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Effect of conformity on evolution of cooperation in a coordination game

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Individual decision-making processes are not solely driven by self-interest maximization but are also influenced by the pressure to conform to the group. In primary games like the prisoner's dilemma, the presence of conformity pressure may facilitate the constructive development of cooperative behavior. In this study, we investigate how conformity influences the growth of cooperation in complicated coordination games. Our findings reveal that, even in the presence of stringent game rules, conformity can promote cooperation. In fact, a certain level of conformity pressure can even eliminate the "defection basin" of deer hunting games played on regular networks. Additionally, we demonstrate that the effect of conformity on cooperative behavior is contingent upon the degree of conformity pressure, with different levels of conformity pressure producing opposite effects. These findings provide novel insights into the promotion of cooperative evolution. For instance, if increasing the reward for cooperation has proven ineffective, manipulating the proportion of initial strategy choices may be a more promising approach.

Keywords: cooperative evolution, complex network, conformity behavior, spatial dynamics

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1. Introduction

Evolution of cooperative behavior has been a subject of interest for sociologists, who study games that involve interactions among intelligent individuals.[1–3] Understanding the evolution, stability, and cohabitation of cooperative behavior among unrelated individuals and communities is crucial, as it lies at the core of the success of human evolution. Despite the fact that interactions among numerous intelligent individuals typically result in competition, cooperative behavior is also quite common.[4,5] The well-known "prisoner's dilemma" suggests that cooperation is impossible because humans are inherently competitive.[6,7] However, applied evolutionary game theory has elucidated different perspectives, demonstrating that cooperation is indeed feasible under certain circumstances.[8–10]

Evolutionary game-theoretic investigations into the evolution of cooperation typically begin with a predetermined game rule, such as the prisoner's dilemma, stag hunting,[11–13] or the public good.[14,15] Assumptions regarding population structure, social interactions, and player information should then be stated to facilitate modeling.[8,16,17] By dissecting these assumptions, we can create a natural competitive environment for cooperation and non-cooperation and thus gain insight into why cooperative behavior is so prevalent in humans. A successful body of literature has resulted from this framework, particularly in the field of complex networks, which considers a topological abstraction of actual complex interconnected systems in society in terms of structural relationships.[18] Nowak's concept of network reciprocity[19] suggests that population structure facilitates the evolution of cooperation by forming clusters. More sophisticated networks, such as small-world networks,[20,21] scale-free networks,[22–25] and multi-layer networks,[26–28] have also been introduced to establish more reliable social interaction models.

The facilitation of cooperative evolution by social diversity depends not only on the structure and type of interaction networks but also on the pattern of interactions between social agents.[29–31] While the decisions of intelligent individuals cannot be fully explained by the "economic man", even as payoff maximization plays a significant role,[32] there are other factors at work.[33–35] A straightforward example is that many individuals will choose to "maxmin" their payoffs, meaning that they will choose the biggest payoff among the worst outcomes produced by all possible situations, or just "max" based on their risk tolerance, while some other may simply follow the crowd without considering the payoff.[32,36–38] This indicates that while the theory of the economic man is often used to study social difficulties such as the prisoner's dilemma, snowdrift game, and public goods game,[39,40] it is still unable to provide a compelling explanation for the pervasive phenomenon of cooperation. People's behavior in society is often motivated not solely by pursuing their own self-interests but by acting in accordance with social norms to align their behaviors, attitudes, and opinions with those of the majority, which is referred to as "conformity".[37,41–44]

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Conformity has emerged as a central topic in the field of sociology and evolutionary games due to its prevalence across a wide range of human cooperation. Researchers studying evolutionary games frequently identify conformity as a distinguishing trait that separates conformists from payoff-driven players. Accordingly, conformists are thought to always adopt strategies that are more common among their peers, regardless of whether it is among the population as a whole or only among their neighbors.[37,41,45] Researchers from different areas obtained a more sophisticated result. Social psychologists have developed a basic paradigm that posits three core motivations for conformity: the need for more accurate information, the desire for social approval, and the maintenance of a positive self-concept.[43,46] Researchers have applied this paradigm to understand conformity in different contexts, such as online crowdfunding marketplaces, where lenders are more likely to conform when their identities are hidden, suggesting that conformity is voluntary rather than innate.[38] Additionally, conformity can explain why herding is more prevalent in the military and among students, and why people tend to conform in political climates with high stakes or risk uncertainty.[44] We propose that herding is not an inherent trait, but rather a choice influenced by a combination of factors, including group qualities, external information, and politics. Drawing from the psychological literature,[47] we argue that the "group gaze" phenomenon in which individuals change their behavior and conform to the group is a powerful force. We refer to these influential factors as "conform pressure". By characterizing the magnitude of these factors, we can quantify the strength of the conform pressure, meaning that people are more likely to prioritize the interests of the group over their own as the conform pressure increases.

We focus on examining the influence of conformity on the ultimate evolutionary outcomes under different population structures and networks, using the currently utilized evolutionary game framework to describe the interaction among social individuals and groupings. Previous research has demonstrated that incorporating conformists can promote the development of cooperation in the prisoner's dilemma game, a well-known example of a simple game rule.[33,37,41,45] However, the prisoner's dilemma has limitations in accurately representing all scenarios of cooperation. Recently, there has been a growing body of literature focused on coordination games,[48–50] which introduced a novel viewpoint by suggesting an amendment to the definition of cooperation, thinking of cooperation as a coalitional strategy choice that is always Pareto optimal in the status quo if it exists.[13,51] The highest overall benefit for the group is attained through Pareto optimality, where the group's overall interests are maximized within the scope of individual interactions. This so-called "cooperative strategy" in evolutionary game theory is typically referred to as a norm or standard for individuals to adhere to in the interest of the group.

This leads us to shift our focus to the evolution of cooperation in more complex coordination games.[52,53] A typical example of a coordination game is the stag hunt game, in which hunting stag has Pareto dominance over hunting hare for two players. However, the game has two Nash equilibrium points, both of which can be seen as group norms, making it impossible to predict the outcome using Nash equilibrium. Due to the complexity of the game scenario, we are particularly interested in understanding how cooperation evolves in this coordination game.[54] In this paper, we examine the evolution of cooperation in a population under the group gaze. In this situation, group members are influenced by the conformity pressure of the group gaze, and each individual may have a different threshold for conformity pressure, leading them to choose between conformist or payoff-driven behavior based on the conformity pressure of their group.

