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Impact of self-interaction on evolution of cooperation in voluntary prisoner's dilemma game

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ABSTRACT

Voluntary participation, as a simple yet valid mechanism to promote cooperation in game theory, has been received a great deal of attention. In this paper, we introduce self-interaction into voluntary prisoner's dilemma game. In detail, cooperator will gain a fixed additional reward by having an interaction with itself, while defector will obtain nothing through self-interaction and loner don't participate in the game. It is shown that cooperative behavior is remarkably facilitated with increase of additional reward by forming huge clusters for low level of temptation to defect. While for large temptation, the system will fall into cycle dominance of three strategies and self-interaction hardly has impact on the evolution of cooperation compared with traditional version.

1. Introduction

According to Darwinian theory of evolution, all species of organisms arise and develop through natural selection, which is the process of eliminating inferior species gradually over time [1]. This means that individuals need to maximize their own benefits for survival within the population, in which any strategy that does not donate themselves will die out eventually. However, cooperative behavior is still ubiquitous ranging from social systems to natural world [2]. In this case, understanding the emergence and maintenance of cooperation among selfish individuals becomes one of the most intriguing puzzles, which attracts myriad of researchers in the field of sociology, biology, ecology, economics, to name but a few [3–5].

To resolve this issue, evolutionary game theory has provided us a helpful mathematical framework and has received great attention [6–8]. In particular, prisoner's dilemma game (PDG), as the most typical social dilemma, is often used to illustrate the social conflicts between two independent peers, which has attracted a great deal of attention both experimentally and empirically [9,10]. Thus, PDG is a pairwise interaction game. In its basic version, two individuals simultaneously decide whether to cooperate (C) or defect (D), and then they will estimate their payoffs in line with their decisions. In PDG, mutual cooperative individuals will both receive the reward R, while mutual defective individuals will suffer the punishment P. If they have a different choice, the cooperative individual will get the sucker's payoff S, and the defective individual will obtain the temptation to defect T. In order to bring PDG into existence, the payoffs mentioned above satisfy the rankings $T > R > P > S$ and $2R > T + S$. These rankings express that defection is the best choice regardless of the opponent's strategy, while mutual cooperation can maximize collective benefits. Obviously, social dilemma arises.

Based on the classic game theory, many mechanisms have been proposed to solve the dilemma of maximizing personal benefits or collective benefits [11–22]. A pioneering work by Nowak and May, which first introduced spatial structure, has attracted extensive concern [11]. Among their research, they found out that cooperators can resist the invading of defectors and even prevail by forming compact clusters, which is called spatial reciprocity. Motivated by this seminal result, various of scenarios have been proposed to explore the evolution of cooperation among structured population. For example, reputation [23,24], aspiration [25,26], memory [27,28], extortion [16,29], voluntary participation [28,30], asynchronous update [31] and so on. Beyond that, different spatial topologies, such as ER random graph [32], small-world network [33], BA scale-free network [34] as well as multilayer coupling network [35], have also enriched the research in this field.

Except for cooperation (C) and defection (D), the third strategy, voluntary participation has been verified as an effective approach to facilitate cooperation [30]. Since voluntary participation means that it is not compulsory for players to take part in the game, play-

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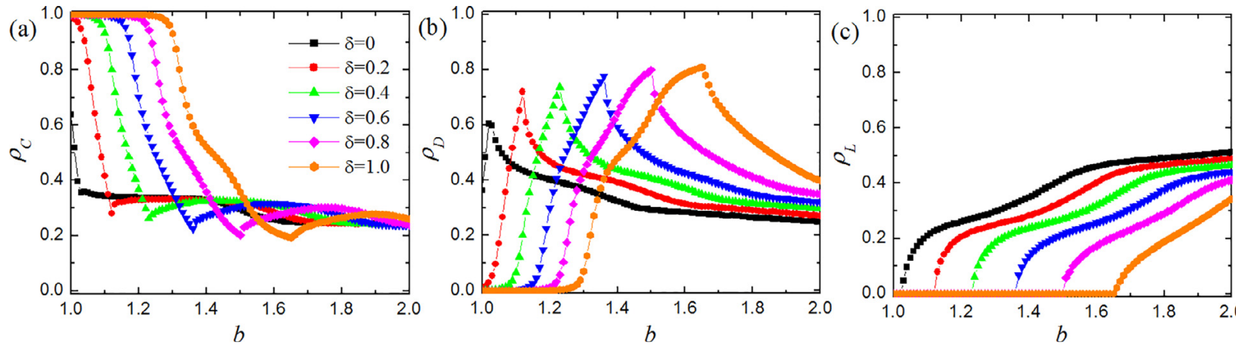

Fig. 1. The fractions of cooperators (ρ_C), defectors (ρ_D) and loners (ρ_L) in dependence on the temptation to defect b for different values of additional reward δ. Depicted results are obtained for $K = 0.1$.

