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Evolution of cooperation driven by incremental learning

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HIGHLIGHTS

- The decision making process is formulated as an incremental learning rule.
- Strategies of players are updated according to self-learning and social-learning.
- Evolution of cooperation in the PD and the SD is inspected.
- We quantify the macroscopic features using six cluster characteristics.
- The time evolution course is examined to analyze the evolutionary results.

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ABSTRACT

It has been shown that the details of microscopic rules in structured populations can have a crucial impact on the ultimate outcome in evolutionary games. So alternative formulations of strategies and their revision processes exploring how strategies are actually adopted and spread within the interaction network need to be studied. In the present work, we formulate the strategy update rule as an incremental learning process, wherein knowledge is refreshed according to one's own experience learned from the past (self-learning) and that gained from social interaction (social-learning). More precisely, we propose a continuous version of strategy update rules, by introducing the willingness to cooperate W, to better capture the flexibility of decision making behavior. Importantly, the newly gained knowledge including self-learning and social learning is weighted by the parameter ω, establishing a strategy update rule involving innovative element. Moreover, we quantify the macroscopic features of the emerging patterns to inspect the underlying mechanisms of the evolutionary process using six cluster characteristics. In order to further support our results, we examine the time evolution course for these characteristics. Our results might provide insights for understanding cooperative behaviors and have several important implications for understanding how individuals adjust their strategies under real-life conditions.

1. Introduction

Social dilemmas constitute situations that individuals take altruistic actions to contribute to collective wellbeing although selfish strategies may lead to better results for their own prosperity and success [1–4]. Generally, mutually cooperative behavior, which is ubiquitous throughout the history of evolution, is regarded as an alternative way for understanding this

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paradoxical outcome [5–14]. That is, cooperation could emerge spontaneously among individuals who care only about their own benefits, resulting in satisfactory social welfare. The emergence and persistence of cooperation have been addressed and investigated by means of game theoretic models by researchers from a broad range of disciplines, from sociology to biology, ecology, economics, and mathematics [15,16]. Among them the prisoner's dilemma game and the snowdrift game have received great attention in both experimental and theoretical studies, and have been adopted as metaphors of behaviors in biological and social systems [17–22]. In particular, it is well accepted that spatial structure facilitates the evolution of cooperation, known as spatial reciprocity [2,4,23–28]. This mechanism allows the coexistence of cooperators and defectors even in the prisoner's dilemma game, and the cooperation dominant state, in some cases.

It is well accepted that the population dynamics in structured games, stemming from the microscopic dynamic or strategy update rules that define how successful strategies spread, have a crucial impact on evolutionary outcomes [29,30]. So it is important to explore the potential dynamic update rules underlying the evolutionary process, which is crucial for understanding the emergence of cooperation. An extremely wide variety of models have been proposed in preceding works, as reviewed comprehensively in Ref. [29], such as those based on replication [31,32], imitation [9,27], and learning [1,33], just to name a few. Among the learning strategies, imitation based processes account for a large proportion of these rules, in which condition a player usually follows the strategy of one of his fellow players. Typically, the players are assumed to adopt strategies from more successful neighbors with certain probabilities since it seems reasonable for the players to imitate his successful neighbors to expect higher payoffs. More importantly, an intensity of selection has been introduced into the imitation process to stress the stochastic strategy adoption phenomenon with errors [34]. Under this condition, an inferior strategy is possible to replace a more profitable one, as is often seen in the society or nature. Another representative strategy update rule is aspiration-based preference learning [12,30,35], under which strategies judged to have resulted in satisfactory payoffs are more likely to be selected and those leading to unsatisfactory payoffs tend to be abandoned, namely *win-stay–lose-shift*.

Although extensive research has been conducted regarding strategy update rules, how strategies are actually adopted and spread within the population is still unknown. Indeed, the important aspect of aspiration lies in that players learn from past experience in an adaptive and myopic fashion [12,29]. However, aspiration puts less emphasis on the interactive nature of decision-making even though players may act based on observed experience of peers. On the other hand, players do not necessarily follow the "*imitate-the-best*" rule and imitation rules have been questioned by recent experimental results for spatial games [36]. Nonetheless, these imitation dynamics could give some useful inspirations for understanding the high levels of cooperation characterized by the underlying dynamics. According to social psychology, individuals' cognitive processes are heavily influenced by those around them and individuals renew knowledge to promote their survival probability through social interactions [33,37–39]. In other words, learning capabilities originate from social interactions, suggesting that social sharing of information provides great evolutionary advantages and offer alternatives to solve complicated social problems.

Considering the above several facts, alternative formulations of strategies and their revision processes exploring how strategies are actually adopted and spread within the interaction network need to be further explored. In this paper, we formulate the strategy update rule as an incremental learning process to address the aforementioned problems, wherein knowledge is refreshed according to one's own experience learned from the past (self-learning) and that gained from social interaction (social-learning) and individuals learn from new information without forgetting prior knowledge. As for the strategies, it is conventional to take two competing strategies, namely cooperation and defection, as responses to social dilemmas. Yet the decision-making process during interaction with others in real-life situations is often sophisticated and much less clear-cut [40,41]. Consequently, we propose a continuous version of strategy update rules, by introducing the willingness to cooperate W, to better capture the flexibility of decision-making behavior. Importantly, the newly gained knowledge including self-learning and social learning is weighted by the parameter ω, establishing a strategy update rule involving innovative element. We should note that the strategy update rules alter the willingness to cooperate rather than the strategies themselves in the context of our work. In this way, we wish to further inspect these microscopic dynamics that describe how individuals adopt and change their strategies. For further details regarding the studied evolutionary game, the underlying microscopic dynamics driven by incremental learning, we refer to the Methods section.

In the present work, we study the evolution of cooperation driven by incremental learning on regular lattices in the prisoner's dilemma game and the snowdrift game. To inspect the underlying mechanisms of the evolutionary process, we elaborated on this subject further by quantifying the macroscopic features of the emerging patterns using six cluster characteristics. In order to further support our results, we examine the time evolution course for these five cluster characteristics. Our results highlight the underlying mechanisms of cooperative behavior and have several important implications for understanding how strategies are actually adopted and spread.

2. Methods

2.1. Games and evolutionary dynamics

Two social dilemmas, the prisoner's dilemma game and the snowdrift game have attracted significant efforts, emerging as two promising metaphors to explore the persistence of cooperation [18,21,22,25]. Notably, variation in payoff ranking for these two games, although trivial, induces a considerable change in the evolutionary dynamics [17]. In well-mixed populations, cooperation based on the snowdrift game seems easy to survive but unlikely for the prisoner's game, whereas