In this article, we explore the impact of various conformity pressure magnitudes on the emergence of cooperation in complex game scenarios. We demonstrate that different levels of conformity pressure can lead to intriguing spatiotemporal patterns. Our study argues that the introduction of conformity can result in more complex evolutionary outcomes in the coordination game of stag hunting. Using a coordination game model and Monte Carlo simulations, we investigate the fascinating spatial phenomenon of population diversity that arises after the introduction of conformity. It shows that the effect of conformity depends not only on its intensity, but also on the game rules and the initial proportion of cooperators. Consistent with previous research in the literature, low conformity pressure promotes the evolution of cooperation, regardless of the initial proportion of cooperators.[34,35,37,55] However, when conformity pressure is high, the results are markedly different. High-intensity conformity pressure amplifies the effect of the initial proportion of strategies, hindering the evolution of cooperation when the proportion of initial cooperators is low. Conversely, when the proportion of initial cooperators is high, conformity pressure can even overcome the defection basin of the stag hunting game and facilitate the development of cooperation. Finally, we discuss the potential sociological implications of our findings.

2. Models

In this study, we focus on a simplified version of the evolutionary stag hunting game, where each individual is classified as either a "stag" or a "hare", and their payoff is determined by pairwise interactions. Hunting for stags indubitably results in a Pareto-optimal payoff for the group, making cooperation possible. Thus, we refer to individuals who hunt stags as "cooperators" and those who hunt hares as "defectors".

In game theory, it is common to represent the set of players who are playing with a particular player i in a given game as θ_i. Similarly, the strategy vector of player i in this game can be represented as ε_i. If we consider a second player j who is also playing the same game with player i, then we can represent the transpose of their strategy vector, $\varepsilon_j^{\mathrm{T}}$, in a similar manner. The total payoff obtained by player i in the τ-th game is calculated as follows:

$$\Gamma_i(\tau) = \sum_{j\in\theta} \varepsilon_i U \varepsilon_j^{\mathrm{T}}. \tag{1}$$

The payoff matrix for this game, denoted by U, corresponds to each combination of strategy choices made by the players involved. The strategy vector for a stag (cooperator, represented by C) is (1, 0), and the strategy vector for a hare (defector, represented by D) is (0, 1). As such, the elements of U represent the payoffs that each player receives based on their chosen strategy and the strategies chosen by the other players in the game:

$$U = \begin{pmatrix} R & S \\ T & P \end{pmatrix}. \tag{2}$$

The act of jointly hunting stag yields a collective reward denoted as R, while mutually betraying one another by hunting hare leads to a payoff of equal value, marked as P. In the event of differential selection, the hare receives a payoff of T and the stag receives a corresponding payoff of S. For simplicity but without loss of generality, $R > T \geq P > S$, $S = 0$, $T = P$.[11] To confirm the validity of our findings, we examined various other scenarios to demonstrate the robustness of our results.

2.1. Replication of dynamic equation construction

Initially, we examine the stag hunting game within the context of the traditional well-mixed network. In this scenario, the group is considered with an unstructured infinite population, which is of sufficient size to dismiss any mutation. To simplify the analysis, we assume that a proportion, denoted as x, of the population adheres to cooperation, while the remaining proportion of $1-x$ opts for defection. The average payoffs for cooperators and defectors are expressed as follows:

$$\mathbb{P}_{\mathrm{C}} = Rx + S(1-x), \tag{3}$$

$$\mathbb{P}_{\mathrm{D}} = Tx + P(1-x), \tag{4}$$

and the average payoff of the population is given by

$$\bar{\mathbb{P}} = x\mathbb{P}_{\mathrm{C}} + (1-x)\mathbb{P}_{\mathrm{D}}. \tag{5}$$

Thus the dynamical equation becomes

$$\dot{x} = x(1-x)(\mathbb{P}_{\mathrm{C}} - \mathbb{P}_{\mathrm{D}}). \tag{6}$$

The average payoffs, denoted as $\mathbb{P}_{\mathrm{C}}$ and $\mathbb{P}_{\mathrm{D}}$, respectively, represent the expected payoffs of individuals choosing different strategies at the corresponding evolution time, as provided above. The noise term in the update strategy is quantified as $K = 0.1$, consistent with previous investigations, which accounts for unpredictable factors, such as potential errors in evaluation or receiving information during the strategy update process.[35,41,56]

Additionally, we introduce an exogenous component, known as conformity pressure ρ, to simulate the potential impact of conformity. The magnitude of the conformity effect experienced by the group ranges from 0 to 1. Specifically, $\rho = 0$ represents the absence of conformity within the population, while $\rho = 1$ indicates complete and unbridled drifting, resembling machines lacking self-awareness. Under the influence of conformity pressure, a proportion equivalent to ρ of individuals within the group is affected. As a result, the transfer rate between different strategies is impacted when the dominant strategy (i.e., the strategy adopted by the majority of individuals) in the population changes. Therefore, after introducing conformity, the dynamical equation is modified as follows:

$$\begin{aligned}\dot{x} = {} & (1-\rho)\{x(1-x)[x(R-T+P-S)+(S-P)]\} \\ & +\rho(1-x), \quad x > 1/2,\end{aligned} \tag{7}$$

$$\begin{aligned}\dot{x} = {} & (1-\rho)\{x(1-x)[x(R-T+P-S)+(S-P)]\} \\ & -\rho x, \quad x < 1/2.\end{aligned} \tag{8}$$

Equation (7) can be simplified to

$$\dot{x} = (1-x)\{x[x(R-T+P-S)+(S-P)](1-\rho)+\rho\}, \tag{9}$$

likewise, Eq. (8) to

$$\dot{x} = x\{(1-x)[x(R-T+P-S)+(S-P)](1-\rho)-\rho\}. \tag{10}$$

2.2. Dynamic model improvement considering advanced levels of intelligence

In real interactions, the behavior of individuals is not solely determined by the prospect of achieving gains. Even if individuals are exclusively motivated by the pursuit of rewards, their decision-making process may be subject to errors, leading them to adopt strategies that offer relatively lower benefits. This mistake is not unique to gain-driven individuals, but also applies to conform-driven individuals. Also, individuals often base their actions on information received within the immediate interaction neighbors rather than considering the larger group dynamics. Acknowledging the existence of such decision-making flaws and recognizing the need to improve the generality of our model, we propose to extend the replication dynamics equation by assuming that individuals possess a high level of intelligence.

