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Correlated asynchronous behavior updating with a mixed strategy system in spatial prisoner's dilemma games enhances cooperation

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ABSTRACT

A new model of mixed strategy system for spatial prisoner's dilemma games is proposed. As an alternative to the typical mixed strategy system, wherein a behavior of either cooperation or defection is stochastically determined for each neighbor based on the agent's overall strategy, in our mixed strategy system, the agent instead correlates his strategies with those of his neighbors. For example, he tends to offer cooperation more frequently to his neighbor who is cooperative more often. This model provides results with significantly enhanced cooperation compared with those obtained with the conventional mixed strategy model. Interestingly, some of the evolutionary paths followed under strong dilemma situations can be divided into two specific periods: Defector-Enduring (D-END), when the number of defectors rapidly decreases, and the subsequent Defector-Expanding (D-EXP), when the surviving defectors' clusters start to expand, allowing the global cooperation fraction to fall to a lower level. The D-END and D-EXP periods seem analogous to the END and EXP periods presented by the author in previous studies.

1. Introduction

The possible causes of the emergence of mutual cooperation in human society as well as among various animal species have attracted significant attention in a wide range of scientific fields (e.g., [1,2]). Evolutionary game theory (EGT) postulates that both theoretical and numerical approaches using simplified templates such as prisoner's dilemma (PD) may shed some light on plausible answers to the mysterious puzzle of why human beings, as well as other animal species, successfully evolve mutually autistic cooperation rather than egocentric defection within their societies (e.g., [3]). The most commonly presumed archetype in EGT is the class of 2×2 (two-player and two-strategy (behavior)) games, where two agents independently offer either cooperation (C) or defection (D) when playing a game. Assuming an infinite and well-mixed population and relying on so-called replicator dynamics, EGT transparently proves that a PD game always ends with an all-defectors state, with no possibility of any surviving cooperators. However, we can observe lots of opposing evidence in the real world, where human and even animal species have successfully established mutual cooperation under (sometimes severe) social dilemma situations. Nowak [4] found that these dilemmas in the real world can be resolved by adding "social viscosity," which can be classified into five fundamental mechanisms. Network reciprocity is one of these five, and it continues to receive intensive attention (for comprehensive reviews, refer to [5–7]), because although the central assumption of the model, i.e., "playing with neighbors on an underlying network and copying a strategy from them," is simple, it still seems very plausible for explaining why cooperation survives in any real context.

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We usually begin with the premise, as mentioned above, that an agent has a discrete strategy that is binary, either C or D, and that the agent provides a consistent binary offering to their opponent, either C or D. We call this the discrete strategy system. In a real context, however, it is more plausible to presume that an agent has a continuous strategy that can be described by a real number between D = 0 and C = 1, and that he offers this real number to his game opponent instead of either pure C or D. This is called the continuous strategy system [8]. There is also another concept, called the mixed strategy system [9], wherein an agent offers either C or D as stochastically determined by his strategy that is defined by a certain real number of [0, 1].

Concerning comparisons among the discrete, continuous, and mixed strategy systems, Zhong et al. reported interesting findings [8]. They found that games on a spatial structure with continuous and mixed strategy systems have equilibria that are quite different from those of the discrete strategy system. In particular, they showed that the continuous strategy in a spatial PD game that has more Chicken-type dilemmas than Stag-Hunt (SH)-type dilemmas [10], where interactions instinctively tend toward a so-called internal equilibrium, realizes a much higher cooperation level than the discrete strategy game. The reason for this is that the offer of a middle cooperative action in a strategy, expressed as a real number of [0, 1], more efficiently and flexibly leads to a more cooperative equilibrium. Moreover, in situations where a game features more SH-type dilemmas than Chicken-type dilemmas, which leads to a somewhat bistable equilibrium wherein all agents are either defectors or cooperators depending on the initial cooperation level, the mixed-strategy game is more likely to result in a cooperative equilibrium.

