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Cooperation in the evolutionary iterated prisoner's dilemma game with risk attitude adaptation

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ABSTRACT

The Iterated Prisoner's Dilemma (IPD) game has been commonly used to investigate the cooperation among competitors. However, most previous studies on the IPD focused solely on maximizing players' average payoffs without considering their risk preferences. By introducing the concept of income stream risk into the IPD game, this paper presents a novel evolutionary IPD model with agents seeking to balance between average payoffs and risks with respect to their own risk attitudes. We build a new IPD model of multiple agents, in which agents interact with one another in the pair-wise IPD game while adapting their risk attitudes according to their received payoffs. Agents become more risk averse after their payoffs exceed their aspirations, or become more risk seeking after their payoffs fall short of their aspirations. The aspiration levels of agents are determined based on their historical self-payoff information or the payoff information of the agent population. Simulations are conducted to investigate the emergence of cooperation under these two comparison methods. Results indicate that agents can sustain a highly cooperative equilibrium when they consider only their own historical payoffs as aspirations (called historical comparison) in adjusting their risk attitudes. This holds true even for the IPD with a short game encounter, for which cooperation was previously demonstrated difficult. However, when agents evaluate their payoffs in comparison with the population average payoff (called social comparison), those agents with payoffs below the population average tend to be dissatisfied with the game outcomes. This dissatisfaction will induce more risk-seeking behavior of agents in the IPD game, which will constitute a strong deterrent to the emergence of mutual cooperation in the population.

1. Introduction

Competition and cooperation are among the mostly noted paradoxical phenomena in the real world. For example, collaboration with competitors in business is common for modern firms [1], which is enforced by the rapid advance in information technology and the globalization of markets. Moreover, strategic alliances increase in various industries every year. Firms are hoping to improve their performances by collaboratively developing new technologies, obtaining critical resources, or attaining economies of scale [2]. Nonetheless, despite the benefit of mutual cooperation, firms still compete with one another for gaining sustained competitive advantages in the marketplace [3]. Then, a question arises as to how cooperation emerges among competitors when they still have strong incentives to compete. The iterated prisoner's dilemma game (IPD) is a prominent paradigm to examine the essence of this problem.

The Prisoner's Dilemma (PD) is a bilateral game in which each player can either cooperate (C) or defect (D) [4,5]. A reward (R) will be given to both players if they cooperate with each other, whereas a punishment (P) will be enforced if they both defect. In the circumstance with one defecting but the other cooperating, the defector will obtain a tempting payoff (T) and the cooperator will receive a sucker's punishment (S). Given the conditions $T > R > P > S$ and $2R > T + S$, a dilemma emerges. Although defection is the dominant strategy for any player, mutual cooperation yields the highest total payoff. The situation will become more complex if the PD is iterated over many rounds (IPD). Thus, the IPD is often referred to as a mixed-motivation game in which opportunities for cooperation and defection (or competition) coexist.

The evolutionary IPD game has been widely employed by researchers to study the evolution of cooperative behavior among selfish individuals [4,6–8]. The researchers usually start with a

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system of multiple agents (players) engaging in recurring IPD interactions while adjusting their own strategies by adaptive learning. As the adaptation proceeds, the aggregation of recurring interactions among agents can generate complex collective behavior of the system [9,10], and the resulting cooperation (or defection) at equilibrium can be analyzed under different scenarios. The aim of this research is to verify what specific factors can influence the emergence of cooperation, and the observed results are used to explain real-world cooperative phenomena.

Evolutionary algorithms have been widely adopted as an appropriate analog for modeling the agents' adaptive learning in the evolutionary IPD game [11]. Agents are generally assumed to adapt their strategies by learning from the better-performing peers in the population. Such a learning mechanism echoes the social learning processes in human social interactions [12–14], in which individuals often draw upon others' experiences to refine own strategies and enhance own behavioral practices [15]. Recently, with the rapid development in behavioral disciplines [16], in which personal traits are commonly treated as independent variables to explain human behavior, it is strongly suggested to design agents with explicit personal traits in light of behavioral studies through the agent-based modeling [17,18].

Risk is a critical feature of individual activities, and risk attitude has been treated as an independent variable in explaining cooperation in the behavioral IPD experiments. Based on the principle that conditional cooperation supports a sub-game perfect equilibrium [19], Snijders and co-workers [20,21] argued that a player' strategy in the IPD game was whether or not to unilaterally exploit the opponent who cooperated conditionally. Their studies showed by behavioral experiments that risk-averse players favored cooperation in such a scenario, whereas risk-seeking players tended to unilaterally defect. However, their formulation of risk involved only individual preferences on gambles between deterministic and variable prospects. No study had explicitly defined what risk was in the IPD game.

