Physica A 512 (2018) 598–611

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

The evolution of cooperation in spatial prisoner's dilemma game with dynamic relationship-based preferential learning

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HIGHLIGHTS

- Introduce dynamic relationship-based preferential learning mechanism into evolutionary prisoner's dilemma game model.
- Construct a method to update the strength of relationship according to mutual strategies.
- Both the sensitivity factor and the preference intensity has multiple effects on promotion of cooperation.
- There exists a trade-off between the influences of the sensitivity factor and the preference intensity.

ARTICLE INFO

Article history:
Received 11 January 2018
Received in revised form 8 April 2018
Available online xxxx

Keywords:
Prisoner's dilemma game
Evolution of cooperation
Learning preference
Dynamic relationship

ABSTRACT

The relationships in human society are heterogeneous and dynamically change with interactions, which have a strong effect on individual's learning behaviors. In this light we present a new mechanism of preferential learning based on dynamic relationship into evolutionary spatial prisoner's dilemma game to further investigate the incentive mechanisms of cooperative behaviors. In detail, we consider that the strength of relationship between pairwise individuals adaptively changes according to their mutual strategies and the adjusting rate is related to individuals' sensitivity to interactions. Based on the heterogeneous and dynamic relationship, individuals prefer neighbors with stronger relationship to learn from instead of learning randomly The learning preference is measured by the preference intensity. By means of Monte Carlo simulations, we find that both the sensitivity factor and the preference intensity have multiple effects on the evolution of cooperation. Furthermore, to validate the multiple effects in a microcosmic view, strategy transitions during the evolution are also discussed. Interestingly, we find that there exists a trade-off between the influence of the sensitivity factor and the preference intensity on the evolution of cooperation. Presented results are robust to variations of the network structures and may provide a new understanding to the emergence of cooperative behaviors.

1. Introduction

Evolutionary game theory has played an important role in studying cooperative behavior in the fields of biology, sociology, and economics [1,2]. Evolutionary games, including the prisoner's dilemma game (PDG) [3–11], the snowdrift game (SG) [12,13], and the public goods game (PGG) [14–18] have been introduced to characterize the evolution of cooperation. Especially, the prisoner's dilemma game and its extensions have been frequently used by researchers to describe the origin of social dilemma and explain the emergence of cooperation. For conventional PDG model, each player has two feasible strategies: cooperation (C) and defection (D). Mutual cooperation brings a payoff R (reward) for each player, while mutual

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https://doi.org/10.1016/j.physa.2018.08.105
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defection results in a payoff P (punishment). If players take different actions, the defector gets T (the temptation to defect) by exploiting the cooperator who only gets S (the sucker's payoff). Accordingly, a PD game exists only when two conditions are satisfied: T > R > P > S and 2R > T + S. Thus mutual defection is the only equilibrium in a single encounter although mutual cooperation can bring larger payoffs for both players. However, the non-cooperative conclusion obviously contradicts the reality that cooperative behaviors are ubiquitous in the world. This contradiction has aroused great interest in the study of possible conditions for the emergence and promotion of cooperation.

Motivated by the fact that individuals are embedded in a social network, Nowak and May originally integrated spatial structure with the PDG, which provides an escape for cooperators from exploitation [19]. In the same vein, small-world networks [20], scale-free networks [21], networks with communities [22] and a number of other topologies [23,24] were also employed in modeling social dilemma. In the study of spatial evolutionary games, it is found that heterogeneity of spatial-structured population is an effective mechanism for cooperation significantly conducive to the emergence of cooperation [25]. Up until now, in addition to the population structure, a series of mechanisms, which are capable of explaining the survivability and sustainability of cooperation, have been proposed in theoretical and experimental studies. In particular, Nowak discussed five rules [26] (kin selection, direct reciprocity, indirect reciprocity, network reciprocity, and group selection) for the evolution of cooperation. Moreover, many other available mechanisms were also thoroughly investigated, including image scoring [27], teaching activity [28], reward and punishment [29,30], memory and conformity [31], preferential learning [32], to name but a few. Although much progress has been made in resolving the conundrum of cooperation, there is still a key defect in most of the prior works. That is, in the real world, social systems are mostly associated with weighted networks and the link weight between pairwise individuals in social networks is often heterogeneous [33–35]. Therefore, it is often improper to place social dilemma models into un-weighted networks. Introducing weighted networks into the evolution of cooperation opened a new window for the subsequent researches.

