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Neighbor-considered migration facilitates cooperation in prisoner's dilemma games

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A B S T R A C T

Migration (e.g. between cities and nations) has been shown to be an effective mechanism in facilitating the evolution of cooperation in spatial games. In contingent migration (e.g. success-driven migration), individuals choose the relocation place based on their expected payoffs. In other words, success-driven migration assumes that individuals make decisions about where to migrate strategically rather than randomly. Existing behavioral experiments have shown that human have other-regarding preference. In this paper, we study individuals' cooperation behaviors in the prisoner's dilemma game on a two-dimensional square lattice, where individuals have other-regarding migration preference. We introduce a neighbor-considered migration strategy, which considers both benefits of individuals and their neighbors. During the migration process, an individual always moves to a reachable empty site with the highest *fairness payoff*, which takes the benefit of all relevant stakeholders (including the particular individual and the neighbors) into consideration. We explore the effect of the different fairness, while considering the individuals when they weigh their own interests and their neighbors' interests. Our simulation results indicate that neighbor-considered migration can effectively promote the level of cooperation by helping cooperative clusters evade the invasion of defectors.

1. Introduction

Cooperation is ubiquitous in nature, and has been observed from the microorganism colony to human society [1,2]. However, the opinion that individuals are selfish is deeply entrenched since Darwin put forward his theory of evolution in 1859. Theoretically, cooperators may take risks of being betrayed so that cooperation should not be a spontaneous behavior in nature [3]. On the contrary, cooperation phenomena are ubiquitous in the real world. Therefore, how cooperation emerges among self-interested individuals has become an open problem in many fields, ranging from biology to sociology

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to economics and so on. Evolutionary game theory provides a powerful tool to analyze this problem [4], where Prisoner's Dilemma Game (PDG) is a frequently used game for theoretical analysis [5]. Most previous studies assume that individuals play the PDG in a well-mixed population [6]. In such models, individuals tend to adopt the defect strategy, which always them to acquire provisionally high payoffs. When a sufficient number of individuals choose to defect, the existence of cooperation is going to be threatened. Thus, cooperation cannot prevail in such an unstructured population. To solve this problem, many efforts have been done to investigate the evolution of cooperation [7,8].

Migration has been studied for over two decades, and has been shown to be an effective mechanism to promote cooperation [9–11]. In the early times, migration was referred to as the diffusion process in population and considered with reproduction under specific environment [12,13]. The dynamics of diffusion process can then be formulated as a replicator equation [6,14,15]. In doing so, Aktipis et al. [16] introduce a simple contingent movement strategy and prove that cooperative individuals with this strategy can outperform the Tit For Tat (TFT) and Win-Stay-Lose-Shift (WSLS) strategies under a wide range of parameter values in a lattice structure. However, the authors do not consider the movement of defectors. Vainstein et al. [17] study the migration in Nowak–May's spatial PDGs, where individuals are able to walk randomly on a spatial lattice as long as there is an empty and available site. They show that cooperation can be sustained when the migration rates are moderate. However, the higher migration rate is propitious to defectors rather than cooperators, since it brings the population close to a well-mixed state. Guan et al. [18] extend the model into the Snow Drift Game (SDG). Sicardi et al. [19] compare the effects of the random migration under PDG, SDG and Stag Hunt Game (SHG). Basically, they show that random migration plays the cooperation inhibiting role in spatial structures in the SDG, while playing the cooperation enhancing role in PDG and SHG. Besides random migration, another significant achievement is the success-driven migration and adaptive migration, where individuals can choose where and when to migrate conditionally [20–22]. For these two strategies, the prevailing of cooperation is remarkable, when random mutations and random relocations challenge the formation and survival of cooperative clusters. Alternatively, some studies focus on the influence of migration range on the formation of cooperation. For example, Liu et al. [23] discuss the impact of migration range and cost of the success-driven migration strategy in PDG. They show that cooperation will prevail when taking both aspects of migration range and migration cost into consideration under certain circumstances. Meanwhile, Suarez et al. [24] study a similar migration mechanism under one-dimensional lattice. Ichinose et al. [25] propose a long-range adaptive migration strategy in PDG, which significantly increases the cooperation level under conditions where the temptation to defect is considerably high. Also, in the complex network environment, a few concepts (e.g. *partner switching* [26,27], and *rewiring mechanism* [28,29]) are very similar with migration. In these studies, self-interested individuals can reconnect with their interaction partners to increase their profits in a resource exchange environment.

Most existing studies assume that individuals are selfish and rational, and they only care about how to maximize their own payoffs. However, evidence from behavioral experiments have presented an inconsistent behavior, or namely *other-regarding preference*, where individuals often take the benefits of themselves and those in the vicinity (i.e., neighbors) into consideration. Other-regarding preference is first proposed in the study of animal behaviors between relatives [30,31]. Then, Nowak and Taylor [32] formalize it to capture the kin and group selection. Hao et al. [33] introduce the concept of socially optimal outcome sustained by Nash equilibrium (SOSNE), which maximizes the sum of all agents' payoffs among all the possible outcomes. Except for the above scenarios, few studies use the other-regarding preference to update strategy [34,35]. To the best of our knowledge, migration with other-regarding preference has not been previously reported.

In this paper, we study the emergence of cooperation from the PDG on a square lattice network while individuals exhibit other-regarding preference on migration. The proposed neighbor-considered migration takes into account the payoffs of the focal individual and its neighbors, and the notation of *fairness payoff* is introduced to describe the difference between its own payoffs and its neighbors' payoffs. We use a fairness parameter α to balance the difference. The weighted sum of them is used to decide where to migrate. By doing so, we further explore the effect of the neighbor-considered migration strategy, and show how to encourage the cooperation among these selfish individuals.

In the next section, we will introduce the model.

2. Model

We consider an evolutionary PDG in this paper. The PDG is a game played by two participants, each of whom decides to cooperate or defect. A summary of notions used in this paper is presented in Table 1.

In a PDG, s_i demotes the strategy of individual i ($s_i = 0$ when i is a defector, while $s_i = 1$ when i is a cooperator). Then, we obtain a payoff according to the 2×2 payoff matrix. We also denote the payoff for mutual cooperation as "reward" or R in short, and the payoff for mutual defection as "punishment" or P. When a cooperator interacts with a defector, "sucker's payoff" S is used for the cooperation behavior, and the "temptation" T is used for the defector behavior. The matrix is constrained by the inequalities $T > R > P > S$ and $2R > T > S$. It means that selfish behavior of participants is most profitable for itself, but it is inferior when compared to mutual cooperation behavior. In other words, cooperation becomes risky, yet attractive as the opponent's decision is unknown. Following previous studies, the value of the payoff matrix can be rescaled without the loss of generality in the PDG [36], we set $T = b$ $(1 < b < 2)$, $R = 1$ and $P = S = 0$, where b is the only variable