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Social influence promotes cooperation in the public goods game

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HIGHLIGHTS

- Propose influence-based imitation pattern for strategy updating.
- Influence-based imitation effectively enhances cooperation level.
- Cooperation-promoting effects of this imitation are robust with variation of population structures.

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ABSTRACT

Previous studies mainly consider the random selection pattern in which individuals randomly choose reference models from their neighbors for strategy updating. However, the random selection pattern is unable to capture all real world circumstances. We institute a spatial model to investigate the effects of influence-based reference selection pattern on the evolution of cooperation in the context of public goods games. Whenever experiencing strategy updating, all the individuals each choose one of its neighbors as a reference with the probability proportional to this neighbor's influence. Levels of individuals' influence are dynamical. When an individual is imitated, the level of its influence increases, thus constituting a positive feedback between the frequencies of individuals being imitated and the likelihood for them to be reference models. We find that the level of collective cooperation can be enhanced whenever the influence-based reference selection pattern is integrated into the strategy updating process. Results also show that the evolution of cooperation can be promoted when the increase in individuals' frequency of being imitated upholds their influence in large magnitude. Our work may improve the understanding of how influence-based selection patterns promote cooperative behavior.

1. Introduction

Cooperative behavior is omnipresent in almost all realistic systems ranging from biological sphere to economic systems to human society [1]. Thus understanding the mechanisms for the emergence and maintenance of cooperative behavior becomes an important question, which has attracted increasing attention of scientists from many academic communities. Among others, evolutionary game theory has become one of the most prevailing yet decisive approaches to understanding

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how cooperation evolves in various social dilemma situations [2,3]. In the framework of evolutionary game theory, the classical paradigms include the prisoner's dilemma game [4–8], the snowdrift game [8–11]. As an alternative, the public goods game, which is also regarded as a multi-person prisoner's dilemma game and governed by group interactions, is also widely employed as a classical paradigm for studying the evolution of cooperative behavior [12]. In a typical public goods game played by G individuals, all individuals simultaneously decide whether to cooperate or not. Cooperators each contribute an amount of c to the public pool, while defectors do not. The total contribution is multiplied by a factor r, and then divided equally among all group members regardless of their contributions. Obviously, defective strategy is the best choice for individuals as $r < G$, while the group can maximize their payoff as a whole if all members do cooperate. The inconsistency in the best choice for individuals and for the group gives rise to the dilemma. More precisely, replicator equations speak that defectors dominate the whole population in a well-mixed population for $1 < r < G$ [13,14]. To overcome the social dilemma, many mechanisms promoting the evolution of cooperation have been proposed [15–21]. Hauert et al. introduced a voluntary participation mechanism into the public goods game, and found that cooperative behavior is promoted by adding the third strategy, namely, loner [16]. Szabó et al. further studied the voluntary participation mechanism in the spatial public goods game and found that the introduction of loners leads to a cyclic dominance between the three strategies and improves the cooperation level remarkably [17]. Santos et al. introduced social diversity through structuring the populations by heterogeneous graphs, and found that it can also result in a substantial and persistent cooperation [18]. Li et al. studied the effects of individuals' memory on the evolution of cooperation under group interactions and found that one step memory is optimal to promote cooperation [19]. For other mechanisms, please see Refs. [22,23].

It should be emphasized that though evolutionary games on complex networks have been very fruitful [3,24–43], previous works mainly focused on random selection rule in which individuals randomly choose reference models from their neighbors for strategy updating. However, realistic situations do not always go this way. Generally, individuals' influence exhibits diversity and is time-changing. In other words, some individuals may influence others more deeply and more frequently, which means that the selection of references does not agree with the random selection pattern. These influential individuals' behaviors are more likely to be imitated [44–46], leading to the expansion of their followers, which perforce further enhances their influences. Closely related examples include the number of movie stars' fans, attractiveness of malls to customers, capitals in banks, popularity of politicians among populace. The herd behaviors in stock market naturally falls into this category [47,48], since most of investors belonging to the same group follow the action of the selected prestigious one who decides to buy, sell or hold the stocks [49,50]. For more literature on Matthew effects and related rich-get richer phenomena, please see Refs. [51–54]. Of interest, Szolnoki et al. have found that incorporating the wisdoms of group into the strategy updating can greatly promote cooperative behavior [55].

These observations catalyze many studies on how the non-random reference selection pattern affects the evolution of cooperation. Gao et al. [5] studied an extended spatial prisoner's dilemma game. In the model, recommended role mechanism is introduced where individuals are allowed to recommend the ones, which they have imitated, to their neighbors for strategy updating. They found that cooperation can be substantially promoted ascribable to this simple recommended mechanism. Very recently, Wang et al. introduced an age-related preferential selection mechanism into the prisoner's dilemma game [56]. Under this mechanism, players can select a reference for strategy imitation from their neighbors with biases correlated to their ages. They found that larger age parameter can markedly promote the formation of large cooperator clusters. Moreover, Refs. [57,58] have reported that the inhomogeneous activity of teaching can promote cooperation. How individuals' aging affects the evolution of cooperation is further investigated in Ref. [59].

We here aim to investigate the effects of influence-based reference selection pattern on the evolution of cooperation in the public goods game. We resort the square lattice to structure the population and study the effects of the proposed reference selection pattern in the context of group interactions. Next we show how the influence-based reference selection pattern affects the evolution of cooperation in more realistic networks including Barabási–Albert (BA) scale-free networks [60] and Watts–Strogatz (WS) small-world networks [61]. In the influence-based reference selection pattern, each player is initialized with equal influence, denoted by a positive real number $\in [0, 1]$. During the evolutionary process, each player acquires its payoff by interacting with all his nearest neighbors. After that, each individual chooses one of its neighbors as a reference with the probability proportional to these neighbors' influences. If one neighbor is picked up and successfully imitated, its influence increases by an influence factor α. In a broader sense, a feedback loop forms between the influence and the frequency of being picked up as model individual [37]. By using agent-based Monte Carlo simulations, we have found that the influence-based reference selection pattern is substantially beneficial for the emergence and sustenance of cooperation. Moreover, this positive effect of promoting cooperation is robust against the variation of interaction networks. Last but not least, we would like to emphasize that influence factor and reputation [19,62] are totally different concepts. Influence represents how often individuals are imitated. Influence factor determines how fast individuals' influences expand. Reputation in Refs. [19,62] is directly determined by how often individuals have cooperated.

2. Model

We consider the evolutionary public goods game on a square lattice with periodic boundary conditions and von Neumann neighborhood [3]. Each node on the square lattice is occupied by an individual. Initially, each individual is designated either as a cooperator or a defector with equal probability. Every individual participates in $G = 5$ groups centered on its nearest neighbors and himself, respectively. In each group cooperators each contribute $c = 1$ to the public pool, while defectors