social network forms a locally-mixed group, within which individuals are homogeneously mixed and have complete information about each other. This is reasonable because in reality, people often organizes activities in groups. In doing so, traditional compartmental models (e.g., the SIR model) can be adopted to characterize the dynamics of disease transmission within an individual's neighborhood. Accordingly, the risk of infection for each individual can be perceived based on the vaccine coverage in his/her locally-mixed neighborhood.

For self-interested individuals, it is better to rationally make vaccinating decisions by weighing their perceived risk of infection and the cost of vaccination based on limited information about their social neighbors. Under such an assumption, we present a memory-based decision-making mechanism that derives *rational* vaccinating behaviors for each individual by perceiving the risk of infection based on the level of vaccine coverage in his/her neighborhood at the previous season. However, many individuals are with bounded rationality, and their vaccinating decisions may be highly influenced by that of their social neighbors (e.g., acquaintances). In this case, imitation is well-studied and extensively-used mechanism to simulate the impact of social influence [29–32]. During an imitation process, an individual randomly chooses another individual from his/her neighborhood as a role model. The strategy of a role model with higher payoff is more likely to be imitated by the individual. Usually, the Fermi function is used to determine the imitation probability [33]. It has been shown that when individuals becomes more adept at imitating successful vaccinating strategies, the equilibrium level of vaccine coverage falls below the optimal vaccination level [29]. Moreover, oscillation in vaccine uptake are more likely when individuals imitate others more readily [32]. In this paper, we adopt an imitation-based decision-making mechanism to depict individuals' vaccinating behaviors based purely on social influence.

Taking into account above-mentioned situations, it would be natural to ask a question: how rational an individual should be in the face of a flu-like seasonal disease? In other words, to what extent will an individual make decision based on rationality or be influenced by his/her social neighbors? In order to answer this question, in this paper, we propose a RL-based decision-making mechanism to explore vaccinating behaviors of voluntary individuals, where they can adaptively choose the memory-based mechanism (i.e., to be rational) or the imitation-based mechanism (i.e., to imitate their neighbors' behaviors) based on their historical decisions with vaccination and associated payoffs. On the one hand, individuals can use the memory-based mechanism to estimate the risk of infection based on the level of vaccine coverage in his/her neighborhood at the previous season (see Section 2.2). By evaluating the relative cost of vaccination and infection, they can calculate the vaccinating probability at equilibrium. On the other hand, individuals can also adopt the imitation-based mechanism to determine whether or not to vaccinate through imitating the vaccinating behaviors from one of his/her social neighbors (see Section 2.3). In Section 2.4, we present a reinforcement learning-based mechanism so that each individual can determine whether or not to be rational at the current season based on their historical choices and associated payoffs. We carry out simulations in scale-free social networks to investigate performance of the proposed mechanisms in structured populations in Section 3. Finally, we conclude this work in Section 4.