Risk-averse players retain steady cooperation with their opponents because the cooperation could minimize the interaction uncertainty and yield stable payoffs for them in the IPD [20,21]. This observation is in accordance with the proposition that firms in the iterated Cournot competition, a realistic IPD situation, would like to coordinate with each other on their production outputs to enhance their income stream stability [22]. Motivated by these studies, we first defined risk as the standard deviation of the one-move payoffs for players in the IPD game [23]. This definition on risk is in line with the concept of "income stream risk" in economics and finance [24], in which risk is conceived as a manifestation of uncertainty or uncontrollability of outcomes [25].

Based on this risk definition, we have re-examined the two-player IPD problem by considering both maximizing average payoff and minimizing risk for players [23]. Computational simulation did demonstrate that risk-averse players favored mutual cooperation in the IPD game [23]. Nonetheless, we focused only on the learning of the IPD for two agents of fixed risk attitudes, but did not consider the possibility of changes in their risk preferences over time. Therefore, we attempt to consider agents of adaptive risk attitudes in this paper by following the fact that risk preference is contextually dependent in human society [26,27].

The evolutionary IPD game with pair-wise interactions of multiple agents is investigated, in which agents play the IPD game by adapting their risk attitudes according to relative performance feedback. Following the prospect theory [26] and empirical findings on human risk behavior [28,29], agents respond to poor performances by taking greater risk or satisfactory performances by avoiding risk (see Section 3.2 for more details). In particular, the poor or satisfactory performances are distinguished by agents in comparison with their own past performances (historical comparison) or with the population's average performance (social comparison). Consequently, the evolution is characterized by the changes of risk preferences in the population, and the resulting outcome should be reexamined. The contributions of this study involve the following three respects:

(1) A novel evolutionary IPD model is formulated with agents of adaptive risk attitudes, which is aligned with the trend of integrating human traits into the agent-based modeling. To our best knowledge, this work is the first attempt to study the adaptive risk behavior in the evolutionary IPD game, in which the effects of historical comparison and social comparison on the evolution of cooperation are investigated particularly.
(2) Based on the evolutionary model, extensive simulation studies are conducted to examine the effect of dynamic risk consideration on the evolution of cooperation. Results indicate that high levels of cooperation can emerge in the IPD even with short game encounters when agents consider only their past payoffs as reference points (historical comparison) to assess their performances for adjusting risk attitudes. The whole population can achieve sustainable high returns at low risk in this case. The speed by which agents change their risk attitudes is shown to have a significant impact on the cooperation.
(3) When agents employ the population's average payoffs as reference points to appraise their performances (social comparison), we find that agents will become more dissatisfied on average. As a result, the evolution leads to a large proportion of highly risk-seeking agents, which deters mutual cooperation and brings low returns to the population. Thus, our findings present the evidence that uncooperative behavior can be perceived as a consequence of social comparison.

The rest of this paper is organized as follows. Section 2 reviews some related literature on the IPD game. Section 3 presents the definition of risk and introduces the theoretical basis for the risk attitude adaptation. Section 4 formulates the proposed evolutionary IPD model with agents of adaptive risk attitudes. The simulation studies are reported in Section 5. Section 6 concludes this study with remarks for future work.

2. Related literature

Games are often employed to model socio-economic phenomena [30], and the evolutionary PD and IPD games have been extensively studied to understand the evolution of cooperation, which has been a considerable concern to evolutionary biologists [31], economists [32,33], social scientists [34], cognitive scientists [35], and even computational scientists [36].

A classical evolutionary PD game involves a population of individuals who play the PD game against each other (called the well-mixed game setting). Because uncooperative individuals (defectors) always have higher average payoff (fitness) than cooperators, defection dominates cooperation in the population, driving cooperators to extinction under natural selection. This evolutionary outcome can be analytically derived in replicator dynamics, imitation dynamics, or selection-mutation dynamics [37]. Nonetheless, because cooperation is the beneficial choice to the whole population, a question arises as to what mechanisms can promote the cooperation in the evolutionary PD game.

Ohtsuki et al. [31] considered an evolutionary PD game with individuals occupying vertices of a graph, in which the edges of the graph determined links between individuals in terms of game interaction. An individual only played the PD game with the connected ones in the population. Ohtsuki et al. [31] found that the graph-based interaction could allow cooperators to form clusters.