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How do the joint effects of aspiration and social influence promote cooperation in the prisoner's dilemma game?

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Various mechanisms have been proposed to promote cooperation in evolutionary games, including aspiration and social influence. However, the joint effects of aspiration and social influence have so far been ignored in the literature. Thus, we discuss the joint effects of aspiration and social influence on promoting cooperation in the Prisoner's Dilemma Game (PDG). We introduce different aspiration tags as different aspirations and different types of neighborhoods as different social influences to reveal how the level of cooperation changes in four heterogeneous micro-environments composed of diverse aspirations and social influences. The Fermi function is adopted as the priority strategy updating rule. Simulation results show that aspiration and social influence mechanisms are jointly effective at improving cooperation in the PDG. More precisely, the aspiration mechanism promotes cooperation unconditionally, but that the social influence mechanism promotes it conditionally.

KEYWORDS

prisoner's dilemma, aspiration, social influence, cooperation, evolutionary game theory

1 Introduction

Cooperation is found in many biological and social systems and typically plays a very important role in the development of these systems [1, 2], so much so that in 2005, Science listed "how did cooperative behavior evolve?" as one of the 25 most critical scientific questions of the 21st century. Indeed, over the past several decades, evolutionary game theory has attracted considerable attention in explaining and exploring the evolution of cooperation [3–6]. Nowak, for example, has devoted his efforts to introducing spatial structure into evolutionary game theory and has put forth five promotion mechanisms for cooperation: kin selection, group selection, direct reciprocity, indirect reciprocity, and network reciprocity [7]. Since this pioneering work, various mechanisms have been proposed to promote cooperation in complex networks, such as reputation [8–11], conformity [12–14], reward and punishment [15–17], heterogeneous investment [18, 19], teaching activity [20, 21], migration [22, 23], noise [24, 25], and memory [26–28]. Aspiration and social influence mechanisms have also begun to garner the attention of many researchers.

In the extant literature, aspiration as an important endogenous feature of individuals has become a vital concern among researchers. Many researchers defined aspiration as the expectation of payoff and introduced a control parameter as the average aspiration level for every individual. A moderate aspiration level has been found to be able to favor cooperative behavior on small-world networks [29] and square lattices [30, 31], when individuals update their strategies synchronously. On the contrary, cooperative behavior is inhibited when the

strategy updating is switched to an asynchronous manner. Still, the involvement of extortioners [32] and the mechanism of migration [33] can facilitate the evolution of cooperation. In addition, aspiration mechanism has usually been studied together with imitation rule. For example, Liu et al. indicated that the invasion of aspiration-driven individuals can boost the cooperation of the imitation-driven individuals [34]. Wang et al. established a new mixed model of combining imitation and aspiration and discussed the effects of aspiration on improving the level of cooperation in different populations, including well-mixed population, structured population, and random matching model [35]. Arefin et al. investigated the coevolution of strategy updating rules of both aspiration and imitation [36]. Furthermore, some researchers proposed a different definition of aspiration, which means the willingness to choose the strategy of a neighbor whose payoff is the highest. They pointed out that heterogeneous aspirations can enhance network reciprocity and resolve social dilemmas [37–39].

Another mechanism, social influence, is also regarded as a crucial factor in an individual's strategy selection. Some researchers believe that the evolution of cooperation can be enhanced when social influence is integrated into the strategy updating process, whether in the PDG [40], PGG [41, 42], and Snowdrift Games (SDG) [43]. Nevertheless, Zong et al. [44] argued that social influence does not always promote cooperation. They classified social influence into weak social influence and strong social influence, and indicated that weak social influence usually inhibits cooperation, while strong social influence has a mediating effect. Inspired by the classification of social influence of Zong et al., we also divided social influence into strong social influence and weak social influence in this study in order to explore the effect of social influence mechanism in the PDG.

Although the effects of aspiration and social influence mechanisms have been explored extensively, there are still three research gaps in the existing literature. First, aspiration has always linked to payoffs, either the expected payoffs of the individual or the highest payoffs of the individual's neighbor. In the real world, however, payoff may not be the only interest for individuals when they interact with others [39]. The other meanings of aspiration have not received much attention. Second, the joint effects of social influence and other mechanisms have yet to be sufficiently studied, and the joint effects of aspiration and social influence specifically have so far been ignored. Third, the simulation models in previous papers are almost entirely at the individual level. The effects of various mechanisms on facilitating the evolution of cooperation at the group level have yet to be fully illustrated.