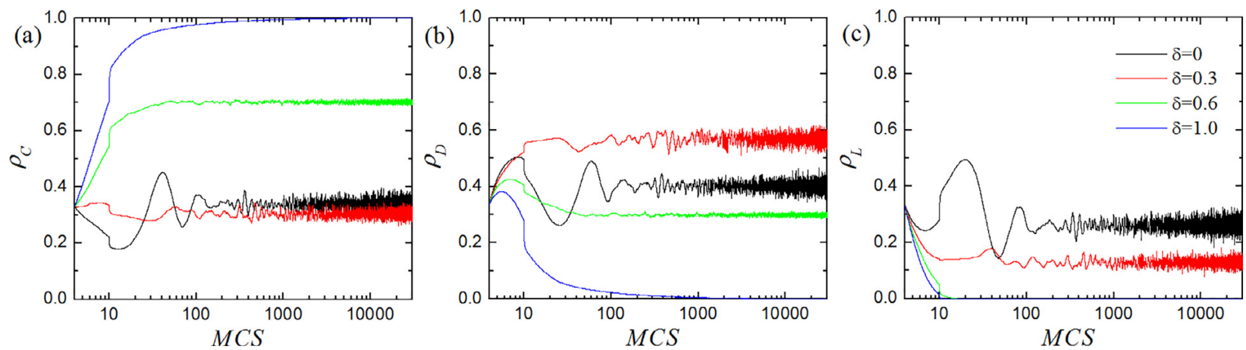

Fig. 2. Time evolution of cooperators (ρ_C), defectors (ρ_D) and loners (ρ_L) for $\delta = 0$, 0.3, 0.6 and 1.0. Depicted results are obtained for $b = 1.2$ and $K = 0.1$.

ers with this strategy are commonly called as loners (L). Under such a setup, loners can refuse to participate in the game and only obtain a small but fixed income. When voluntary participation is involved, system would no more come to a deadlock in state of mutual defection, instead, it would step into a rock-scissors-paper-like dynamics with cyclic dominance, i.e. L invades D invades C invades L. In this case, many studies about voluntary participation also emerged. In Ref. [36], Wu et al. considered spatial prisoner's dilemma game with volunteering in Newman-Watts small-world networks and found out that agents are willing to participate in the game in typical small-world region and intensive collective oscillations arise in more random region in case of very low temptation to defect. In addition, Luo et al. studied the evolution of prisoner's dilemma game with volunteering on interdependent networks, which showed that cooperation is elevated into a higher level when voluntary participation is considered [37].

Furthermore, most previous works assume that focal player can only interact with its nearest neighbors and gain its payoff. However, self-interaction should not be ignored equally in real life, such as self-examination. Motivated by this fact, Li et al. explored the role of self-interaction in the evolution of cooperation, in which a cooperative player will acquire an additional and fixed reward $R = 1$, and manifested that cooperation is greatly facilitated when considering self-interaction [38]. Moreover, a recent work considered three types of additional payoffs instead of the fixed reward R, and demonstrated that self-interaction is a potential and effective means to enhance the behavior of cooperation [39]. Along these works, we further introduced self-interaction into voluntary prisoner's dilemma game and found that cooperation is remarkably enhanced with increment of additional reward. Compared with the previous work with self-interaction only, the introduction of voluntary participation could avoid falling into the deadlock of mutual defection.

The rest of this paper is structured as follows. First, in Section 2, we will describe the model of voluntary prisoner's dilemma game with self-interaction in detail. Subsequently, we will provide simulation results and discussions among them in the next section. Lastly, the main conclusion is given in Section 4.

2. Model

The proposed mechanism is carried out in traditional prisoner's dilemma game (PDG) with volunteering, where players can choose one strategy from cooperation, defection and voluntary participation in each round of game. The evaluation of benefits of cooperators and defectors is based on payoffs of weak PDG, while loners and their opponents will always obtain the small and invariable payoff $0 < \sigma < 1$. Without loss of generality, we set $R = 1$, $T = b$ $(1 \leq b \leq 2)$ and $P = S = 0$. Based on this, the payoff matrix can be written as:

$$\begin{array}{cccc} & C & D & L \\ C & 1 & 0 & \sigma \\ D & b & 0 & \sigma \\ L & \sigma & \sigma & \sigma \end{array} \tag{1}$$

According to the existing works, we fix $\sigma = 0.3$ in the full paper.

We use a regular $L \times L$ square lattice with periodic boundary conditions as the simplest interaction network to describe a structured population. Each node represents a player in repeated game and is assumed to interact with four neighbors who connected with. Initially, each player is randomly set as cooperator (C), defector (D) or loner (L) with equal probability. That is to say, each strategy covers one-third of the square lattice.

The game is iterated forward in accordance with the Monte Carlo (MC) simulation procedure. At each time step, focal player x interacts with its four nearest neighbors and obtains its payoff P_x according to payoff matrix mentioned above,

$$P_x = \sum_{i \in \Omega_x} P_i \tag{2}$$