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Voluntary vaccination dilemma with evolving psychological perceptions

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ABSTRACT

Voluntary vaccination is a universal control protocol for infectious diseases. Yet there exists a social dilemma between individual benefits and public health: non-vaccinators free ride via the herd immunity from adequate vaccinators who bear vaccination cost. This is due to the interplay between disease prevalence and individual vaccinating behavior. To complicate matters further, individual vaccinating behavior depends on the perceived vaccination cost rather than the actual one. The perception of vaccination cost is an individual trait, which varies from person to person, and evolves in response to the disease prevalence and vaccination coverage. To explore how evolving perception shapes individual vaccinating behavior and thus the vaccination dynamics, we provide a model combining epidemic dynamics with evolutionary game theory which captures the voluntary vaccination dilemma. In particular, individuals adjust their perception based on the inertia effect in psychology and then update their vaccinating behavior through imitating the behavior of a more successful peer. We find that i) vaccination is acceptable when the expected vaccination cost considering perception and actual vaccination cost is less than the maximum of the expected non-vaccination cost; ii) the *evolution* of perception is a "double-edged sword" for vaccination dynamics: it can improve vaccination coverage when most individuals perceive exaggerated vaccination cost, and it inhibits vaccination coverage in the other cases.

1. Introduction

Vaccination is the most economical and effective public health intervention to control infectious diseases. Considering religious beliefs and civil liberties, voluntary vaccination policies are implemented in many countries. With voluntary vaccination, individuals voluntarily decide whether to vaccinate or not. Wherein minimizing costs is the guideline for individuals' decision-making. Both vaccination and non-vaccination can bring costs. A vaccinator will bear vaccination cost, which includes vaccine cost, time loss, possible side effects, and things like that. For non-vaccinators, their costs further depend on their healthy status. If a non-vaccinator gets away with being infected, he/she does not bear any loss. Whereas if a non-vaccinator is infected, he/she will bear infection cost, which includes suffering from illness, medical treatment fees, loss in productivity, and so on. The probability of non-vaccinators being infected relates to the proportion of vaccinators in the population. Furthermore, non-vaccinators' expected cost and thus individuals' decision-making depend on the other individuals' behavior. Therefore, voluntary vaccination can be studied in the framework of game theory, which describes the situation where individuals' payoff depends on the strategies of others in the population (Feng et al., 2017; Li and Wang, 2015; Pacheco et al., 2009).

Previous studies have combined a game-theoretical model with an epidemic model to study voluntary vaccination (Bauch, 2005; Bauch and Earn, 2004; Bauch et al., 2003; Fu et al., 2010; Galvani et al., 2007; Wu et al., 2011; Zhang et al., 2010). They find that there is a social dilemma between individual benefits and public health in the coupled disease-behavior system. Specifically, the individual optimum level, at which individual cost minimizes, is less than the population optimum level, at which the cost of the whole population minimizes. In disease-behavior systems, individuals decide whether to vaccinate or not according to the costs of vaccination and infection. Typically, the actual costs of vaccination

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and infection are assumed to be known, and studies focus on how vaccination strategies (Bhattacharyya and Bauch, 2011; Poletti et al., 2009; Reluga, 2010), the update rules of strategies (Fu et al., 2010; Shim et al., 2012), and population structures (Bhattacharyya and Bauch, 2010; Chapman et al., 2012; Perisic and Bauch, 2009) influence vaccination dynamics. In fact, the actual costs are inaccessible for individuals. That's because an individual can not have connections with all the other individuals in the population, and it is hard to get the accurate information on vaccination and diseases from the connected ones.

Empirical studies have shown that individuals' decision-making depends on their perceived costs of vaccination and infection instead of the true costs (Bish et al., 2011; Coelho and Codeço, 2009; d'Onofrio et al., 2011; Reluga et al., 2006; Xia and Liu, 2014). Generally, perceived costs differ from the true ones. The discrepancy dramatically influences vaccination dynamics. For example, the measles-mumps-rubella (MMR) vaccine scare occurred in England and Wales in the 1990s (Jansen et al., 2003). At that time, people believed the false rumor that MMR vaccine caused autism. Their perceived vaccination costs were much greater than the true vaccination cost. And they refused to vaccinate their children. Then the vaccination coverage declined and measles outbreaks occurred. On the other hand, perceived costs may be lower than the true cost. Consider influenza vaccines having side effects. They may cause fever. An individual has taken influenza vaccines several times. Fortunately, the individual has never run a fever caused by the vaccines and never heard other vaccinated individuals suffered side effects. So, the individual may perceive influenza vaccines have no side effect, and his/her perceived vaccination cost is less than the true cost. How do perceived costs shape individual vaccinating behavior and thus the vaccination dynamics? To address this, we study the voluntary vaccination dynamics with perception. We assume all the individuals know the actual infection cost, and perceive vaccination cost. So, perception in this paper refers in particular to the perception on vaccination cost. Perception is an individual trait. It varies from person to person. There are two main reasons for this. One is individuals have various ways to obtain information, such as chat with friends, news media, and online social media. The other one is the circumstances around individuals are different (Fierro and Liccardo, 2013). Individuals getting false information on side effects of a vaccine perceive high vaccination cost. And individuals whose friends get away with the side effect of a vaccine perceive low vaccination cost (Anon, 2000; Yarwood et al., 2005). To complicate matters further, individual perception evolves along with disease prevalence and vaccination coverage. In previous studies of vaccination dynamics with evolving perceptions, perceptions have been assumed to evolve according to the curves assumed in advance (Bauch and Bhattacharyya, 2012; Nakamaru and Dieckmann, 2009). Moreover, Bayesian theory has been used to characterize perception update based on reported cases of disease and potentially adverse events from the vaccine (Coelho and Codeço, 2009; Xia and Liu, 2014). Here, based on the inertia effect in psychology (Huff et al., 1992; Tripsas and Gavetti, 2000), we propose a self-learning perception update rule, which depends on individuals' own perceived and actual payoffs. With this update rule, individuals prefer keeping their perceptions when they bear medium costs; otherwise, they adjust their perceptions.