In an attempt to remedy these research gaps, we define aspiration as the individual's preference for strategy (cooperation or defection) and focus on the joint effects of aspiration and social influence mechanisms at both the individual and group levels in the PDG. Specifically, we consider aspiration as the internal preferences of each individual, which divides the population into positive aspiration (preference for cooperation strategy) group and negative aspiration (preference for defection strategy) group, and we consider social influence as the external characteristic of each individual, which divides the population into strong social influence group and weak social influence group. Based on this classification, individuals with different aspirations and different social influences constitute four kinds of groups, or four heterogeneous

micro-environments. This paper investigates the evolution of cooperation in these four micro-environments and reveals the joint effects of aspiration and social influence mechanisms on promoting cooperation in the PDG.

The rest of this paper is structured as follows. In the Section 2 we introduce the details of our model. Large-scale simulation results are used to explain the evolution of cooperation in the Section 3. Finally, we summarize the main findings in the Section 4.

2 Model

We arrange the evolutionary game on a square lattice with periodic boundary conditions. Each node signifies an individual, and each individual has 4 or 8 neighbors. An individual with 4 neighbors is in the "von Neumann" neighborhood, which is considered to have weak social influence (W). An individual with 8 neighbors is in the "Moore" neighborhood, which is considered to have strong social influence (S). We introduce r as the ratio of strong social influence individuals to investigate the effect of social influence mechanism on improving the level of cooperation. Moreover, in our real life, for example, the extravert usually maintains a positive relation to the outside world and enjoys making friends, while the introvert tends to focus more on the inner world and withdraws from social activities [45]. Thus, we introduce an aspiration tag (+ or -) for each individual. An individual with the positive aspiration tag (+) tends to choose cooperation strategy, while an individual with the negative aspiration tag (-) tends to choose defection strategy.

We set the population size as $N = L \times L$ ($L = 100$). Initially, each individual selects one of the two strategies, cooperation (C) or defection (D) with equal probability. During the process of the evolutionary game, if both individuals choose cooperation, they both receive the reward R . If both individuals choose defection, they both receive the punishment P . If one individual chooses the defection strategy and the other chooses the cooperation strategy, the defector gains the temptation T while the cooperator has to bear the cost S . For simplicity, we follow previous studies [46–49] and adopt a variant of the PDG, which is also known as the "weak PDG" [4]. The payoff matrix of this model is as follows:

$$M = \begin{pmatrix} R & S \\ T & P \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ b & 0 \end{pmatrix} \quad (1)$$

We use Eq. 2 below to calculate an individual's accumulated payoff after interacting with all his neighbors. For each individual i , P_i is the accumulated payoff, Ω_i is the set of individual i 's neighbors, j is one of individual i 's neighbor in his neighborhood, u_i and u_j denote the strategies of individual i and his neighbor j , respectively. u_i^C indicates that individual i selects cooperation, u_i^D indicates that individual i selects defection, and M is the payoff matrix.

$$P_i = \sum_{j \in \Omega_i} u_i^j M u_j, u_i^C = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, u_i^D = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (2)$$

During the process of strategy updating, the Fermi function [50] is the priority. That is, after the first step in which an individual chooses cooperation or defection with equal probability, he updates his strategy by learning the strategy of a randomly selected neighbor with probability:

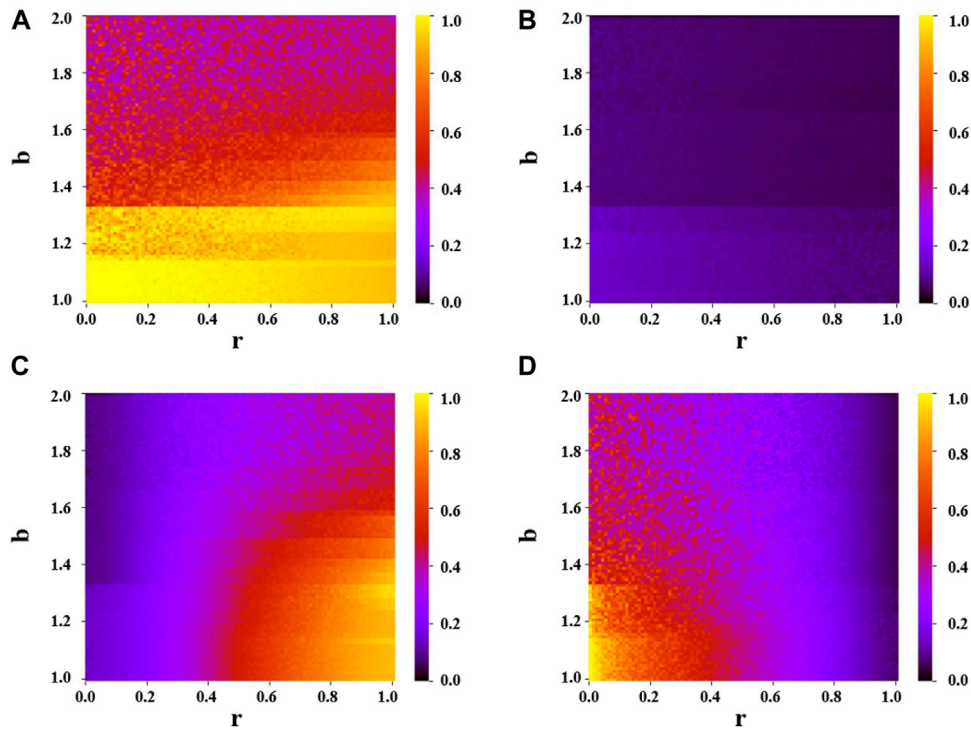


FIGURE 1
 Color plots of the level of cooperation in the (A) +S + W case, (B) -S -W case, (C) +S -W case, and (D) -S + W case. The horizontal axis r in each plot signifies the ratio of strong social influence individuals and satisfies $0 \leq r \leq 1$. The vertical axis b in each plot signifies the temptation to defect and satisfies $1 < b \leq 2$.

$$W(S_j \leftarrow S_i) = \frac{1}{1 + \exp[-(P_j - P_i)/K]} \quad (3)$$

where K refers to environmental noise introduced to permit irrational choices. Without loss of generality, we set $K = 0.1$. S_i is individual i 's strategy, S_j is neighbor j 's strategy (j is a randomly selected neighbor from i 's neighborhood), P_i is individual i 's accumulated payoff, and P_j is neighbor j 's accumulated payoff.

According to Eq. 3, the probability of individual i adopting his neighbor j 's strategy is divided into 3 cases. (1) If $P_j < P_i$, the probability is between 0 and 1/2. (2) If $P_j = P_i$, the probability is equal to 1/2. (3) If $P_j > P_i$, the probability is between 1/2 and 1. When the probability is between 0 and 1/2, the individual maintains his own strategy. When the probability is between 1/2 and 1, he changes the strategy by copying his neighbor's strategy. However, when the probability is equal to 1/2, the individual updates his strategy according to his aspiration tag. If the aspiration tag is positive (+), the individual chooses cooperation strategy. If the aspiration tag is negative (-), the individual chooses defection strategy. Thus, the strategy updating rule is defined as:

$$S_i = \begin{cases} S_i, & \text{if } P_j < P_i \\ S_j, & \text{if } P_j > P_i \\ C, & \text{if } P_j = P_i, \text{ aspiration tag} = "+" \\ D, & \text{if } P_j = P_i, \text{ aspiration tag} = "-" \end{cases} \quad (4)$$

where i denotes the focal individual, and j denotes one of i 's neighbors who was selected at random in i 's neighborhood. P_i

and P_j represent the accumulated payoff of i and j , respectively. S_i and S_j represent the strategies of i and j , respectively. C refers to cooperation strategy, and D refers to defection strategy.

We use the Monte Carlo method to simulate the evolution of cooperation with 10,000 Monte Carlo steps (MCS). Our focus is on how the fraction of cooperators (F_c) changes under four different micro-environments and the joint effect of aspiration and social influence mechanisms on the evolution of cooperation.

3 Results

The purpose of this work is to explore the joint effects of aspiration and social influence mechanism on promoting cooperation in the PDG and to explain how the level of cooperation changes under heterogeneous micro-environments composed of different aspirations and social influences. In our model, individuals with different aspirations and social influences give us four cases of heterogeneous micro-environments: +S + W (all the individuals have positive aspirations), -S -W (all the individuals have negative aspirations), +S -W (strong social influence individuals have positive aspirations, but weak social influence individuals have negative aspirations), and -S + W (strong social influence individuals have negative aspirations, but weak social influence individuals have positive aspirations). The color plots below show the level of cooperation in the simulation of each of the four different cases.