In this scenario, players interact within large groups but only with a limited number of randomly selected players, and

their income comes from n games with randomly chosen opponents. Under these conditions, Eqs. (3) and (4) can be rewritten as

$$\mathbb{P}_{\mathrm{C}} = nRx + nS(1-x), \tag{11}$$

$$\mathbb{P}_{\mathrm{D}} = nTx + nP(1-x). \tag{12}$$

Players interact at random, and each player engages in a game with n players, thus satisfying the mean field's approximate condition.[56–58] We use Γ to represent the transfer probability between different strategies, which is replaced by a simple fitness in the replication dynamics equation. As a result, we obtain a new collaborator proportional dynamics equation

$$\dot{x} = (1-x)\Gamma(D \to C) - x\Gamma(C \to D). \tag{13}$$

In the case of the Fermi rule, the transition rates are

$$\Gamma(C \to D) = \frac{1}{1+\exp[(\mathbb{P}_{\mathrm{C}} - \mathbb{P}_{\mathrm{D}})/K]'}, \tag{14}$$

$$\Gamma(D \to C) = \frac{1}{1+\exp[(\mathbb{P}_{\mathrm{D}} - \mathbb{P}_{\mathrm{C}})/K]'}. \tag{15}$$

Thus, Eq. (13) becomes

$$\dot{x} = \frac{x(1-x)\tanh[n(x(R-T+P-S)+(S-P))]}{2K}. \tag{16}$$

Next, we consider individuals who have been influenced by the conformity. In the absence of any strategy preference, conformists are likely to adopt the prevalent strategy within their interaction range. In a large population, it is impossible to determine whether the interacting individuals belong to the same population, nor can we infer the probability of their encounter. However, in our model, we focus solely on the process of strategy evolution, allowing us to simplify the model's solution.

We use Γ_ρ to denote the probability of transfer between different strategies of a conformist after receiving the influence of conformity

$$\Gamma_\rho(C \to D) = \frac{1}{1+\exp[(x-\rho_{\mathrm{C}}^*)/K]'}, \tag{17}$$

$$\Gamma_\rho(D \to C) = \frac{1}{1+\exp[(x-\rho_{\mathrm{D}}^*)/K]'}, \tag{18}$$

where ρ_{C}^* and ρ_{D}^* denotes the conform thresholds used by the conformist to judge whether to adopt the strategy or not, respectively. Typically, ρ_{C}^* and ρ_{D}^* are set to 1/2. This is a special value that has been widely used by scholars studying the evolutionary game of conformity. This setting assumes that the population itself has no preference for either cooperative or defection strategies, allowing for a better understanding of the learning mechanism of conform in the evolutionary impact of cooperation.

The equation for the proportion of cooperators in the population becomes

$$\begin{aligned}\dot{x} = {} & (1-\rho)[(1-x)\Gamma(D \to C) - x\Gamma(C \to D)] \\ & + \rho[(1-x)\Gamma_\rho(D \to C) - \rho\Gamma_\rho(C \to D)].\end{aligned} \tag{19}$$

With Eqs. (14), (15), (17), and (18), the dynamical equation becomes

$$\begin{aligned}\dot{x} = {} & (1-\rho)\frac{x(1-x)\tanh[n(x(R-T+P-S)+(S-P))]}{2K} \\ & + \rho\frac{\mathrm{e}^{[(x-1/2)/K]} - x(1+\mathrm{e}^{[(x-1/2)/K]})}{1+\mathrm{e}^{[(x-1/2)/K]}}.\end{aligned} \tag{20}$$

Given that $0 < x < 1$ and $0 < 1-x < 1$, we observe that, for a fixed value of x, an increase in ρ leads to a greater influence on $\dot{x}$ and subsequently results in a decrease in the impact of game revenue on the evolutionary outcome and even make this impact may eventually become negligible.

Consequently, we can conclude Assumption 1.

Assumption 1 A minimum conformity pressure exists, causing the dominant strategy to eventually become the evolutionary outcome of the population.

Moreover, in the initial replication dynamic equation, we can derive the relationship among game parameters, the proportion of cooperators, and its rate of change $\dot{x}$ with ease. Specifically, if the proportion of cooperators, x, is greater than $1/2$, the condition $x(R-T+P-S)+(P-S) > 0$ is equivalent to $\dot{x} > 0$. Conversely, if x is less than $1/2$, the condition $x(R-T+P-S)+(P-S) < 0$ is equivalent to $\dot{x} < 0$. If we denote the parameter $(P-S)/(R-T+P-S)$ as λ, we can represent the attractiveness of the "hare" strategy basin[13] that can be used to describe the size of the defection temptation.

By utilizing the relationship between x and λ, we can accurately determine the direction of the evolutionary outcome. Specifically, when the cooperative strategy dominates ($x > 1/2$) and the game rules favor cooperation ($x > \lambda$), the evolutionary result will inevitably lead to full-C. Conversely, when the defection strategy dominates ($x < 1/2$) and the game rules do not favor cooperation ($x < \lambda$), the evolutionary result will tend towards full-D. Then we can assume that a game rule threshold λ exists, which ensures that the evolutionary outcome always tends towards game rule favorable evolution and ignore the impact of conform pressure. However, this threshold may not be readily discernible when there is a conflict between the dominant strategy and the game rules.

At the advanced level of intelligence, as indicated by Eq. (20), the influence of conformity is significant enough to alter the direction of evolution. This implies that the introduction of conformity can lead to a shift in strategy choice, thereby breaking the dominance of defection even when the game rules are unfavorable to cooperation.

Assumption 2 There exists a fundamental threshold for the stag strategy, and altering the level of conformity pressure

can only impact the rate of evolution towards an advantageous strategy, rather than the final outcome.

Previous literature has also verified the impact of the game benefit parameters on the evolution of cooperation,[59] although the results are not completely consistent on regular networks with different degrees, and the evolutionary equilibrium point separating the all-C phase and the all-D phase has also changed, it still meets the same law: When λ is closer to 0, the initial cooperator density required to achieve all-C is smaller. When λ is closer to 1, the population is more likely to evolve into all-D.

