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Evolution of cooperation with interactive identity and diversity

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ABSTRACT

Interactive identity and interactive diversity are generally regarded as two typical interaction patterns in living systems. The former describes that in each generation every individual behaves identically to all of its opponents, and the latter allows each individual to behave diversely to its distinct opponents. Most traditional research on the evolution of cooperation, however, has been confined to populations with a uniform interaction pattern. Here we study the cooperation conundrum in a diverse population comprising players with interactive identity and with interactive diversity. We find that in homogeneous networks a small fraction of players taking interactive diversity are enough to stabilize cooperation for a wide range of payoff values even in a noisy environment. When assigned to heterogeneous networks, players in high-degree nodes taking interactive diversity significantly strengthen systems' resilience against the shifty environment and enlarge the survival region of cooperation. However, they fail to establish a homogeneous strategy 'cloud' in the neighborhood and thus can not coordinate players in low-degree nodes to reach a socially optimal cooperation level. The most favorable outcome emerges when players in high-degree nodes take interactive identity and meanwhile others adopt interactive diversity. Our findings reveal the significance of the two typical interaction patterns and could be a good heuristic in coordinating them to achieve the social optimum in cooperation.

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1. Introduction

Given that one's reproductive success relies much on its fitness, why an individual often reduces its own fitness to benefit potential competitors in a competitive world? This evolutionary conundrum has long been a challenge since Darwin (1859), and attracts ample attention from different disciplines (Maynard Smith, 1982; Sigmund, 1993). Evolutionary game theory provides a powerful mathematical framework for exploring underlying mechanisms to resolve the cooperation dilemmas (Smith and Price, 1973). Recent studies, including theoretical analysis (Ohtsuki et al., 2006), simulation tests (Nowak and May, 1992) and behavioral experiments with human subjects (Rand et al., 2014), have proved that spatial structures facilitate persistent cooperation (Nowak, 2006), which further shifts our attention from traditional well-mixed settings to structured setups (Allen et al., 2017; Fu et al., 2009; Li and Wang, 2015; Ohtsuki and Nowak, 2006; Peña et al., 2016; Perc et al., 2017; Perc and Szolnoki, 2010; Qin et al., 2017; Wang et al., 2015). Especially, the related advances in large-scale data analysis and in online recruitment have revealed that social interactions in human society could be described by models entailing complex networks, such as small-world (Watts and Strogatz, 1998), scale-free (Barabási and Albert, 1999) or temporal networks (Holme and Saramäki, 2012; Li et al., 2017; 2016b). Indeed, an array of studies have been devoted to elucidating the cooperation dynamics in these social networks, where nodes represent individuals and links indicate social ties (Li et al., 2016b; Perc et al., 2013; Santos and Pacheco, 2005; Szabó and Fáth, 2007).

Most classical studies under this framework have been performed with the assumption that in each generation, every individual is either a pure cooperator selflessly serving for all neighbors or a pure defector relentlessly exploiting all neighbors (Allen et al., 2017; Fu et al., 2009; Li and Wang, 2015; Nowak and May, 1992; Ohtsuki et al., 2006; Ohtsuki and Nowak, 2006; Peña et al., 2016; Rand et al., 2014). This kind of interaction pattern, behaving identically with a fixed strategy across all interactions, is termed interactive identity (Su et al., 2017; 2016b). However, as evidenced by personal emotions (Szolnoki et al., 2011; 2013), egalitarian preferences (Dawes et al., 2007; Fehr and Schmidt, 1999), competition of male baboons (Kitchen et al., 2005), and parochial altruism (Choi and Bowles, 2007), in realistic situations, an individual

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may make diverse behavioral decisions when interacting with different opponents (Fehl et al., 2011; Jansen and van Baalen, 2006; Sun and Yang, 2014; Szolnoki and Perc, 2012; Wardil and da Silva, 2009), termed interactive diversity (Su et al., 2017; 2016b). Furthermore, given that variation in cognitive ability or sensory acuity often causes the difference in behavioral decision rules used in animals' contests (Briffa and Elwood, 2005; 2009) and human's competition (Bentley et al., 2011; Fiske, 2009), in many realistic social systems, individuals with different interaction patterns interlace together (Plaistow et al., 2004). How interactive identity and diversity affects the evolution of cooperation, up to now, still remains elusive. Especially, when players are endowed with heterogeneous social ranks, collective influence, or other traits (Bergman et al., 2003; Perc et al., 2014; 2008; Santos et al., 2008), how do players with different interaction patterns coordinate to reach the social optimum (Szolnoki and Perc, 2014; 2016)? Investigating the respective roles of the two interaction patterns in an evolutionary system makes much sense.

