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Heterogeneous game resource distributions promote cooperation in spatial prisoner's dilemma game

Guang-Hai Cui [a,*], Zhen Wang [b], Yan-Cun Yang [a], Sheng-Wen Tian [a], Jun Yue [a]

[a] *School of Information and Electrical Engineering, Ludong University, Yantai 264025, China*
[b] *School of Cyberspace, Hangzhou Dianzi University, Hangzhou 310018, China*

HIGHLIGHTS

- We introduce a spatial prisoner's dilemma game which considers individual abilities to establish games.
- We confirm that the heterogeneous distributions of individual game resources promote evolution of cooperation.
- The cooperation can be promoted more effectively when the distribution of game resources is more heterogeneous.
- The central pure cooperators with larger game resource capacities play a key role in the maintenance of cooperation.

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ABSTRACT

In social networks, individual abilities to establish interactions are always heterogeneous and independent of the number of topological neighbors. We here study the influence of heterogeneous distributions of abilities on the evolution of individual cooperation in the spatial prisoner's dilemma game. First, we introduced a prisoner's dilemma game, taking into account individual heterogeneous abilities to establish games, which are determined by the owned game resources. Second, we studied three types of game resource distributions that follow the power-law property. Simulation results show that the heterogeneous distribution of individual game resources can promote cooperation effectively, and the heterogeneous level of resource distributions has a positive influence on the maintenance of cooperation. Extensive analysis shows that cooperators with large resource capacities can foster cooperator clusters around themselves. Furthermore, when the temptation to defect is high, cooperator clusters in which the central pure cooperators have larger game resource capacities are more stable than other cooperator clusters.

1. Introduction

Cooperation is ubiquitous in biological, social and economic systems [1–4]. Explaining the maintenance and evolution of cooperation among rational and selfish individuals in such systems still remain a major challenge [1,2]. Evolutionary game theory, which began with the objective of solving biological questions, has been a general framework to investigate the evolution of cooperation in such scenarios [5–7]. The prisoner's dilemma game (PDG) has attracted significant efforts, emerging as a famous metaphor for the problem of cooperation in two-player games. In the PDG, two rational individuals simultaneously and independently choose to either cooperate or defect. The two individuals obtain a reward R if they both select to cooperate, and they receive a punishment P if they both defect. When the two individuals choose different actions,

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* Corresponding author.
E-mail addresses: cuigh@ldu.edu.cn (G.-H. Cui), wangzhen@hdu.edu.cn (Z. Wang).

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the defector obtains the payoff T as an exploiter, whereas the cooperator obtains the sucker's payoff S. Moreover, the payoff rank satisfies $T > R > P > S$ and $2R > T + S$. T is the highest payoff in PDG and is regarded as the temptation to defect. Although mutual cooperation can bring the highest global benefit, it is clear that the optimal choice for an individual is to defect regardless of the action of the opponent. This selection causes a social dilemma that characterizes the conflict between individual and public interests.

After the seminal work of Nowak and May on the evolution of cooperation in spatial PDG [8], various mechanisms, such as reward [9,10], punishment [11–15], time scale [16–18] and mobility [19–22], have been proposed to solve the dilemma and explain the evolution of ubiquitous cooperative behaviors based on spatial evolutionary game theory. Moreover, the effects of some diverse or heterogeneous characteristics of individuals on cooperation also have been studied, such as social diversity [23], heterogeneous vertex or link weight [24–33], heterogeneous investment [34,35], diverse targets [36,37] and inhomogeneous activity [38–41]. Most of these works are based on a common, simplifying assumption that individuals establish games against every neighbor on the contact network determinably in per unit of time. Thus, the rounds of games an individual can establish is equal to the number of the individual's topological neighbors. Actually, in real social networks, the edge between an individual and one of its neighbors in the contact network only depicts the potential interaction tag between them, and an individual's ability to establish games is independent of the number of neighbors. Furthermore, for an individual, the neighbors with whom to interact per unit of time are not deterministic [42–47]. In this sense, an individual may only establish interactions with a few neighbors, and the number of interactions with a specific neighbor may be more than one. For example, in the science collaboration network, on one hand, although some scientists may have many collaborators, their collaboration number may be small. On the other hand, the collaboration number of some scientists who have few collaborators may be very large.

Poncela et al. [48] studied the effect of restricting the number of interactions that an individual is allowed to establish per unit of time when involved in a PDG on SF networks. Every individual in the model can only establish a fixed number k^* of interactions randomly chosen from its topological neighbors, regardless of the topological connectivity of the individuals. In this paper, our motivation is to study the influence of heterogeneous distributions of individual abilities to establish games on the evolution of cooperation in a spatial PDG. To this end, we first introduce the spatial PDG, which considers individual abilities to establish games. In the game, individual resource capacities are defined to depict the quantities of individual game resources, which determine individual abilities to establish games per unit of time. When an individual establishes a round of game, its game opponent is randomly selected among its topological neighbors, instead of performing games with each neighbor once [42–44]. Second, we study the influence of individual game resource distributions on cooperation by considering three types of distributions that follow the power-law property. Surprisingly, by means of Monte Carlo simulations, we find that cooperation can be significantly enhanced compared with the normal situation, in which quantities of individual game resources are the same and the game opponent is randomly selected among topological neighbors. In particular, a higher cooperation level can be achieved for more heterogeneous levels of resource capacity distributions. Moreover, further analysis from a microscopic perspective shows that cooperators with larger game resource capacities play an important role in the promotion of cooperation, and the surviving cooperator clusters in which the central pure cooperators have larger game resource capacities are more stable than other cooperator clusters when the temptation to defect is high.

The remainder of this paper is organized as follows. In Section 2, we describe the model of PDG, taking into account individual abilities to establish games and the simulation model. We then present the main results and discussion in Section 3. Finally, conclusions are summarized in Section 4.

2. Model

2.1. Spatial prisoner's dilemma game with game resources

We consider an evolutionary PDG on a two dimensional square lattice network with periodic boundary conditions. Every node on the network represents an individual in games. In terms of the weak PDG in Nowak and May's seminal work [8], the values of payoffs are rescaled as follows: $T = b, R = 1, S = P = 0$. In the adjusted payoff matrix, $b\,(1 \leq b \leq 2)$ is the single adjusting parameter and represents the temptation to defect. Although the payoff rank cannot strictly satisfy the condition $T > R > P > S$, the model can capture the essential feature of the original PDG and is widely used in evolutionary PDG studies [49,50].

In studies, we define parameter Rs to characterize the quantities of individual game resources that are used to establish games, namely the game resource capacity of individuals, which is calculated as follows:

$$Rs_i = 4 * A * \xi + \overline{Rs} \tag{1}$$

where $\overline{Rs}$ indicates the average resource capacity of all individuals in the network. Because we consider the von Neumann neighborhood in square lattice networks, $\overline{Rs} = 4$ can ensure that the average resource capacity of all individuals is the same as in the normal scenario (the resource capacity of each individual is 4). A is a scaling parameter that determines the undulation of individual resource capacity distributions ($0 \leq A \leq 1$), the game will return to the normal form when $A = 0$. Since the power-law distribution was found in many real networks [51,52] and has been widely used in research [53–55], we here study the effects of three types of game resource distributions that follow the power-law property. ξ is a number