Let us be concerned with the mixed strategy game in the following argument. Besides the concept of whether each agent updates his strategy synchronously or asynchronously, the mixed strategy can define another concept: whether each agent updates his behavior synchronously or asynchronously. Most previous studies assuming a mixed strategy system have presumed asynchronous behavior update, where a focal agent stochastically determines C or D independently for each of his neighbors by drawing a random number to determine strategies one by one. For example, the focal agent (denoted i) may offer cooperation twice and defection six times if his strategy, s_i, is 0.75. In this process, how agent i offers the two Ds. and six Cs to his eight neighbors is randomly determined. On the other hand, with synchronous behavior updating in a mixed strategy system, the choice of C or D is made stochastically just once for each time-step, and this C or D is applied throughout all the games of the focal agent. Miyaji et al. [11] explored systematic and intriguing simulations comparing those two methods, and found that the idea that network reciprocity is degraded to an increasing degree, which has been commonly taken within the community as an accepted truth, is not true when one applies a mixed strategy system with synchronous behavior updating.

One interesting question, when we cling to asynchronous behavior updating in a mixed strategy system, is whether cooperation can be bolstered if a certain correlated manner of offering cooperation/defection to neighbors, instead of random offering, is presumed. Let us return to the previous example of $s_i = 0.75$. This idea leads us to think about what happens if we presume a positive correlation between the sequence of two Ds. and six Cs, and the neighbors' strategy or fitness, for instance. As further explanation, if there is positive correlation with the neighbors' strategy, the focal agent offers D only to his neighbors with the smallest and second smallest strategy, and otherwise offers C (see Fig. 1). Likewise, if negative correlation with the neighbors' fitness is presumed, the focal agent only affords D to his neighbors who had the largest and second largest fitness at the previous time-step. The former example seems somewhat like the Tit-For-Tat (TFT) mechanism [12] because an agent preferentially offers C to his neighbors who have highly cooperative tendencies if the positive correlation strategy is applied. However, it is unlike TFT in the sense that an agent does not completely determine their offer based on what his particular neighbor offered to him at the previous time-step. Still, this TFT-like feature leads us to expect that there is some possibility of observing significantly enhanced network reciprocity compared with that obtained with the usual mixed strategy system. One plausible question to criticize this idea is that how an agent can know his neighbors' current mixed strategy. Thus, we presumed in the present model that the strategy and fitness of his neighbors in the previous time-step is disclosed and the focal agent can use those.

In this paper, we focus our attention on this point.

"Networks of networks" as the covering theme of this special issue primarily implies a multi-layer network system. By what point the model we are trying to discuss in

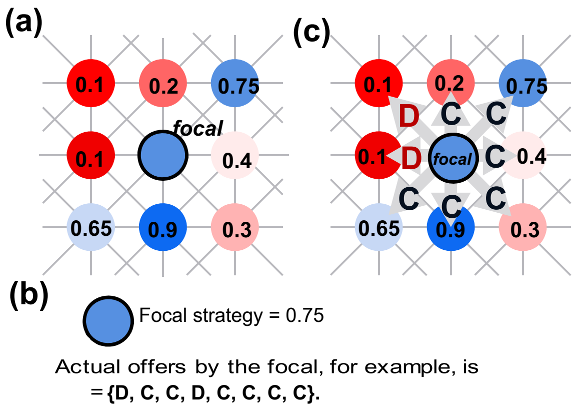

Fig. 1. A mixed strategy system considered with positive correlation between focal offers and the strategies of neighbors is schematically shown. Panel (a) shows one example, where the focal agent, who is relatively cooperative with his strategy of 0.75, has eight neighbors whose strategies are described by each of the numbers. As shown in panel (b), the focal agent decides his actual offers to his neighbors by comparing $s = 0.75$ and each of the eight random numbers. In this example, it is a set of {D, C, C, D, C, C, C, C}. As in panel (c), each of {D, C, C, D, C, C, C, C} is assigned to each of his neighbors according to their strategies with positive correlation. Hence, the focal agent offers D to the most defective two neighbors, and offers C to the other neighbors.