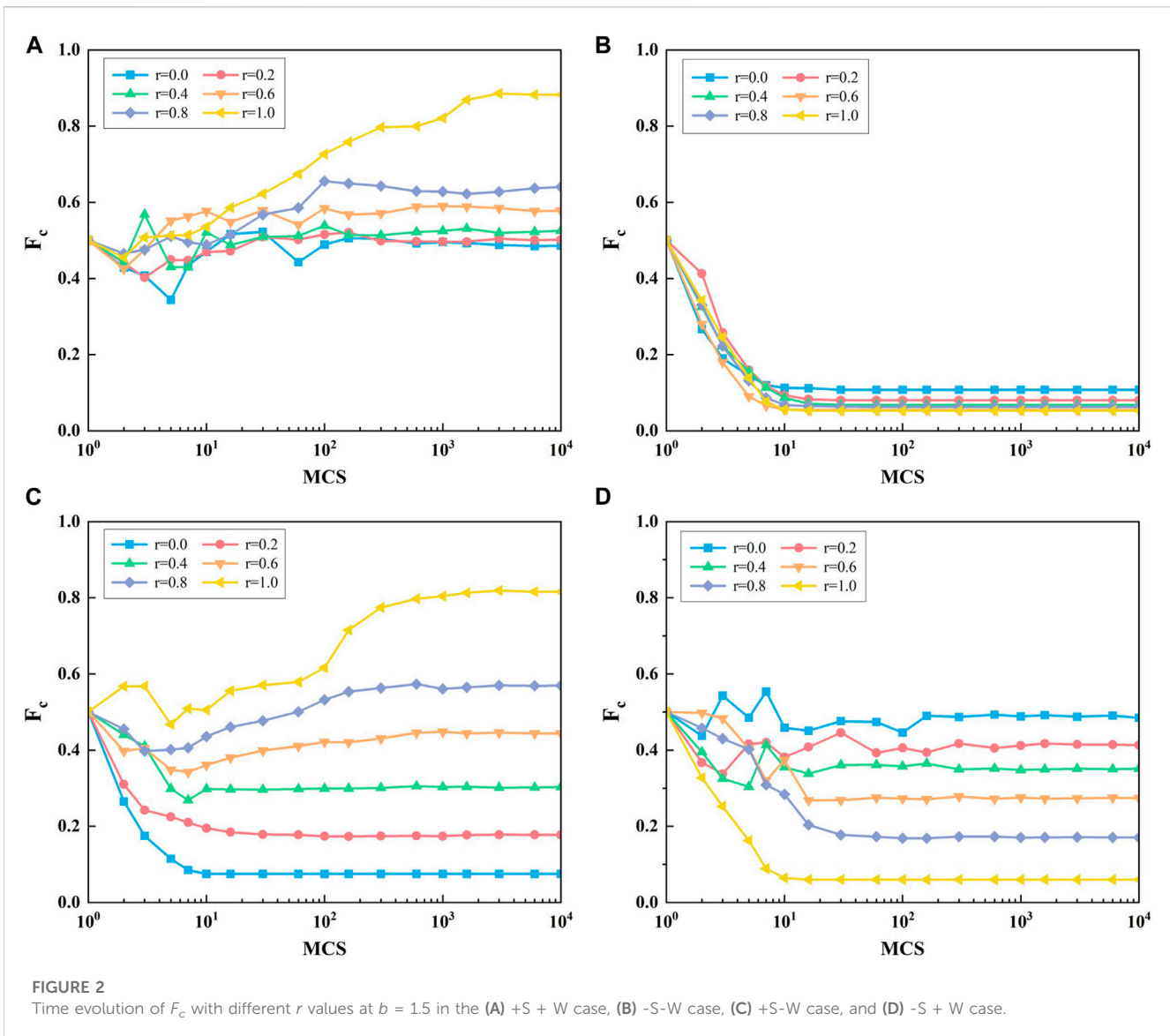


Figure 1A shows the highest level of cooperation, followed by Figures 1B, C, D. Moreover, as shown in Figure 1A, when b is at a medium-high level, the larger the ratio of strong social influence individuals is, the higher the fraction of cooperators. Thus, we conclude that of the case with positive aspiration and strong social influence results in the most cooperation.