To describe the possible evolutionary equilibrium points, we proceed by solving the replicated dynamic equations. When $x > 1/2$, the equilibrium points comes to: $x = 1$, and

$$x^* = \Big\{(1-\rho)(P-S) \pm \sqrt{[(1-\rho)(P-S)]^2 - 4\rho(1-\rho)(P+R-S-T)}\Big\} \times \Big[2(1-\rho)(P+R-S-T)\Big]^{-1}. \tag{21}$$

As $P-S < P+R-S-T$, it becomes

$$x^* = \Big\{(1-\rho)(P-S) + \sqrt{[(1-\rho)(P-S)]^2 - 4\rho(1-\rho)(P+R-S-T)}\Big\} \times \Big[2(1-\rho)(P+R-S-T)\Big]^{-1}. \tag{22}$$

When $x < 1/2$, the equilibrium points are given by $x = 0$, and

$$x^* = \Big\{(1-\rho)(R+2P-2S-T) \pm \sqrt{-(\rho-1)^2(R-T)^2 + 4\rho(1-\rho)(R+P-S-T)}\Big\} \times \Big[2(1-\rho)(P+R-S-T)\Big]^{-1}. \tag{23}$$

As $P > S$, in the same way,

$$x^* = \Big\{(1-\rho)(R+2P-2S-T) - \sqrt{-(\rho-1)^2(R-T)^2 + 4\rho(1-\rho)(R+P-S-T)}\Big\} \times \Big[2(1-\rho)(P+R-S-T)\Big]^{-1}. \tag{24}$$

As demonstrated in the equation, the equilibrium points are influenced by both the game rules and the conformity pressure. Those former two assumptions suggest that the impact of conformity pressure varies with changes in the game rules and the proportion of the dominant strategy. Manipulating the proportion of dominant strategies within the population leads to varying roles for conformity pressure. The introduction of conformity pressure results in different evolutionary outcomes for the population, which is dependent upon the proportion of dominant strategies.

The population dynamics after the introduction of higher intelligence also supports the same conclusion. However, due to the increased complexity of the equations, it is more challenging to draw analytical conclusions. When considering the boundary condition of subordinate pressure, i.e., $\rho = 1$, Eq. (20) can be expressed as

$$\dot{x} = \frac{e^{[(x-1/2)/K]} - x(1+e^{[(x-1/2)/K]})}{1+e^{[(x-1/2)/K]}}. \tag{25}$$

In this context, we can easily identify three equilibrium points of the population: $x = 1$, $x = 0$, $x = 1/2$. By setting the subordination threshold ρ^* to 1/2, which represents a neutral drift, the coexistence equilibrium point for the population is established.

Consequently, we can infer that the influence of conformity pressure on the evolution of population cooperation is contingent upon a range of factors and is positively correlated with its own magnitude.

Assumption 3 The impact of conformity pressure on the evolution of cooperation within the population is closely tied to both the distribution of strategies and the magnitude of the conformity pressure.

We simulate in more realistic regular networks and test our conjectures by observing the microscopic mechanisms in the network. In order to verify our conclusions obtained in the well-mixed network, we investigate stag hunting game on the square lattice, where each node in the regular network of side length $L = 100 \times 100$ has four neighbors, for making comparisons with past research easier.[13,37,41] To elucidate the impact of conformity, we posit a population composed of self-interested individuals, all subject to conformity pressure that is parameterized by probability ρ. Specifically, a proportion ρ of individuals will adopt a conformity-driven strategy. Self-interested players follow profit-maximizing principles, while conformists are driven by a desire to fit in with the group. During the strategy update phase, we randomly select a revenue-driven player i and allow them to play with all their neighbors, yielding a revenue of $\mathbb{R}_i$. Similarly, we randomly select a neighbor j of player i and allow them to play with all their neighbors, yielding a revenue of $\mathbb{R}_j$. The probability that individual i will imitate the strategy of individual j in the next game is then given as follows:

$$\Gamma(\varepsilon_i \leftarrow \varepsilon_j) = \frac{1}{1+\exp((\mathbb{R}_i - \mathbb{R}_j)/K)'}. \tag{26}$$

Conformity-driven players, constituting a proportion of ρ in the population, do not optimize their strategies based on the benefits they offer. Rather, they adopt the most prevalent strategies within their interaction range. The strategy update process for these conformists entails comparing the number of strategies adopted by their neighbors. The policy update rules for conformists are given by i.

$$\Gamma\left(\varepsilon_i \leftarrow \frac{k_i}{2}\right) = \frac{1}{1+\exp[(\delta_{\varepsilon_i} - \frac{k_i}{2})/K]'}. \tag{27}$$

The number of players who have adopted strategy ε_i within player i's interaction scope is denoted by δ_{ε_i}, while k_i represents the degree of player i in the network. Conformists are highly likely to adopt the most prevalent approach (either C or D) in their local neighborhood. However, taking into account the potential effects of noise and the environment, there remains a small probability that a conformist will conform to the strategy of a small group of neighbors.

In each Monte Carlo step (MCS) of the simulation experiment, N basic stages are continuously repeated, affording each participant plenty opportunities to modify their strategy. All simulation results were produced on the same network. Our findings were observed after sufficient time has elapsed for the system to reach a static state. To minimize inaccuracies, we conducted thousands of simulations and computed the data, eliminating aberrant data points using standard deviation before obtaining the average value.

3. Results

3.1. The influence of conformity at varying magnitudes on the evolutionary dynamics of cooperation

The results are depicted in Fig. 1, where the abscissa represents the initial cooperator ratio of the population, and the ordinate represents the attractiveness of the hare-hunting strategy basin. As previously stated, game rules closer to 1 indicate a greater favor ability towards defection, while those closer to 0 favor cooperation. Different color curves, which represent critical states of different conform pressures, distinguish the final outcomes of population evolution ranging from full cooperation to full defection.

With the introduction of lower conform pressure, the blue curve ($\rho = 0.3$) and yellow curve ($\rho = 0.6$) indicate a larger full cooperation zone, and the area of full cooperation without integration is significantly smaller than the area with different levels of conform. This suggests that the introduction of conform can promote cooperation in coordination games to a certain extent, similar to that of $P \cdot D$. However, with the introduction of higher conform pressure, the red curve ($\rho = 0.9$) displays a similar trend to the straight line of $k = 1$. This indicates that as conform pressure increases, the evolution result becomes biased towards the dominant strategy, indicating that conform here only enhances the rate of evolution of the dominant strategy, instead of promoting cooperation.

In addition, our results indicate that the blue curve ($\rho = 0.3$) is particularly effective in promoting cooperation when the initial cooperation strategy is low ($x_0 < 0.3$) compared to the black curve, which does not incorporate conformity. These findings suggest that the blue curve can also evolve to full cooperation instead of only following the dominant strategy. Conversely, when $\rho = 0.6$, the impact of promoting cooperation in low x_0 regions is not significant. Furthermore, when $\rho = 0.9$, herding factors are no longer conducive to cooperation in low x_0 regions and can even restrict its development, leading to full defection.

That give us Result 1.

Result 1 The impact of conform pressure of the evolution of population cooperation in coordination games vary depending on the initial cooperation ratio and its scale.

These results highlight the critical role of conform pressure in shaping the evolution of population cooperation in coordination games. Furthermore, our findings suggest that the effectiveness of different strategies can vary, depending on the initial cooperation ratio and the level of conform pressure. Future research should examine the implications of these results for understanding social behavior in real-world situations.