Here we extend the scope of evolutionary games by introducing players taking interactive diversity (abbreviated 'IND players') to traditional populations filled with players taking interactive identity (abbreviated 'INI players'). To capture realistic scenarios, we incorporate random exploration, frequently observed in behavioral experiments and proved to heavily jeopardize cooperation (Allen et al., 2012; Traulsen et al., 2009), into this study. We demonstrate that in homogeneous networks, sparse IND players are sufficient to stabilize cooperation in a noisy environment. The increasing density of IND players further boost cooperation to a remarkably high level. We provide theoretical predictions for two typical scenarios, where IND players take up or disappear from the population. The analytical results are validated by Monte Carlo simulations and robust against different exploration rates. When interactions are defined in heterogeneous networks, the evolutionary outcomes depend on not only the density but also sites of IND players. IND players indeed enhance systems' resilience against the shifty environment and enlarge the survival region of cooperation. However, when occupying hubs (high-degree nodes), they are unable to establish a homogeneous strategy 'cloud' in their neighborhood, and thus fail to coordinate players in low-degree nodes to achieve a socially optimal level of cooperation. For the most favorable outcome, players with the highest degree should treat equally to all neighbors and meanwhile others behave diversely. Our work therefore clarifies the effects of the two interaction patterns on the evolution of cooperation and confirms their individual significance in shaping the social optimum.

2. Model

We consider stochastic evolutionary game dynamics in the Prisoner Dilemma. There are two optional strategies, cooperation (C) and defection (D). For mutual cooperation, both participants obtain the same reward R. For mutual defection, they are given the same punishment P. Otherwise, the participant taking unilateral cooperation receives the sucker's payoff S, while the other adopting defection gets the temptation T. For simplicity, we make $R=1$, $P=0$, $T=1+r$, and $S=-r$, where r represents the cost to net benefit ratio. Apparently, for $r>0$, defection is the preferred choice of each player, which leads to mutual defection despite the fact that mutual cooperation is more beneficial.

Fig. 1 illustrates a population comprising players taking interactive diversity (abbreviated 'INI players') and players taking interactive identity (abbreviated 'IND players'). IND players constitute a fraction ρ of the population and are scattered randomly in spatial structures.

Here we briefly introduce the evolutionary process. Each player occupies a node and is randomly initialized to a cooperator (cooperating with all neighbors) or a defector (defecting to all neighbors). Both cooperators and defectors make up 50%, respectively. In each generation, each player plays games with its all neighbors with corresponding strategies whilst accumulating payoffs (Fig. 1a). At the end of each generation, a random player is selected to update all of its strategies, in consistent with the asynchronous update rule (Fig. 1b). We incorporate random exploration to model realistic scenarios and test the robustness of our model (Traulsen et al., 2009). In each strategy update step, with the probability μ, random exploration happens, and strategies are updated to cooperation or defection with the same likelihood. With the probability $1-u$, players update strategies by imitating a reference player. As shown in Fig. 1b, when an INI player y updates its strategies, it randomly chooses a neighbor z for reference and imitates z (exactly, imitating z's strategy towards y) in terms of the probability determined by Fermi function (Su et al., 2016b; Szabó and Töke, 1998; Traulsen et al., 2007)

$$f(\Pi_y-\Pi_z)=\frac{1}{1+\exp(\beta(\Pi_y-\Pi_z))},$$

where Π_y denotes y's payoff, Π_z denotes z's payoff, and β represents the noise level allowing irrational choice. We make $\beta=1$ although we have checked that results are qualitatively similar for a broad range of values of β. Here we have to point out that for an INI player y, once acquiring a strategy from the reference player z, y applies this strategy in all interactions next generation. Thereby, an INI player adjusts all strategies within one step. For an IND player x (see Fig. 1b), it updates its strategies sequentially in different update steps. When x updates its strategy towards z, it chooses z for reference with the the probability p and a random neighbor among the rest (v or w) with the probability $1-p$. We make $p=0.99$, and thus z is more likely to be selected, in line with the principle that x's strategy towards z is more dependent on z than on others (Nowak and Sigmund, 2005; Trivers, 1971). Once confirming the reference player, assuming z, x imitates z's strategy according to the above Fermi function.

3. Results

We begin with a study in a square lattice with periodical boundary conditions. This setting precludes the difference in individuals' attributions except the interaction pattern. Thus obtained results intuitively show the effects of interaction patterns on the evolution of cooperation. Then we make a further investigation in the heterogeneous structured population where players differ in the number of social ties. The population size is $N=1600$. All simulation results in this paper are obtained over 2×10^7 generations after a transient generation of 2×10^9. To further improve accuracy, all equilibrium values are averaged over independent 100 simulations (10 simulations with independent 10 realizations of each network).

3.1. Evolution of cooperation in the square lattice

As shown in Fig. 2a, in the traditional population comprised of INI players ($\rho=0.0$), cooperators easily perish even in a considerably weak social dilemmas ($r=0.02$). When a few IND players are introduced to such a population, cooperation survives in the competition with defection. As the temptation to defect increases, the critical fraction of IND players sufficient to maintain cooperation rises. Besides, Fig. 1a sees a monotonous rise of cooperation level as the increasing ρ for a wide range of r. We provide theoretical predictions of the stationary cooperation frequency for two representative scenarios, namely, IND players disappearing from ($\rho=0.0$, Appendix A) and taking over ($\rho=1.0$, Appendix B) the

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