In contrast to the un-weighted networks, the weighted networks can reflect not only the presence or absence of a relation, but also the subjective closeness and duration of relationship [36,37] or frequency of contact [38–40] between two players. In the last few years, a number of evolutionary PD games built on weighted networks have been proposed [41–45]. For example, in order to know whether the heterogeneity of link weight can facilitate cooperation, researchers constructed simulation models on weighted networks where the link weights followed different pre-specified distributions [46–48]. The results showed that the network with heterogeneous link weights outperformed the homogeneous link weights in the facilitation of cooperation and a proper level of heterogeneity can lead to the highest cooperation level under a particular temptation b. In most of the works with weighted networks, link weights were set to directly influence the individuals' payoffs or utilities (the individuals' payoffs are weighted by the value of link weights), thus the evolutionary results were affected under this setting. However, the nature of social relation between a pair of individuals in social networks is likely to affect the behavioral preference even more directly. An empirical study conducted by Harrison et al. suggest that individuals are generally willing to suffer greater cost for close friends [49], in other words, the relationship has an inevitable impact on individuals' reciprocal behaviors. Inspired by this, Xu et al. investigated the effect of relationship-based investment preference on the evolution of cooperation by modeling evolutionary PD game on weighted network where link weights represent the closeness of relationships [50]. And it is found that a moderate preference can greatly promote the diffusion of cooperation, while an extremely strong preference can hinder the cooperative behaviors conversely. In addition to the reciprocal preference, many other preferences are evidently influenced by relationships as well, such as altruistic preference, learning preference and so on. In particular, the learning preference is closely associated with relationships, a fact which is easily ignored in investigations but prevalent in the society. As an old saying goes, "He who stays near ink gets stained black". And that indeed is true in society. Because of intimacy and trust, we usually learn from our close friends thus our behaviors are assimilated by them. Given the above empirical observations, we introduce learning preference into the evolutionary PDG model to investigate how such relationship-based preferential learning mechanism affects the evolution of cooperation.

As is the general case in studies of cooperation in networks, all neighbors share the same possibility to be chosen for players to learn from according to deterministic rules [19,51]. In contrast, under preferential learning mechanism, neighbors with stronger connections are more likely to be chosen. Importantly, relationships (link weights) in social networks are typically dynamic [52], changing in response to the strategies of individuals [53]. In return, the relationships affect the strategies of players. Therefore, for better mimicking the reality, we assume that link weights dynamically change with interactions. To address the preferential learning mechanism and avoid the influence of heterogeneity of network structure, we consider primarily the prisoner's dilemma game on square lattice. Furthermore, for the sake of rigor, simulations are also conducted on heterogeneous networks. The results show that the introduction of preferential learning mechanism has multiple impacts on the promotion of cooperation, which are universal to both homogeneous networks and heterogeneous. As relationship-based learning preference is ubiquitous in human society, our study may shed some new light on resolving the social dilemmas in the real world.

This paper is organized as follows. The model with preferential learning mechanism is constructed in Section 2. The main results and discussions are given in Section 3 and Section 4. Conclusions are given in Section 5.

2. Model

In this study, we take into account the classical two-strategy prisoner's dilemma game, in which the elements of payoff matrix follow the previous studies: $R = 1$, $P = S = 0$, and $T = b\,(1 < b < 2)$, thus the game is controlled by a single