Another significant body of evidence supporting the effectiveness of conformity in promoting cooperation is the absence of "stubborn defection" in high-risk areas after incorporating the conformity factor. Without the herd factor, when λ exceeds 0.75, the black curve transforms into a straight line which has a slope $k = 0$ after reaching this threshold, indicating that cooperation cannot develop successfully, regardless of the initial ratio of cooperators.

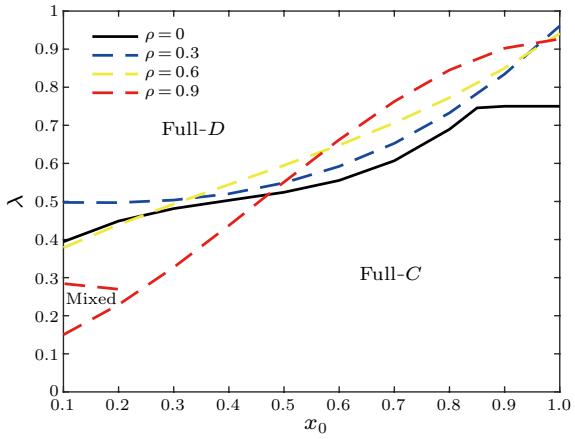


Fig. 1. Phase diagram of the λ–x_0 evolution of the stag hunting game. The solid black line indicates the boundary between full cooperation and full defection when no herding factor is introduced. To explore the effect of introducing conformist participants, we also plot the same boundary for $\rho = 0.3$, $\rho = 0.6$, and $\rho = 0.9$ using blue dashed, yellow dashed, and red dashed lines, respectively. Notably, at $\rho = 0.9$, the boundary is structurally broken, and a high proportion of followers can lead to the simultaneous existence of both cooperative and defection strategies.

3.2. The evolution of cooperation in a spatially structured population under different conformity pressures

Our discussion of the spatial dynamic evolution results further supports this conclusion. The evolving system of the stag hunting game exhibits a more complex game scenario near the critical point. The structural characteristics of the square lattice network result in a defection domain in the stag hunting game (under this game rule, the evolving system will eventually achieve complete defection), supported by the presence of *stubborn betrayers*, players who will choose defection

regardless of their neighbor's action. This defection domain is particularly stable in a traditional stag hunting game, but conformity-driven individuals can help cooperators form clusters that are harder to invade, which undermines the robustness of the defection domain and shows a more complex evolutionary signature. As long as the coupling structure of betrayers exists, it is difficult for the defection strategy to be invaded by the cooperator strategy, and the defection strategy remains stable even in the initial state with a high proportion of cooperators, eventually occupying the entire population, resulting in full defection. By comparing the evolutionary results with different levels of conform pressures, we obtain some more complex evolutionary conclusions.

We investigate the rate of evolution of the stag hunting game on a $K = 0.1$, $L = 100 \times 100$ square lattice network while controlling for the values of λ and x. To better understand the impact of ρ on the evolutionary result of the game, we consider four distinct values of the proportion of conform pressure, namely 0, 0.3, 0.6, and 0.9. We choose these values based on the fact that those too close to 0 or 1 are not statistically significant.

Our primary objective is to quantify the impact of ρ on the evolution of the stag hunting game under different conditions of λ and x. To achieve this, we perform tens of simulations for each parameter setting and record the evolutionary results for different initial proportions of cooperators and conformists. We then calculate the average evolutionary step, eliminating outliers using the standard deviation method. As the evolutionary step size fluctuates significantly at the critical value and often has different evolutionary results, we use the reciprocal of the evolutionary step to represent the rate at which the population evolves to full cooperation and take negative values to represent the rate at which the population evolves to full defection. We magnify these values by the same multiple and represent them as α, which can be used to represent the evolve velocity.

By holding the values of λ and x constant, we aim to isolate the effect of ρ on the evolutionary outcome. We measure the rate of evolution α for each of the four values of ρ and compare the results. Our approach provides a comprehensive understanding of the dynamics of the stag hunting game under different parameter settings, highlighting the role of ρ in shaping the evolutionary trajectory.

Figure 2(a) illustrates the impact of varying λ and x while fixing $\rho = 0$. Obviously, the population exhibits a preference for full cooperation as x increases, while it shifts towards complete defection as λ increases. Interestingly, when λ reaches the threshold of 0.75, a sharp transition occurs, and the yellow domain which represent cooperation suddenly gives way to the blue domain which represent defection. This leads to a defection domain in the population, with λ exceed 0.75 inevitably resulting in complete defection irrespective of the initial cooperator ratio. While the growth of initial cooperators can temporarily delay the onset of full defection, it cannot ultimately reverse the evolutionary outcome.