Furthermore, we observe that the aspiration mechanism plays a decisive role in promoting cooperation. Positive aspiration always promoted cooperation. Comparing Figures 1A, B, we find that the fraction of cooperators decreases rapidly when the tag of aspiration changes from positive to negative. The same phenomenon can also be seen by comparing Figures 1C, D. The high level of cooperation emerges in the lower right area of Figure 1C, and in Figure 1D, the level of cooperation in the lower left area is high. These two areas are the regions where individuals have the positive aspiration tag. This result tells us that increasing the proportion of individuals with positive aspiration and inspiring the aspiration of all the individuals to cooperate are fundamental to improving the level of cooperation. Additionally, comparing Figures 1A, D, we find that the level of

cooperation in the right area of Figure 1D is very low, which is because the strong social influence individuals have negative aspiration to cooperate. That is, although individuals have strong social influence, without positive aspiration to cooperate, they cannot enhance cooperation and may even inhibit it. Likewise, the level of cooperation in the left area of Figure 1D is high when compared to Figure 1B. That is, although individuals have weak social influence, as long as they have positive aspiration to cooperate, they can improve the surrounding environment and promote cooperation. As the Chinese proverb says, do not do evil things though they may be insignificant and do not give up good things though they may be minor matters. Therefore, individuals should maintain positive aspiration to cooperate, no matter the social influence is strong or weak.

By contrast, we observed that the social influence mechanism only promoted cooperation conditionally. Comparing Figures 1C, D, the area of the high level of cooperation in the case of +S -W is larger than that in the case of -S + W, which indicates that strong social influence individuals have a greater effect on facilitating the

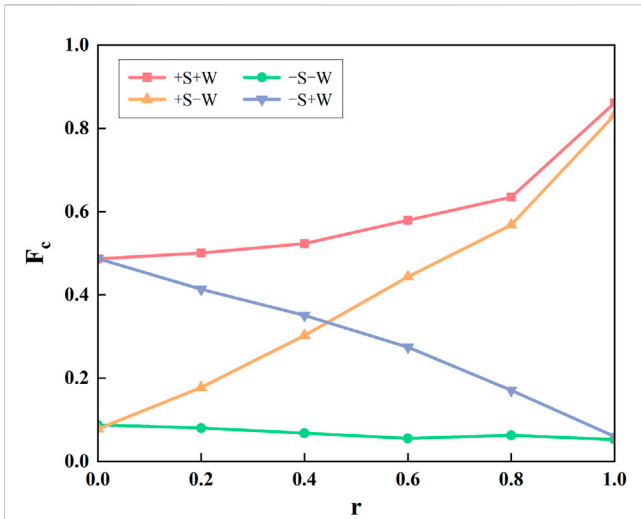


FIGURE 3
The variation of F_c with different r values at $b = 1.5$ in four heterogeneous micro-environments of different aspirations and social influences.

level of cooperation than weak social influence individuals. However, the effect does not always promote cooperation. As shown in Figures 1A, B, we find that when b is at a medium-high level, as the proportion of strong social influence individuals increases, the fraction of cooperators increases in the case of +S + W but decreases in the case of -S-W. That is, when all the individuals have positive aspirations to cooperate, improving their social influence can promote cooperation, but when all the individuals have negative aspirations to cooperate, improving their social influence undermines cooperation. Therefore, transforming the strong social influence individuals with negative aspiration into positive ones or improving the social influence of individuals with positive aspiration can effectively promote cooperation.

In order to explore the changes of cooperation levels over time, we plot the time evolution of F_c with $r = 0.0, 0.2, 0.4, 0.6, 0.8, 1.0$, as shown in Figure 2. Here we set $b = 1.5$ since according to Figure 1, the differences in the four cases are most obvious at this value of temptation.

