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The impact of loners' participation willingness on cooperation in voluntary prisoner's dilemma

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ABSTRACT

Why would natural selection favor the prevalence of cooperation within the groups of selfish individuals? A fruitful framework to address this question is evolutionary game theory, the essence of which is captured in the so-called social dilemmas. Voluntary participation is considered as an effective approach to promote the persistence of cooperative behavior. Because three strategic types of players lead to a rock–scissor–paper dynamic with cyclic dominance. There is no doubt that loner has played a very important role. Thus we introduce a parameter p represents loners' participation willingness in order to explore the impact of its on cooperation in voluntary prisoner's dilemma. Large quantities of simulations demonstrate that for traditional case ($p = 1$), three strategies will coexist. However, with p decreases, loners will greatly increase, and cooperation level declines, because defectors can be suppressed very fast. More interesting, when defectors completely vanish, cooperation becomes the best strategy, and holds the whole system. Thus our work present a viable method of understand the ubiquitous cooperative behaviors in nature and hope that it will inspire further studies to resolve social dilemmas.

1. Introduction

Understanding the emergence and stability of cooperation among unrelated individuals represents one of the major challenges in evolutionary biology and behavioral sciences [1–5]. Evolutionary game theory provides a simple yet powerful framework to solve this puzzle [6–8]. As one typical game, the prisoner's dilemma game (PDG) has become a worldwide known paradigm for studying the evolution of cooperation [9,10]. In the original PDG, two players simultaneously decide whether to cooperate or defect. They will receive the reward R (punishment P) if both cooperate (defect). While a player cooperates and the other defects, the former will get a sucker's payoff S and the latter will receive a temptation to defect T. These payoffs satisfy the characteristic payoff ranking of the prisoner's dilemma: $T > R > P > S$ and $2R > T + S$ [11–13]. Thus two players will inevitably fall into the social dilemma, in which what is best for the individuals and what is best for the group.

In recent years, aimed at solving the social dilemma, a great number of approaches have been proposed. Nowak reviewed five rules for the promotion of cooperation named kin selection, direct reciprocity, indirect reciprocity, network reciprocity, and group selection in 2006 [14,15]. In particular, network reciprocity, is a well-known dynamical rule that fosters the prevalence of cooperation, has inspired many works to investigate the evolution of cooperation on network. In line with this framework, a lot of works aimed at offset the above unfavorable outcome has been proposed. For example, reputation [16–18], aspiration [19–25], environment [26–30], reproductive ability [49,50], features of players [31–35], small-world network [44,45], interdependent network [46], scale-free network [47,48], to name but a few examples [51–54]. In addition, human experiment, as a critical tool for testing predictions of theoretical models and investigating human cooperation, has been received much attention [36].

Voluntary participation is also considered as one effective approach to promote persistent cooperative behavior. Apart from traditional two strategies (cooperate and defect), the introduction of a third strategy called Loner (L), someone who do not willing to participate in PDG would rather take a small but fixed payoff, can lead the system to a rock-scissor-paper cyclic dominance [37]. Szabó and Hauert considered the voluntary prisoner's dilemma game on structured population and found that cooperative behavior can be maintained for the risk averse loners introduce a cyclic dominance into the system [38,39]. Luo et al. showed that voluntary participation could effectively promote the density of cooperation [42]. Chen et al. allowed for voluntary participation in the evolutionary PDG on regular lattices and scale-free networks, and focused

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on the strategy density and the evolution behavior of the system, finally, demonstrated that the voluntary participation mechanism promote the cooperative behavior in evolutionary games [43]. There is no doubt that loner has played a very important role in promoting the cooperative behavior.

Inspired by the aforementioned, a simple but thought-provoking question was raised: how cooperation level will if loner update his strategy according to his willingness? To this aim, we use a probability p represents the loner's participation willingness on cooperation in voluntary prisoner's dilemma. Through numerical simulation, we found that cooperation can be greatly enhanced even the temptation to defect is relatively large for moderate value of p. In the following, we will first describe the modified prisoner's dilemma game with voluntary participation in Section 2, later show the numerical simulation results in Section 3; and last summarize our conclusions.

2. Model

We investigate a voluntary prisoner's dilemma game with players located on a square lattice of size $L \times L$ with periodic boundary conditions, in which each interaction node will be occupied by a game player. Here each player adopts one of three strategies: cooperate (C), defect (D), or loner (L) with equal probability. Based on the weak PDG: $R=1$, $P=S=0$, and $T=b$. Thus the voluntary PDG characterized by the following payoff matrix:

$$M = \left[\begin{array}{cccc} & C & D & L \\ C & 1 & 0 & \sigma \\ D & b & 0 & \sigma \\ L & \sigma & \sigma & \sigma \end{array}\right] \qquad (1)$$

where $b(1<b\leq 2)$ is the temptation to defect and $\sigma \in (0,\ 1)$ denotes the payoff of both the loner and its co-player. Following previous works [39,41], we set $\sigma = 0.3$ in this article.