To figure out the voluntary vaccination dynamics with evolving perceptions, a minimal model is proposed by us. The model focuses on vaccination dynamics over several epidemic seasons. In each epidemic season, the vaccination dilemma is described by a two-stage game: the first stage of vaccination campaign and the second stage of disease transmission (Fu et al., 2010). In the first stage, individuals update their strategy, consisting of the perception on vaccination cost and vaccinating behavior. As vaccinating behavior is driven by perception, individuals adjust their perceptions first, and then update their vaccinating behavior (Doutor et al., 2016; Galvani et al., 2007; Xia and Liu, 2014). In the second stage, the disease spreads, and the epidemic model determines whether a non-vaccinator becomes infected or not. When the disease outbreak ends, the population goes into the next epidemic season. Our model captures the adaptiveness of the coupled disease-behavior system (Galvani et al., 2016): individuals adjust perceptions and vaccinating behaviors in response to the progress of disease and the others' vaccinating behaviors.

This paper tries to address two issues: i) what's the voluntary vaccination dynamics with perceptions on vaccination cost; ii) how the evolution of perception influences vaccination dynamics. For issue i), we study the case of fixed perception, where individual perception does not change over time, and the case of evolving perception, where perception changes in response to dynamic vaccination coverage and disease prevalence. Then, issue ii) is explored by comparing the vaccination dynamics for these two cases.

2. Model

Consider an infinite and well-mixed population, where voluntary vaccination is implemented. Our model focuses on vaccination dynamics over several epidemic seasons. Specifically, we focus on the vaccination dynamics for pediatric diseases (e.g. measles, mumps, rubella and pertussis), and the players of the vaccination game are parents (Bauch, 2005). Here, an epidemic season is defined as the duration between the ends of two successive outbreaks. And for every epidemic season, the voluntary vaccination dilemma is described by a two-stage game (see Fig. 1). Stage 1 is the vaccination campaign. At this stage, no one is infected, and individuals update their strategies. At stage 2, diseases spread, and individuals have no chance to adjust their strategies. We assume vaccines provide perfect immunity, and vaccinators cannot be infected. However, non-vaccinators take a risk of being infected.

Individual strategy is specified by two traits: the perception on vaccination cost, and the vaccinating behavior. Here, we assume all the individuals get the actual infection cost, which is set to be 1 for simplicity, but perceive vaccination cost. For an individual, the perception, which describes the relationship between actual vaccination cost and perceived vaccination cost, is either high or low. They are denoted by P_h and P_l, respectively. The former (latter) shows that the perceived vaccination cost is greater (less) than the actual one. Thus, compared to individuals with actual vaccination cost, individuals with high (low) perception have negative (positive) attitudes towards vaccination. Vaccination and Non-vaccination are two optional vaccinating behaviors. They are denoted by V and N, respectively. Therefore, the strategy set is $\{P_hV, P_lV, P_hN, P_lN\}$.

As the introduction of perception on vaccination cost, individuals have actual payoffs and perceived payoffs. For vaccinators, the actual payoff is $-r$, where r $(0 < r < 1)$ denotes actual vaccination cost. The perceived payoff of individuals with P_hV is $-H_pr$ ($H_p > 1$ is the ratio of perceived vaccination cost to actual vaccination cost for vaccinators with high perception), and the perceived payoff of individuals with P_lV is $-L_pr$ ($0 < L_p \leq 1$ is the ratio of perceived vaccination cost to actual vaccination cost for vaccinators with low perception). For non-vaccinators, the actual payoffs further depend on their health status. If a non-vaccinator is healthy, the payoff is 0; otherwise, it is -1. Because all the individuals know the actual infection cost, non-vaccinators' perceived payoff is the excepted value of their actual payoffs. Thus, the perceived payoff for non-vaccinators is $-1 \cdot w(x_h + x_l) + 0 \cdot (1 - w(x_h + x_l)) = -w(x_h + x_l)$, where $w(x_h + x_l)$ denotes the probability of a non-vaccinator being infected when the fraction of vaccinators in populations is $x_h + x_l$. For the voluntary vaccination game with perception on vaccination cost, potential strategies, actual payoffs, and perceived payoffs are summarized in Table 1.