Here we find that after a brief period of fluctuation, at approximately 30 MCS, most of the F_c values gradually become stable. After 1000 MCS all F_c values reach the steady state. The case

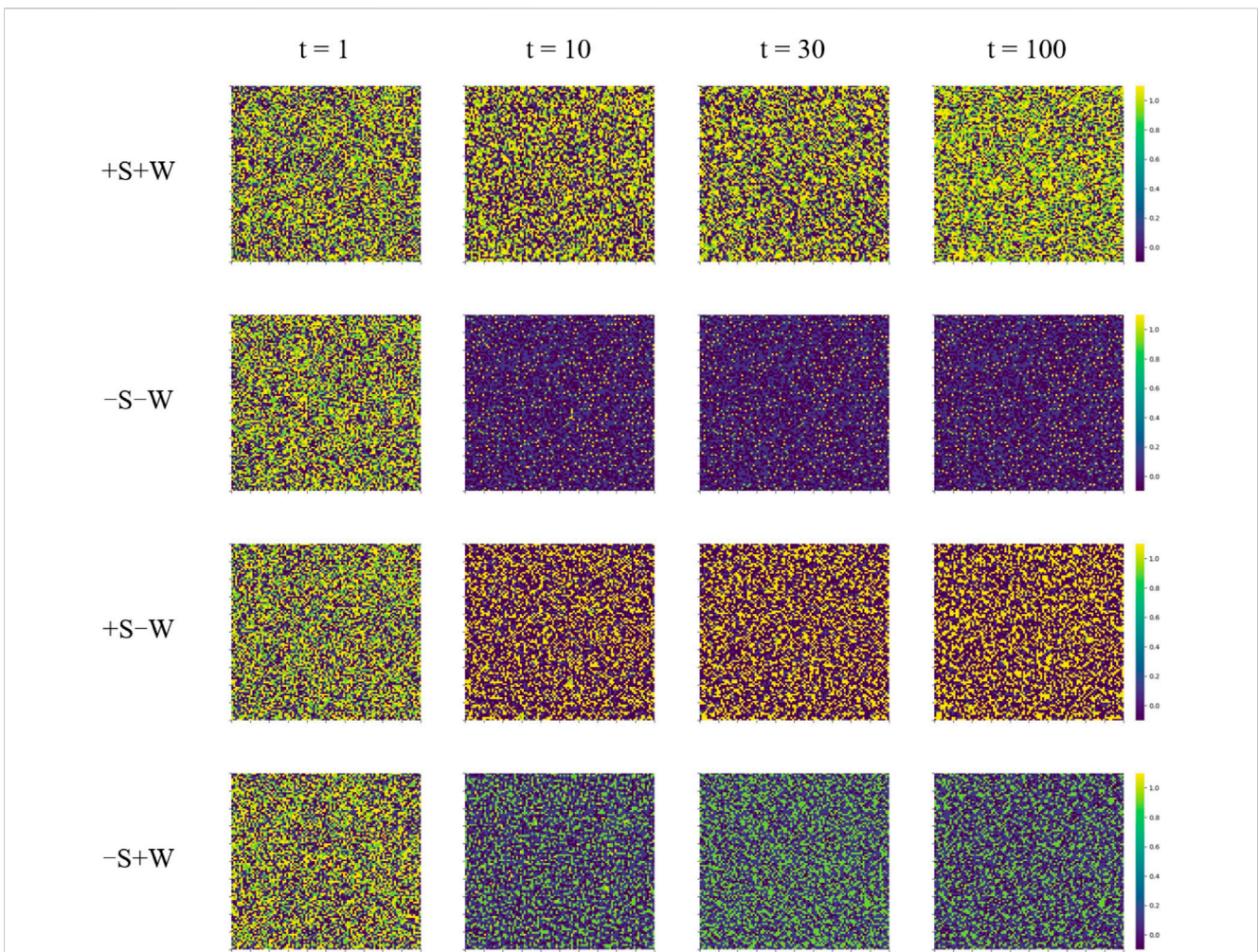


FIGURE 4
Evolutionary snapshots of individuals distribution at various MCS for $b = 1.5$ and $r = 0.5$. Strong social influence cooperators, strong social influence defectors, weak social influence cooperators, weak social influence defectors are colored yellow, green, dark blue, and purple black, respectively. The rows depict results for the case of +S + W, -S-W, +S-W, and -S + W from top to bottom. The MCS for each row are 1, 10, 30, and 100 from left to right.