The game is iterated forward in accordance with the Monte Carlo simulation procedure comprising the following elementary steps. First, in each time step, a randomly selected individual x interacts with his direct neighbors and accumulate his total payoff P_x Then it chooses at random one neighbor, say y, who also gets his payoff P_y in the same way. Finally, player x adopts the strategy s_y from the selected player y with a probability given by Fermi function as follows:

$$W(s_x \leftarrow s_y) = \begin{cases} \dfrac{1}{1+\exp[(P_x-P_y)/K]} & s_x = C, D, \\ p\dfrac{1}{1+\exp[(P_x-P_y)/K]} & s_x = L \end{cases} \qquad (2)$$

where K denotes the amplitude of noise or its inverse ($1/K$), the so-called intensity of selection [40].

Since loner is a risk averse player, who would rather choosing the most safer strategy because it ensures that the payoff is moderate, we introduced parameter p, controls the willingness of loner updating his strategy, into the system. Cooperator and defector is a player that pursuit highest payoff, so they will update their strategy in each Monte Carlo step. When $p=1$, it will turn to the traditional voluntary prisoner's dilemma game. While $p=0$ will inevitably lead the system falling into the homogeneous loner state.

During one full Monte Carlo step (MCS) each player is selected once on average to change its strategy. Simulation results presented below were carried out on populations comprising 500×500 to 2000×2000 individuals. Besides, the key quantity the fraction of three strategies are determined within the last 5×10^3 full MCS over the total 3×10^4 steps. Moreover, to avoid additional disturbances, the final results were averaged over up to 10 independent realizations for each set of parameter values in order to assure suitable accuracy.

3. Results

We start by examining the impact of participation willingness on evolution of cooperation. Fig. 1 depicts frequency of strategies as a function of b for different values of p. $p=1$ returns the traditional version, where loner keeps the same probability of strategy update with cooperator and defector. From Fig. 1(a), it is clear that cooperation has a fast decline at small b. Because there are no sufficient loners to provide effective remission against defectors' exploitation. That means that defection can temporarily obtain large benefit. However, with increase of b, the low cooperation and fast increasing Loner enforce defector to decline until a stable level. From Fig. 1(b), we can see that decreasing p will makes the decay of defection more obviously, because more loners exist. Interesting, sufficient small p will lead to greatly different scenario: cooperation and defection will directly decline with the fast outbreak of loners. However, when defection dies out, choosing loner becomes naturally meaningless, because it cannot bring high benefit. At the same point, Loner dies out as well and cooperation completely dominates the system, even if temptation to defection is super large (see Fig. 1(c) and (d)). Thus, decreasing the participation willingness will directly promote cooperation and resolves the social dilemma.

Subsequently, it is interesting to see how the participation willingness impacts the evolution of strategies. Fig. 2 depicts the time evolution of different strategies under different values of p. For traditional case (Fig. 2(a)), defection will reach a peak at early stages, because its advantage in payoff guarantees its expansion. At the same time, loners and cooperators are really depressed, especially cooperation level close to 0. The great lack of cooperation enables defection to lose payoff advantage and thus make most defectors turn to loners. Due to fixed and small payoff, more loners return cooperation, which will lead to the subsequent rock-scissor-paper cycle until they reach stable level. For middle p values ($p=0.6$ and 0.3), such a cycle becomes less and less obvious, because bigger peak and dominance of loners well suppress the early exploitation of defection. In particular, $p=0.6$ can only maintain less defection (close to 0), when loner reach its first peak. With super-low level of defection, loner and cooperator will keep large fluctuation even if there has been long-term transition. The most interesting is that for small p will lead to a completely different scenario: the whole process is composed of one rock-scissor-paper cycle. At early stages, though defection has expansion, the fast outbreak of loner will directly impede its exploitation and even make defection vanish. When defection dies out, loner will turn to cooperation due to more collection benefit, with complete disappear of defection (i.e. enemy), loner becomes an inferior choice and cooperator reaches its full dominance soon. Thus, participation willingness directly affects the rock-scissor-paper cycle with its decrease, such cycle becomes less and less impressive, which produce loner cooperation level. However, for super small value, there is one such cycle, which but leads to full cooperation soon.

To complete a clear understanding for the role of participation willingness, Fig. 3 depicts the frequencies of strategies on $b-p$ panel. For traditional case ($p=1.0$), three strategies will coexist when b is a little larger. This is caused by the disappearance of loners. However, with p decreases, loners will greatly increases, and cooperation level declines, because defectors can be suppressed very fast (which is represented in Fig. 2). If the first peak of defectors during its evolution is suppressed, loners will dominate the system. From Fig. 3(b), we can see when defectors completely vanish, cooperation becomes the best strategy, and holds the whole system. That is to say, low p will generate an optimal situation for cooperation. Thus participation willingness plays a key role in promotes cooperation.

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