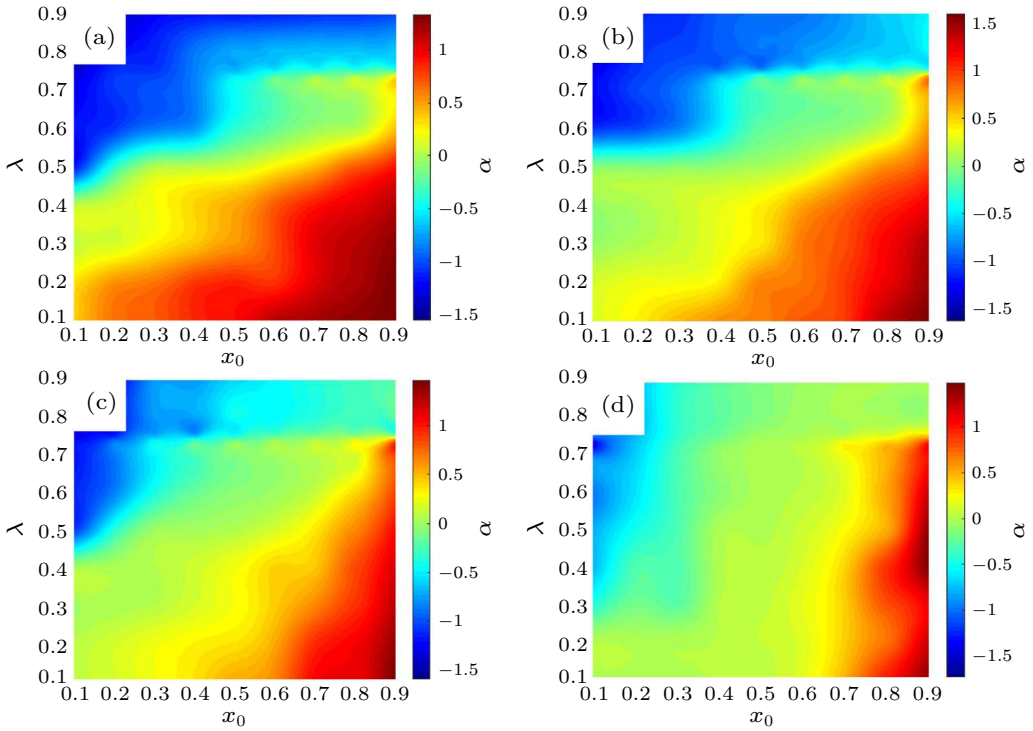


Fig. 2. The rate of evolution of the stag hunting game on a $K = 0.1$, $L = 100 \times 100$ square lattice network at the levels of conform pressures $\rho = 0$, 0.3, 0.6, and 0.9, controlling for the values of λ as well as x, where the abscissa represents the initial cooperator ratio of the population, and the ordinate represents the attractiveness of the hare-hunting strategy basin, α represent the evolve velocity (we choose 0.1–0.9 as the parameter range because values too close to 0 or 1 are not statistically significant).

Conversely, when λ is small, the population tends to develop complete cooperation, even with a minute proportion of initial cooperators. This conclusion is not entirely consistent with uniformly mixed populations, where the evolutionary outcome is solely determined by the ratio between x and λ. Instead, the structural properties of the network play a vital role, causing λ to exert a more significant influence, especially when its value is close to 0 or 1, thereby exhibiting a strong pro-evolutionary effect on the spatial structure. When λ falls within the meaningful definition domain's center, the initial cooperator ratio and the hare basin significantly impact the evolutionary result, demonstrating convergence with the uniform mixed population to some extent.

The apparent demarcation line at $\lambda = 0.75$ between the regions represented by consistent behavioral outcomes (C or D) that the population eventually evolves becomes blurred with the introduction of the conformity, and the population can no longer maintain a high evolutionary rate to defection, which means evolution drifts toward full cooperation. This is especially evident when a high conform pressure, i.e., high proportion of conformity players is introduced, as the high proportion of conformists preempts the set clusters with a high proportion of cooperative players, preventing the betrayers from forming a solid coupling structure on the network, allowing the cooperators to successfully invade the defection domain that existed in the traditional stag hunting game and facilitating the cooperation evolutionary occurrence of the population.

While Figs. 2(b) and (c) demonstrate that a low level of conform pressure can promote cooperation, the evolutionary results presented in Fig. 2(d) indicate that the light yellow area representing cooperation in the left region of the population state with a small percentage of initial cooperators is invaded by the blue area representing defection. This finding is consistent with our hypothesis and suggests that high conform pressure in complex networks also leads to failure of cooperative evolution when cooperation is non-dominant strategies.

We have examined the impact of the conformity on the cooperation evolution of populations. By varying the scale of conform pressure, we observed a significant decrease in the blue region that corresponds to rapid evolution towards complete defection, as well as an increase in the color region that represents the evolution towards full cooperation. This finding suggests that the final evolutionary outcome of the population has been altered, i.e., from all-C to D or all-D to C, rather than merely affecting the rate of evolution in original direction. At the intersection of the color regions corresponding to full cooperation and full defection, the effect of conformity is more pronounced. As the parameter ρ increases, all regions become lighter in color, indicating that the population requires more time to reach the final evolutionary outcome. Our study shows that incorporating conformity into the spatial structure of the stag hunt results in a more nuanced evolution of cooperation, characterized by more than just modest changes in the rate of evolution at tipping points.

Drawing on the aforementioned Assumption 2, our inquiry has established the evolutionary influence of conformity on cooperation through the lens of spatial dynamics. As a corollary, we are pleased to introduce Result 2.

Result 2 Incorporating conformity into the spatial dynamics of the stag hunting game has the potential to surpass the defection domain threshold in the game, consequently enhancing the evolution of cooperation.

To assess the effectiveness of conformity in promoting cooperation in a particular coordination game, we conduct further analysis using parameter settings similar to previous studies. The cooperators in the stag-hunting game on a rule network will spontaneously form clusters when the game rules are favorable, making it challenging to intuitively evaluate the utility of conformity. To overcome this challenge, we employ more challenging rules for the stag-hunting game, specifically, the ratio of rabbit hunting payoffs to stag hunting payoffs is greater than 1/2. We also fix the hare basin while varying the conform pressure and initial cooperator ratio to evaluate the impact of cooperative evolution in the presence of the conformity.

Figure 3 presents a comparison of the evolutionary transient states of the stag-hunting game before and after the introduction of the conformity, which illustrates the evolutionary outcomes for $\lambda = 0.6$, while adjusting for the scale of conform pressure ρ and the starting proportion of cooperators x.

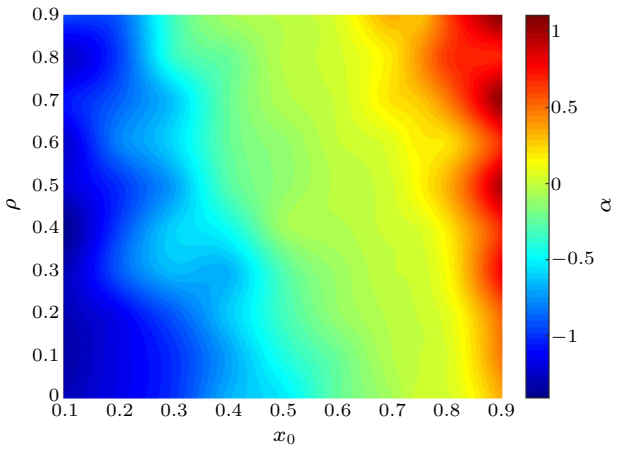


Fig. 3. The rate of evolution results for varying ρ and x stag hunting games on a network of $L = 100 \times 100$ squares for $\lambda = 0.6$, $K = 0.1$, where the abscissa represents the initial cooperator ratio of the population, and the ordinate represents the scale of conform pressure, α represents the evolve velocity.

As demonstrated in Fig. 3, an increase in the initial proportion of cooperators x leads to a transformative shift from all-D to all-C. When the initial proportion x is extremely small, this prompts a very rapid pace of evolution to all-D, which slows down to 0 as x increases until it increases again after

changing the sign of the rate to positive. Moreover, an increase in ρ has little effect when the scale of the initial proportion of cooperators is small, but after $x > 0.3$, a higher ρ slows down the pace of advancement of the group towards complete treachery until $x = 0.5$. At this point, a light yellow region appears in Fig. 1, indicating that two possible results of population development are possible: full-C or D. After $x > 0.6$, the higher ρ value ensures that the population should evolve towards all-C.