of +S + W had the highest F_c (close to 0.9) when $r = 1.0$. This result proves the above conclusion. Furthermore, although these four cases of heterogeneous aspirations and social influences are four micro-environments, they together constitute a macro-environment. Any small change will thus affect the whole environment. For example, as shown in Figures 2B, D, we find that even transforming the aspiration of weak social influence individuals from negative to positive can greatly facilitate cooperation. According to the theory of Parsons [51], society is a unified system composed of many interdependent parts, and if one part changes, it will influence the other parts as well as the whole. In our model, changes in an individual's behavior can affect their surrounding micro-environment and thus the macro-social system. As the saying goes, no snowflake in an avalanche ever feels responsible. The behavior of individuals is especially critical. Therefore, each individual should make his efforts to maintain a positive aspiration and improve his social influence.

In order to compare the changes of F_c values in the four cases more clearly, we calculated the average F_c values of the 10,000 MCS with different r values and present the variation of F_c , in Figure 3.

As shown in Figure 3, the F_c values of individuals with positive aspirations are higher than the F_c values of individuals with negative aspirations, which indicates the unconditional promotion effect on cooperation of aspiration mechanism. However, comparing the lines of +S-W and -S + W, we find that in the case of +S-W, the F_c values increase with r , but in the case of -S + W it decreases with r . This result tells us that the promotion effect on cooperation of social influence mechanism is conditional. When the strong social influence individuals have positive aspirations, increasing their proportion can indeed facilitate more cooperation, but when the strong social influence individuals have negative aspirations, increasing their proportion destroys cooperation.

In order to show the evolution of cooperation in the four cases visually, we selected 16 evolutionary snapshots (see Figure 4) of four kinds of individuals (strong social influence cooperator, strong social influence defector, weak social influence cooperator, weak social influence defector) at $r = 0.5$.

As shown in Figure 4, the fraction of cooperators in the case of +S + W is significantly lower than that in the case of -S-W, which shows the pivotal role of positive aspiration in improving the level of cooperation. Moreover, the level of cooperation in the case of +S-W is higher than that in the case of -S + W, which reveals the important effect of strong social influence on facilitating the evolution of cooperation. These results provide new evidence to illustrate the effects of aspiration and social influence, and prove the previous conclusions once again from a different angle.

4 Conclusion

In this work, we discussed the joint effect of aspiration and social influence on promoting cooperation and how the level of cooperation changes in four heterogeneous micro-environments in the PDG. Different aspirations are the internal preferences of each individual, and were reflected by different aspiration tags. Different social influences are the external characteristics of each individual, and were reflected by different types of neighborhoods. Our simulation results show that in all the micro-environments the aspiration mechanism always promoted cooperation, but that the

social influence mechanism only did so in certain circumstances. That is, the aspiration mechanism promotes cooperation unconditionally, while the social influence mechanism promotes it conditionally. The joint effect of aspiration and social influence is thus effective way to improve the level of cooperation. Transforming individual's aspiration from negative to positive as well as improving the ratio of strong social influence individuals with positive aspirations are two effective ways that directly enhanced cooperation.

For the aspiration mechanism, no matter whether the social influence of an individual was strong or weak, positive aspiration always promoted cooperation. Even if individuals have strong social influence, they cannot promote cooperation without positive aspiration. However, even if individuals have weak social influence, they can improve their surrounding micro-environment and promote cooperation as long as they have positive aspirations. Therefore, inspiring the aspirations of all individuals to cooperate leads to increased cooperation. For the social influence mechanism, strong social influence did not always promote cooperation. When all the individuals had positive aspirations to cooperate, improving their social influence promoted cooperation, but when they all had negative aspirations to cooperate, improving their social influence actually undermined cooperation. Therefore, changing the negative aspirations of strong social influence individuals to positive ones or strengthening the social influence of individuals with positive aspirations can effectively promote cooperation.

Finally, from a sociological perspective, changes of individual behavior can affect their surrounding micro-environment and thus the macro-social system. We hope our work can deepen the understanding of the joint effects of aspiration and social influence on the evolution of cooperation and provide some insights into exploring the emergence and maintenance of cooperation under heterogeneous micro-environments composed of other internal preferences and external characteristics. In the future, we will also explore the evolution of cooperation at larger population sizes.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

CL: conceptualization, methodology, data analysis, and writing-original draft. HW: visualization, data analysis and writing-original draft. YD: conceptualization, methodology, writing-original draft and review, and supervision.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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