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Enhancement of cooperation in the spatial prisoner's dilemma with a coherence-resonance effect through annealed randomness at a cooperator–defector boundary; comparison of two variant models

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HIGHLIGHTS

- We explored how cooperation in spatial prisoner's dilemma games is enhanced by a coherence-resonance effect through annealed randomness at a cooperator-defector boundary.
- We presumed two models; action error, and payoff noise.
- We explain the detailed enhancement mechanism behind the two models by referring the concept END and EXP we proposed.

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ABSTRACT

Inspired by the commonly observed real-world fact that people tend to behave in a somewhat random manner after facing interim equilibrium to break a stalemate situation whilst seeking a higher output, we established two models of the spatial prisoner's dilemma. One presumes that an agent commits action errors, while the other assumes that an agent refers to a payoff matrix with an added random noise instead of an original payoff matrix. A numerical simulation revealed that mechanisms based on the annealing of randomness due to either the action error or the payoff noise could significantly enhance the cooperation fraction. In this study, we explain the detailed enhancement mechanism behind the two models by referring to the concepts that we previously presented with respect to evolutionary dynamic processes under the names of enduring and expanding periods.

1. Introduction

Evolutionary game theory sheds light on the mysterious puzzle of how human beings as well as other animal species successfully evolved altruistic cooperation rather than selfish defection [1]. The prisoner's dilemma (PD) game, one of the four game classes within 2×2 (two-player and two-strategy) games, wherein two agents independently decide between either cooperation (C) or defection (D), has provided a quantitative foundation for this discussion. Meanwhile, network reciprocity, one of the five fundamental mechanisms for solving social dilemmas by adding "social viscosity" [2], has received intense attention [3–5], because although the central assumption of the model, namely, "playing with neighbors on an underlying network and copying a strategy from them", is simple, it still seems to be a plausible explanation of how cooperation enables survival in any real context.

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Meanwhile, the term coherence resonance, generally, refers to a phenomenon in an excitable system where an appropriate extent of noise generates excitation-events that maximize its periodicity or coherence. If a game's dynamics assuming network reciprocity intrinsically has oscillatory nature and would evolve with addition of certain amount of noise, enhanced cooperation would be expected to observe.

For the last decade, the focal point of the argument regarding network reciprocity has been reversing the question of what additional mechanism can bolster network reciprocity beyond that offered by the original model, that is, the spatial prisoner's dilemma (SPD) game. Amid hundreds of previous studies, several works have relied on coherence resonance to enhance cooperation by means of introducing a stochastic framework into the SPD game. Adding randomness into the underlying network [6,7], which is realized by presuming a small-world network instead of a regular lattice graph, has been confirmed to enhance network reciprocity. Adding randomness into a payoff matrix is also able to bolster network reciprocity [8–13]. Another method we recently reported [14] is that of adding an action error (not copy error) to enhance cooperation in SPD, which is also a framework based on stochastic noise promoting cooperation.

Besides these studies, there is another interesting contention concerning coherence resonance that stems from the dynamic process perspective, namely, quenched and annealed randomness, which has attracted physicists' attention because of an analogy to the dynamic processes for the growth of crystal structures. In fact, several pioneering works [15–17] have confirmed that introducing quenched or annealed randomness into an interaction network further increases the number of cooperators after an interim equilibrium that uplifts the final cooperation fraction to the end of each evolutionary episode. From application point of view, several precursors are concerned on the effect of noise added to the system [18,19].

Meanwhile, we have been looking into how network reciprocity can be established and have proposed the following concept [20–22] to address the question from a dynamics viewpoint. This concept states that an evolutionary course transition from an initially random state (for example, see Fig. 1(a-1)) to a final equilibrium state (Fig. 1(a-4)) may be divided into two temporal periods. In the course of our studies, we have carefully observed the mechanisms in these two periods (see Fig. 1(A)). Here, the term enduring period (END) is used to refer to the initial period in which the global cooperation fraction, P_c, decreases from its initial value. The initial state may have an equal number of cooperators and defectors randomly assigned on an underlying network. The term expanding period (EXP) is used here to refer to the period following the END. During the EXP, the global cooperation fraction, P_c, increases because the cooperators' clusters that survive the END begin to expand by letting neighboring defectors become cooperators. The substantially important point that we have highlighted in previous works is that dividing an evolutionary course into END and EXP helps us understand its dynamics to foster network reciprocity. This is schematically suggested by a comparison of the evolutionary course (a-1), (a-2), (a-3), and (a-4) with that of (a-1), (a-2), and (a-5) in Fig. 1, since the phenomenon taking place in both periods is quite different from the dynamics viewpoint. The events in END can be said to be dynamic events relaxing the skewed state imposed by an initial condition, whereas the events in EXP, occurring after those on END, can be seen as a rebound process from the initial impact to approach an equilibrium state.

At present, we face one challenging question. If there is a certain mechanism enhancing network reciprocity that specifically works in EXP rather than in END, can we find a more efficiently enhanced network reciprocity by introducing this specific mechanism only after an evolutionary episode reaches an interim equilibrium (see Fig. 1(B))? If yes, it may be possible to call this mechanism an annealing model for enhancing the cooperation in SPD games. In this context, we terms that "annealing" is a supplementary frame to add some stochastic noise after a timing an evolutionary episode once attains to a stable state to the original SPD model, which is able to let cooperation fraction improve from the temporary state to another stable state.

The aforementioned background is the motivation behind this work. In this study, we discuss new network reciprocity models that use a framework for annealed randomness that can be fully justified by the human social context showing that our new models significantly enhance cooperation and plausibly explain the origin of this surging cooperation by referring to the concepts of END and EXP.

2. Model setup

At every time step in the devised model, each agent in the network (agent i) plays PD games with their immediate neighbors and obtains payoffs from all of the games, which implies the accumulated payoff is presumed. The underlying topology is a two-dimensional lattice graph (hereafter lattice) with degree $k = 8$. The boundary of the network is looped. The total number of agents is $N = 10^4$. After each time step, each agent synchronously updates his/her strategy. In a PD game, a player receives a reward (R) for each instance of mutual cooperation (C) in which they partake and a punishment (P) for each mutual defection (D). If one player chooses C and the other chooses D, the latter obtains a temptation payoff (T), and the former is labeled a sucker (S). Without losing mathematical generality, a PD game space can be defined by presuming $R = 1$, $P = 0$, $S = -D_r$ and $T = 1 + D_g$, where D_g and D_r imply a chicken-type dilemma and a stag hunt-type (SH-type) dilemma, respectively [23]. Thus, the payoff matrix can be denoted as $\mathbf{M} = \begin{pmatrix} R & S \\ T & P \end{pmatrix} = \begin{pmatrix} 1 & -D_r \\ 1 + D_g & 0 \end{pmatrix}$. PD, is one of the four classes of 2×2 games as mentioned before, simultaneously has a chicken-type dilemma and a stag hunt-type dilemma, which are formulated by $0 < D_g$ and $0 < D_r$. In the following discussion, the PD game class is limited by assuming $0 \leq D_g \leq 1$ and $0 \leq D_t \leq 1$. An agent updates his or her strategy in a deterministic way. In this model, the imitation