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Promotion of cooperation by adaptive interaction: The role of heterogeneity in neighborhoods

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HIGHLIGHTS

- Adjusting interaction willingness with different neighbors can promote cooperation.
- Proper probability of neighbor distinguishing can bring high group payoff.
- The mechanism of the pattern formation at different evolutionary stages is analyzed.

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ABSTRACT

Evolution of cooperation in prisoner's dilemma games has been studied extensively in the past decades. Recent studies have investigated the effect of adaptive interaction intensity on spatial prisoner's dilemma, showing that if individuals can adjust their interaction intensity with each opponent at the same extent, cooperation can be promoted in a proper scale. However, the previous studies about adaptive interaction willingness do not consider the heterogeneity of the opponents. In this paper, a simulative model is developed to examine whether and how the interactive diversity influences cooperation in the spatial prisoner's dilemma games, in which individuals consider the corresponding behavior of different opponents. The simulation results show that the proposed mechanism can effectively promote cooperation, and the average payoff of the system can significantly be improved by high interaction intensity between cooperators. In addition, we also show four kinds of different individuals to analyze the evolution progresses. The simulations show that cooperators on the boundary decrease their interaction willingness, which makes the boundary defectors lose their opportunity to participate in the interaction and be invaded by cooperators.

1. Introduction

The evolution of cooperation among selfish individuals is one of the major challenges in both biological and social systems [1]. Among numerous methods of cooperation research, evolutionary game theory provides a suitable theoretical framework to study the emergence and persistence of cooperation [2]. As one of the most famous social dilemma games, the prisoner's dilemma game (PDG) describes the conflict between what is best for the group and what is best for the individual [3,4].

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To understand the evolution of cooperative behavior in complex system, five major mechanisms have been proposed, i.e. kin selection [5], direct reciprocity [3], indirect reciprocity [6], spatial reciprocity [7,8] and group selection [9]. As one of the important mechanisms to escape the dilemma, spatial reciprocity arouses widespread attention, because it provides a simple but effective model to describe the evolution game on structured space. It is known that spatial structures generally promote the evolution of cooperation because spatial locality helps cooperators interact more often with other cooperators than defectors [7]. The microscopic explanation for this phenomenon is that cooperators can form spatial clusters where the boundaries, although exploited by defectors, protect the internal cooperators [10–12]. The spatial reciprocity provides an explanation for the survival of cooperator in real social systems [13].

The interactive diversity, defined as the discriminative acts of individuals in different interactions [14,15], can promote cooperation effectively. Traulsen et al. first studied individual's interaction with a probability [16], which could lead to a high level of cooperation in a finite well-mixed population. Moreover, Chen et al. studied the interaction stochasticity in spatial repeated PDG, reporting cooperation can be promoted in optimal regions [17]. It is also worth mentioning that using different strategies against different neighbors [14,18–20] explains the ubiquitous cooperation and individuals distinct responses in different interactions. Besides, a variety of mechanisms have also been put forward to promote cooperative behaviors between individuals, such as neighborhoods [21], time scale [22] and reputation [23,24].

Many studies focus on the interaction willingness in evolutionary games because whether to participate in the game may not be an 'all-or-nothing' option but rather 'probabilistically' changing according to the diversification of risk [25]. Based on this point, interaction stochasticity is extended to well-mixed populations [16,18] and spatial PDG [17,24,26]. Li et al.'s work showed that cooperation can be promoted, if individuals can properly adjust interaction willingness based on the variation of payoff [27]. Specifically, if an individual's total payoff increases (decreases) comparing with that in the previous generation, he will enhance (reduce) his interaction willingness with all his neighbors to the same extent. Their work provides a new perspective for evolutionary games, suggesting that adaptivity is a potential mechanism to enhance cooperation. However, in their work each individual treats all its neighbors equally. This strategy may be exploited by defectors. Considering interactions between a cooperator and his Von Neumann neighbors (3 cooperator and 1 defector), the interaction willingness with all neighbors could be improved if the payoff is higher than the previous generation. Obviously, the improvement of interaction willingness benefits cooperators and defectors simultaneously. A reasonable means to overcome this drawback is to distinguish the traits of neighbors in the adjustment of individual's interaction willingness. Such differentiation of neighbors is often observed in real social systems. For example, businessmen prefer to interact with reciprocal partners, rather than treacherous ones. Thus, it is worthwhile to take the heterogeneity of neighbors into account in individuals' adjustment of their interaction willingness.

In this paper, we investigate the evolution of cooperation by changing the interaction willingness with each neighbor based on the corresponding payoffs. Fraction of cooperation is improved significantly, with consideration of the of neighbor heterogeneity. Furthermore, we explore the underlying mechanism of the cooperation emergence and the process of evolution by analyzing the snapshots of typical distributions.

2. Model

We consider the evolutionary Iterated Prisoner's Dilemma game on a $50 * 50$ square lattice where each individual is locating on one site of the lattice randomly and only interacts with its four immediate neighbors. When the game starts, individuals simultaneously decide whether to cooperate, C (denoted by two-dimensional unit vector $s_C = [1, 0]^T$) or to defect, D (denoted by unit vector $s_D = [0, 1]^T$). According to their choices, individuals will receive payoffs which can be expressed by a general $2 * 2$ payoff matrix. Without loss of generality, we use the payoff matrix A adopted by Nowak and May [7]. It is as follows,

$$A = \begin{pmatrix} R & S \\ T & P \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 1+b & 0 \end{pmatrix} \tag{1}$$

where $b \in (0, 1)$ is the temptation to defect for the PDG. The payoff of the individual i with one of its neighbor j at generation t can be expressed as $P_{ij}(t) = s_i^T A s_j$, where s_i and s_j denote the strategies of individual i and j, respectively. s_i^T means the transpose of the state vector s_i. The total payoff $P_i(t)$ of the individual i with all its neighbors $j \in \Omega_i$ at generation t is denoted as $P_i(t) = \sum_{j\in\Omega_i} P_{ij}(t)$, where Ω_i is the neighborhood of individual i.

In evolutionary iterated prisoner's dilemma, an individual's willingness to attend game with each other changes at every generation. Let $\omega_{ij}(t)$ denotes the interaction willingness between individual i and j at generation t. Two individuals decide whether to interact with each other according to the probability $\omega(t) = \frac{\omega_{ij}(t)+\omega_{ji}(t)}{2}$, which is adopted by Li et al. [27]. Individuals are more inclined to take part in games with a larger $\omega(t)$. When $\omega(t) \to 1$, it is as same as the traditional lattice game where individuals interact with all Von neighbors. On the contrary, the interaction willingness between individuals tends to be 'frozen' while $\omega(t) \to 0$, which means there is almost no interaction. In the process of random interactions, it is likely that individual i can successfully interact with some neighbors (if any) while the remainder interactions would fail. We regard the neighbors who actually participate in game with i among i's neighbors as the *effective neighbors* of i at generation t, denoted as $N_i(t)$. The interaction intensity of an individual is determined by $I(t) = \frac{N_i(t)}{k_i}$, where k_i characterizes the number of all i's neighbors [23].