Throughout Fig. 3, the color region slopes to the upper left, indicating that conformity reduces the threshold of the initial proportion of cooperators required for the population to reach all-C. That's to say, the conformity factor facilitates the occurrence of cooperative evolution.

3.3. The complex evolutionary dynamics of introducing conformity at the critical point in the evolution of a population

Similarly, the exposition of the conformity presents several distinct characteristics. To further scrutinize its impact, we examine the evolutionary dynamics of the phase transition regime. Notably, the critical domain of the phase transition at $\rho = 0.3$ exhibits a non-smooth overabundance, and the developmental trajectories of the population towards full-C or full-D manifest striking dissimilarities. We illustrate the evolutionary dynamics of the population towards full-C and full-D under similar parameters for various MCS steps in Figs. 4 and 5.

Figure 4 depicts the scenario where cooperators failed to form clusters with conformists in time to resist the initial invasion. Consequently, the conformity participants were swayed by the high proportion of the defection strategy, leading to their conversion to betrayers. Subsequently, the betrayers invaded and eliminated the cooperative strategy, driving the population to evolve to full-D. In contrast, Fig. 5 illustrates that, with an increased number of MCS steps (30×10^3), cooperators were able to form clusters with conformity participants in time, inducing self-interested individuals around them to cooperate, ultimately causing the population to evolve to full-C.

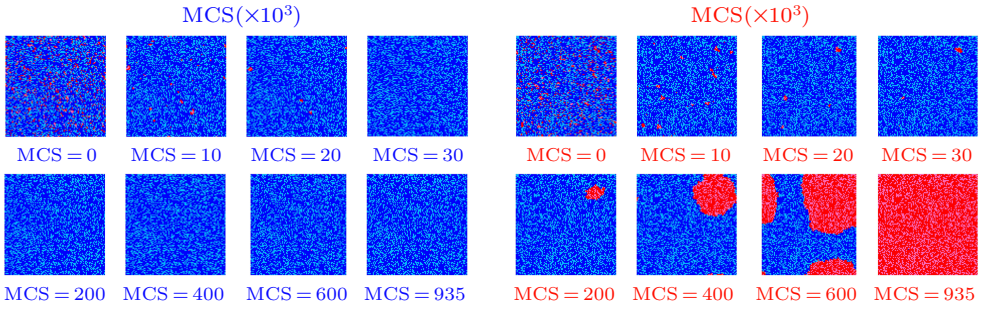


Fig. 4. Transient evolutionary dynamics of the stag hunting game on a 100×100 square lattice network with $K = 0.1$, where $\rho = 0.3$, $\lambda = 0.5$, and $x = 0.2$. The figure illustrates the system's evolution reaches opposite outcomes under the same initial conditions over different Monte Carlo steps (MCS). We use a color scheme to represent the four types of players in the game: light red represents conformity-driven cooperators, dark red represents payoff-driven cooperators, light blue represents conformity-driven betrayers, and dark blue represents payoff-driven betrayers. The results indicate that the system's transient dynamics are complex and can lead to unpredictable outcomes, highlighting the need for further research in this area.

The evolutionary process described herein is not solely contingent upon the values of ρ, λ, and x. In some small parameter ranges, it is also influenced by stochastic factors such as the initial placement of strategies on the network and noise, leading to more complex evolutionary outcomes. The red dashed line in Fig. 1 delineates the mixed region where cooperators and betrayers coexist in the spatial structure when $\rho = 0.9$, and both λ and x values are small (we verified the validity of this finding using Monte Carlo simulations of 1010 rounds). In this scenario, spatial clusters are difficult to invade. However, the prevalence of conformists currently hinders cooperators from benefiting from the high proportion of payoff-driven individuals to exert an influence, ultimately resulting in the coexistence of a small number of betrayers with the majority of cooperators in space. This phenomenon reflects the role of conformity in a different way; namely, conformity may impede the evolution of cooperation. This conclusion is predicated on the fundamental condition that the initial proportion of cooperators is small and that the benefits derived from cooperation far exceed those from defection.

The lower value of ρ, when the game rule favors cooperation ($\lambda < 0.5$), facilitates the formation of clusters of payoff-driven cooperators and conformity-driven individuals. This allows them to avoid being influenced by the initial high proportion of defection strategies and forming defection clusters that are difficult to change their strategies through benefit inducement. When the conform pressure is high, namely conformists represent a large proportion of the population, the situation becomes more complex. In the presence of more betrayers in the population, the high proportion of conformity-driven players quickly helps the defection strategy to spread, leading to the formation of clusters of conformity-driven betrayers that are difficult to change their strategies. This eventually leads to the evolution of the population into a full-scale defection when the game rule favors defection ($\lambda > 0.5$).

In contrast, in the presence of more cooperators in the

population, a high proportion of conformity-driven players adopt the cooperative strategy, they can rapidly propagate through numerical advantage and destroy the coupling structure formed by the highly attractive hare basin as the initial proportion of cooperators rises. This facilitates the evolution of cooperation. This brings us back to our previous conclusion that a high level of conform pressure amplifies the impact from the initial strategy and exhibits a different effect on the evolutionary outcome rather than a one-way pro-cooperation effect.

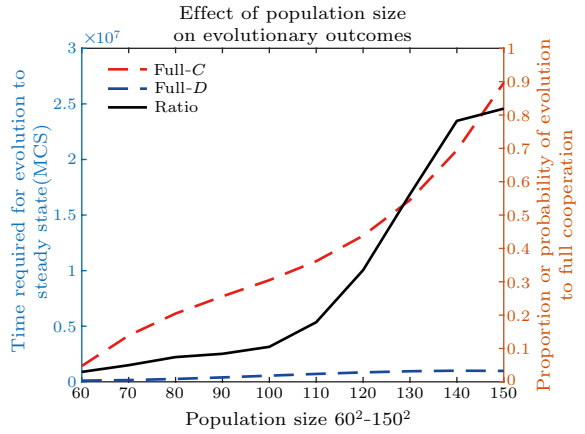


Fig. 5. Evolutionary outcomes examined by manipulating the population scale in the stag hunting game on on different square lattice networks with $K = 0.1$, where $\rho = 0.3$, $\lambda = 0.5$, and $x = 0.2$. The red dashed line represents the duration required for populations of varying sizes to evolve towards full cooperation, the blue dashed line represents the duration required for populations of different sizes to evolve towards full defection, and the black solid line indicates the probability of eventual cooperation for the corresponding population size. The results described were obtained by cumulatively computing and averaging 450 simulations for each population scale, resulting in a total of 4500 simulations.

