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Impact of shill intervention on the evolution of cooperation

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HIGHLIGHTS

- We introduce shills into the public goods game on a scale free network and study the impact on the evolution of cooperation.
- High-level cooperation and better social welfare could be simultaneously induced by tuning the distribution coefficient α.
- Desirable outcomes are associated with large α for tense dilemma and small α in relaxed cases.
- We observe a transition of the composition of equilibrium cooperators.
- These results are somehow affected when we attenuate the heterogeneity of the network.

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ABSTRACT

The practical significance of effective intervention in collective behavior has its roots not only in frequent migration in the modern society, but also in the actual demands of real-world applications for system efficiency improvement. Within the framework of soft control, this paper focuses on an evolutionary public goods game staged on a scale free network and explores the dependence of the evolution of cooperation on the intervention of a fraction of shills, who follow the Fixed-Cost-per-Player paradigm while the locals follow the Fixed-Cost-per-Game paradigm. We demonstrate that higher cooperation levels and better social welfare could be simultaneously induced by tuning the distribution coefficient α, where desirable outcomes are associated with large $\alpha > 0$ for tense dilemmas while small $\alpha < 0$ leads to satisfactory results when the enhancement factor γ increases. Moreover, we observe a transition of the composition of equilibrium cooperators from full dominance of shills to co-existence of shills and locals, and the boundary has a positive correlation with α. These results are somehow affected when we attenuate the heterogeneity of the network by relating individual fitness to payoffs averaged over its connectivity. Our findings may not only shed some light on the mechanism behind the evolution of cooperation from the perspective of external intervention, but also provide a feasible way to effectively intervene in the evolutionary outcomes of negative scenarios.

1. Introduction

For studying dilemmas between individual interests and social welfare in group interactions, the public goods game (PGG) has long been considered as a paradigm [1–3]. In its original form, the PGG involves a group of players who hold the

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same amount of resource and simultaneously decide whether or not to invest into a public pool. Particularly, a cooperator (C) contributes an amount c ('cost'), whereas a defector (D) nothing. The contributions are collected and multiplied by an enhancement factor $\gamma > 1$, which reflects the synergetic effects of cooperation. The resulting sum is then equally distributed among all players, irrespective of their strategies. From the perspective of game theory, Ds would do better by free riding on Cs' efforts, although the group would maximize its profits if all participants cooperated. Since selfish individuals are aware of this, they all decide to defect, causing the tragedy of the common. This dilemma is relaxed when γ increases towards infinite but tense confliction arises as γ approaches 1. In sharp contrast, however, cooperation is ubiquitous in real life and plays a key role in the evolution of self-organized systems, ranging from biological systems to economic activities of human beings [4–6]. As a consequence, it has drawn increasing interests to explore how cooperation evolves and contends with competition. This issue is often tackled within the framework of evolutionary game theory [7–13] and various mechanisms have been proposed accordingly. Possible solutions include, but not limited to, spatial extensions [14–16], iterated interaction and reciprocity [17–19], co-evolution [20–24], chaotic environments [25], mobility to avoid nasty encounters [26,27], voluntary participation [28–31], as well as punishment and reward [32–34]. In addition, the differences of network reciprocity between PGGs, multi-player games, and spatial prisoner's dilemma games have also been investigated in Ref. [35].

In recent studies of cooperation evolution, diversity [36] has also been acknowledged to be a powerful catalyst for the richer spectrum of individual fitness it produces. Departure from the regular scenario was pioneered by Santos and Pacheco, who staged players on a scale free (SF) network of contacts (NOCs) with a power-law degree distribution [37]. Due to the topological heterogeneity of the population structure and social diversity associated with the number of interactions one is engaged in, cooperation becomes the dominating trait for a wider range of parameters [38]. Another aspect of diversity concerns differences in cooperative investment, where Cs contribute, instead of a fixed amount c, part of their resource according to different rules. Such mechanisms include equal allocation [39], unequal payoff allocation [40], high-quality preference [41], degree difference [42,43], and the conditional reactive case [44]. In addition, the effects of diversity have also been explored regarding individuals' strategies [45], imitation capacities [46,47], and learning approaches [48]. Although the current framework of evolutionary game theory has achieved immense success in demonstrating the prevalence of cooperation, most of the literature has focused on interpretation by taking into account internal heterogeneity only. On the contrary, diversity has scarcely been studied from the perspective of external intervention of alien individuals.

The main aim of this paper is to investigate how the diversity caused by external intervention affects the evolution of cooperation and seek approaches for controllable intervention in collective behavior of complex systems. In fact, research on external intervention is of practical significance for real world applications. On the one hand, empirical studies have shown that, with ever increasing global and local migration in the modern society, individuals with diverse backgrounds and acting rules have more opportunities to come across and intervene in each other [49,50]. On the other hand and more importantly, effective intervention into collective behavior is required in many real-world applications for system performance improvement or disaster avoidance. Actually, there exist many hostile scenarios [51], where desirable outcomes cannot be expected out of the original system. So far, effective intervention in complex systems remains an open and challenging quest, especially when the local interaction rules of the original individuals are hard to be directly changed, e.g., the behavioral rules of crowds fleeing out of a fire and the motion rules of individual birds flying in a flock [52,53].

Recently, Han et al. have developed a novel framework of soft control via bringing in a fraction of controllable agents, termed as shills, into the original population consisting of normal individuals, termed as locals [54]. By this means, the population may gradually grow out of dilemmas to better-off situations under the guidance of the shills, who are allowed to adopt elaborated strategies or updating mechanisms. To date, the concept of soft control has been investigated in several preliminary works. Wang and Han [55] pioneered the application of soft control to an evolutionary game within a complete interaction population, where shills adopted the frequency-based tit for tat (F-TFT) and were assumed to share knowledge for normal agents. Following this, the authors [56] extended soft control to a spatially structured population and studied the effects of swarm intelligence inspired shills by an iterated prisoner's dilemma (IPD) game staged on a square lattice. However, these works [55,56] can hardly represent realistic scenarios, as they both studied soft control on regular NOCs [37], where it is impossible to evaluate the impact of the degree distribution pattern of shills because every vertex has the same connectivity. For more details of the novel notion of soft control, we refer to Refs. [54–56].

Since a characteristic fingerprint of many realistic NOCs is closely related to a power law dependence of the degree distribution [57,58], the question concerning effective intervention in hostile scenarios with SF NOCs is of practical importance. Although social diversity related to SF NOCs indeed contributes to the emergence and promotion of cooperation in PGGs, there still exists a wide range of parameters, for which cooperation is strictly dominated [39]. To resolve this dilemma, we bring in a fraction of controllable shills into an evolutionary PGG staged on SF NOCs and try to seek answers to the following questions: (1) What happens if a small fraction of shills with stingy cooperative strategies invade? (2) Under what condition can cooperation and social welfare be both promoted? (3) Does one type of individuals dominate the other, or they co-exist in the equilibrium state? (4) How does the distribution of shills affect the outcome?

In this work, we developed a model within the framework of soft control and study what occurs depending on the distribution of shills and the game strength. Our model involves two types of individuals, namely locals and shills, who follow different cooperative investment rules when choosing to contribute. To be specific, as original individuals in the population, the locals are generous and follow the so-called Fixed-Cost-per-Game paradigm by contributing a fixed amount c to each game, while the shills are invading aliens who are stingy in that they hold a total amount of c and allocate it equally among all games, which is termed as the Fixed-Cost-per-Player paradigm. In addition to the strategies, individual