



Heterogeneous investments promote cooperation in evolutionary public goods games

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HIGHLIGHTS

- Heterogeneous investments promote cooperation.
- The microscopic mechanism behind the promotion of cooperation is revealed.
- Heterogeneous investments lead to more robust clusters of cooperators.
- Future research in terms of asymmetric influences on game dynamics is discussed.

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ABSTRACT

The public goods game is widely accepted as a suitable theoretical paradigm for explaining collective cooperation. In this paper, we investigate the impact of heterogeneous investments on cooperation in groups, where the investment of one player to a particular group depends on the fraction of cooperators in that group. Our research reveals that the level of cooperation is significantly promoted as the level of heterogeneity in the investments increases. By studying the payoffs of players at the boundaries of cooperative clusters, we show that the positive effect on the evolution of cooperation can be attributed to the formation of clusters that are more robust against invading defectors. The presented results sharpen our understanding of cooperation in groups that are due to heterogeneity and related asymmetric influences on game dynamics.

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1. Introduction

The emergence of cooperation among selfish individuals contradicts Darwin's theory, which has attracted much attention in diverse disciplines [1–7]. To explain this challenging issue, researchers often resort to a powerful theoretical framework of evolutionary game theory [8–11]. Two simple games, the prisoner's dilemma game and the snowdrift game, are widely used as typical paradigms in this field. In a typical prisoner's dilemma or snowdrift game, each player can adopt two pure

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strategies: cooperate (C) or defect (D). Then, the players play the game in pairs to earn payoff. If they both take the same action for C or D, each will get a payoff of reward (R) or punishment (P). If they choose distinct strategies, the defecting player is tempted to achieve the maximum payoff (T), and the cooperating player receives the sucker payoff (S), with the precondition $2R > T + S$. The ranking of these four payoff for the prisoner's dilemma game is $T > R > P > S$, and it is $T > R > S > P$ for the snowdrift game. The main difference between the games is that the evolutionary stable strategy in the prisoner's dilemma game is mutual defection, whereas in the snowdrift game, mutual defection leads to the lowest payoffs for both players [12–15].

As the prisoner's dilemma game and the snowdrift game are generally used to characterize pairwise interactions, the public goods game (PGG) is used for group interactions [16]. Indeed, the PGG has received unprecedented attention in the physics community in the past decade [17–42]. In the original PGG model, all N participants simultaneously decide whether to contribute (cooperate) or not (defect) to a common pool. Then, the total investment of all cooperators in the public pool is multiplied by a factor r ($1 < r < N$) and contributes equally to all players, regardless of their contributions. Namely, the whole system can reach the best state when all participants invest with the maximum amount to the public pool. However, the Nash equilibrium in PGG is all defection. Participants are faced with the temptation of free riding because all players do better when contributing zero than when they contribute something, regardless of what anyone else does, which can also be called the “tragedy of the commons” [43].

Many real-world systems can be described as networks, in which nodes represent the interacting individuals and edges characterize their interactions. One interesting research direction is to study the evolutionary game dynamics on networks. It has been shown that cooperative behavior can emerge when individuals interact on networks, including regular lattices, small-world, scale-free and dynamical networks [44,2]. Recently, several mechanisms have been put forward to illustrate the evolutionary cooperation of PGG. Guan et al. found that the variation in strategy transfer capability can promote the cooperation level [45]. Segbroeck et al. studied the evolutionary dynamics of repeated group interactions, leading populations to engage in dynamics involving both coordination and coexistence [46]. Santos et al. found that social diversity can remarkably promote cooperation on heterogeneous graphs [47]. Szolnoki et al. focused on the PGG with delayed distribution and found decelerated invasion and waning-moon patterns [48], while in [49] it was even found experimentally that punishment diminishes the benefits of network reciprocity, to name just some examples.

In many previous mechanisms, one cooperator will contribute the same value to the participating groups. However, in reality, the investment of each cooperator can be heterogeneous according to the environment. Thus, it is natural to consider investment heterogeneity in the PGG model. Cao et al. studied an unequal investment mechanism on a scale-free network, in which the investment of players is related to its degree [50]. Yuan et al. presented an investment heterogeneity mechanism in PGG on a square lattice, which allowed the investment of cooperators to be mapped to the fraction of cooperators inside [51]. Both works found that cooperation is promoted by the heterogeneous investment mechanism; however, the total investment of each player is rather different. To further explore the effect of heterogeneous investment on cooperation, we fix the total investment of all players to be 1. It is found that cooperation is still markedly enhanced, and the results are examined by the payoff differences along the boundaries of cooperative domains from a microscopic point of view.

2. The model

Here, each player is located on a site of 100×100 square lattice with periodic boundary conditions and interacts with its Von Neumann neighborhood. Initially, all players are designated as a cooperator (C) or a defector (D) with equal probability 0.5. Then, each player participates in $k_i + 1$ PGG groups, where one PGG group is centered around itself and the other k_i groups are correspondingly centered around their nearest neighbors [47]. The total investment of all players is set to 1. Here, we hypothesize that the investment of a cooperator in a PGG group depends on the proportion of cooperators inside that group. g_x^y is the investment of player x in the PGG group centered around y .

$$g_x^y = \frac{s_x(N_c)_y^\alpha}{\sum_{j \in \Omega_x} (N_c)_j^\alpha} \tag{1}$$

where N_c is the number of cooperators inside x -centered PGG group and Ω_x is the community composed of the neighbors of x and itself. $s_x = 1$ represents C and $s_x = 0$ represents D. All contributions are multiplied by the factor r and are then equally divided among all players. Under such a mechanism, the payoff of an individual x associated with the PGG group centered on individual y is given by

$$m_{x,y} = \frac{r}{k_y + 1} \sum_{i=0}^{k_y} g_i^y - g_x^y \tag{2}$$

where i represents the i th neighbors of player y . The total payoff of the player x can be expressed as

$$M_{x,y} = \sum_{y \in \Omega_x} m_{x,y} \tag{3}$$

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