However, just as individuals do not experience the same pressure to conform when confronted with an invitation to a weekend party from a friend, a corporate mandate to attend an event, or even a social norm, it becomes necessary to examine the role of population size in the evolution of cooperation evolution. In general, without accounting for regulation, population size tends to be positively correlated with the intensity of conform pressure, i.e., larger population sizes exhibit greater conform pressure. Our simulations do not incorporate this relationship, as population is primarily determined by population attributes such as firms, societies, and classes instead of amounts, and these attributes that determine population size and, consequently, the pressure to conform. Therefore, it may be more meaningful to explore the relationship between different population attributions and the conform pressure.

Simultaneously, the same population attributes can vary in size, such as giant firms across countries and small private firms, prompting an examination of the impact of significant population size changes on evolutionary outcomes when considering conformity. By manipulating the size of the matrix network, we simulate evolutionary dynamics within populations of different sizes while keeping the other parameters constant.

As anticipated, larger population sizes require a longer time for the system to reach equilibrium, while smaller population sizes expedite the attainment of equilibrium. On the one hand, the increase in population size augments the complexity of the evolving system, leading to a longer and outstanding varying time for the system to evolve towards cooperative stability, while the time required to reach full defection varies marginally. On the other hand, enlarging the population size enhances the facilitative effect of conformity on cooperation, even when the magnitude of conform pressure is determined a priori, i.e., the relationship of the stronger conform pressure associated with larger populations is removed.

Specifically, larger populations have a greater likelihood of initial cooperation between conformists adopting the cooperator strategy to form clusters that resist invasions by defectors. This can be attributed to the increased probability of localized homogeneous regions emerging within larger populations, where conformists initially adhering to cooperative strategies coalesce into small clusters. Once this structure stabilizes, it leads a gradual infiltration of cooperators to the periphery, ultimately enabling the population to evolve towards complete cooperation. This invasion process unfolds gradually but persistently, increasing the probability that the critical point will eventually transition to full cooperation as the population size grows, meanwhile significantly prolonging the time required to reach eventual stability.

This influence can be conceptualized as the mechanism through which conformists exert a homogenizing influence. Thus, the role of conformity is simply to homogenize populations locally, and the previous argument that conformity facilitates cooperation is because payoff-driven cooperators form spatial structures that lead to spatial reciprocity. The emergence of conformity can make this structure more robust and spread more widely and rapidly. Therefrom, we can get result 3.

Result 3 Implications of conformity for cooperative evolution through self-homogenization.

Therefore, the conformity factor can sometimes be a penalty when the proportion of initial betrayers in a population is too high. This validates the fact that governments are often ineffective in encouraging the population to cooperate by improving the benefits of cooperation. Instead, it is more effective to control the choice of initial cooperation strategies through coercion based on conformity considerations.

It is important to note that the evolutionary process is not only dependent on the values of ρ, λ, and x, but also subject to stochastic factors such as the initial position of the strategies in the network and noise, which can lead to more complex evo-

lutionary results in some small parameter ranges. The mixed region formed by the red dashed line in Fig. 1 indicates that cooperators and betrayers coexist in the spatial structure when $\rho = 0.9$ and both λ and x values are small. This finding was verified in the Monte Carlo step of 1010 rounds. In this case, because spatial clusters are hard to invade, cooperators and betrayers coexist in the space, reflecting the role of conformity in hindering the evolution of cooperation. However, this conclusion is based on the basic condition that the initial proportion of cooperators is small and the benefits from cooperation are much higher than those from defection.

4. Discussion

We investigated how the introduction of conformity leads to the evolution of cooperation in a stag hunting game. Individuals make the decision to subordinate their own interests to the group interest with a probability proportional to the level of conformity pressure. This probability is determined by the level of conform pressure. By incorporating conformity into the game dynamics, we were able to expand upon previous findings in the literature and demonstrate that the presence of conformity can enhance network reciprocity in coordination games, leading to more favorable outcomes in social dilemmas.[37] Our results highlight how consistency can promote cooperation in challenging situations.

Based on the simulation results near the critical point, we can conclude that even in the presence of "stubborn defectors", a high initial proportion of cooperators and conformity pressure can rapidly form a cluster of cooperators and drive the evolution of the population towards full cooperation, thereby preventing the spread of defectors. The impact of high conformity pressure requires further investigation, as its viability depends on the magnitude of the pressure and the specific game and payoff structures. Since there is no inherent strategic preference for conformity, payoff-driven players in the population will influence the conformists to adopt their strategy. Our experimental results demonstrate that conformity not only promotes the cooperative evolution of populations but also exhibits diverse characteristics depending on the game rules and proportion of conformity-driven individuals in the population. This underscores the importance of the population's initial state: attractive payoffs may not be the sole determinant of cooperation, and governments may need to consider controlling the initial strategies of the population through conformity-based coercion to effectively address social dilemmas.

Our work makes a novel contribution to the literature by not only extending previous research on the role of conformity in the evolution of cooperation from a game-theoretic perspective, but also investigating the impact of varying levels of conformity on cooperative outcomes. Our findings demonstrate that in games with multiple equilibria, the effects of conformity on the population's behavior can be more intricate compared to games with a single equilibrium. Furthermore, we reveal that stochasticity can give rise to variations in the effects of new factors on evolutionary outcomes, which leads to substantial differences in simulation results. Nevertheless, our results obtained by fixing the conformity pressure level and varying other parameters still highlight that conformity has distinct effects on the evolution of cooperation depending on the specific game context.

The motivation for this study stems from the COVID-19 outbreak in Wuhan, China, which prompted the government to implement city-wide closures to manage the epidemic. As a result, hospitals in Wuhan experienced a surge in patient volume, with a large portion of these individuals seeking medical attention for common seasonal illnesses or for psychological reasons. This phenomenon, known as herd behavior, occurs when individuals in a group follow the actions of others after social learning due to a lack of information about a situation. Nevertheless, this paper does not explore what behavior causes conformity, but only studies the impact on the cooperative evolution of the population when the factor of conformity appears. The results of this paper suggest that conformity may contrarily affect the evolution of cooperation, which could fill in as a component of an explain of the present circumstance. While this paper does not investigate the specific behavior that causes conformity, it examines the impact of conformity on the cooperative evolution of the population. Our findings suggest that conformity may have a detrimental effect on the evolution of cooperation, which could help explain the current situation. We recommend future research to investigate the multi-party and multi-round iterative public goods distribution game process using the multi-element public goods evolution game.

Acknowledgments

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