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Review

Reputation and reciprocity

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Abstract

Reputation and reciprocity are key mechanisms for cooperation in human societies, often going hand in hand to favor prosocial behavior over selfish actions. Here we review recent researches at the interface of physics and evolutionary game theory that explored these two mechanisms. We focus on image scoring as the bearer of reputation, as well as on various types of reciprocity, including direct, indirect, and network reciprocity. We review different definitions of reputation and reciprocity dynamics, and we show how these affect the evolution of cooperation in social dilemmas. We consider first-order, second-order, as well as higher-order models in well-mixed and structured populations, and we review experimental works that support and inform the results of mathematical modeling and simulations. We also provide a synthesis of the reviewed researches along with an outlook in terms of six directions that seem particularly promising to explore in the future.

Keywords: Pattern formation; Monte Carlo method; Complex network; Evolutionary game theory; Cooperation; Social physics

Contents

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1. Introduction

Although the Darwinian theory of evolution favors the competition between individuals to maximize their own interests, the cooperation or collaboration still exists within many social animals [1–3] such as ants, bats, wild geese, primates and so on, even in the human society. Thus, how to understand the widespread cooperation has become a challenging task in the field of biology, physics or mathematics, which is one of 25 scientific puzzles to be pretty much resolved in the 21st century voted by the famous *Science* magazine [4].

To be particularly mentioned that, five rules have been identified to support the emergence of cooperation, which include kin selection, direct reciprocity, indirect reciprocity, group selection, spatial or network reciprocity [5]. Among them, indirect reciprocity has been extensively investigated in the recent years [6,7] since it involves the individual reputation building, moral evaluation and complex interplay inside the population with increasingly cognitive demands. Therefore, exploring the impact of indirect reciprocity on the evolution of cooperation has received a great deal of attention within the academia, which aroused the huge interest of many scholars ranging from biologists [8,9], mathematicians [10,11], physicists [12–14], even to economists [15,16].

At present, the role of indirect reciprocity has been probed in detail along two key pathways. On one hand, theoretical analysis and numerical simulations based on computing skills are adopted to study how the indirect reciprocity or reputation influences the individual decision confronting strategy selection and the evolution of cooperation [17,18]. In particular, based on the indirect reciprocity, Nowak and Sigmund [6] seminally presented a novel framework of image scoring to measure the individual reputation, where the focal player will decide whether to cooperate or donate according to his opponent's score, and it was clearly stated that the emergence of indirect reciprocity plays a decisive role in the evolution of cooperation. Afterwards, several theoretical works indicate that the image scoring mechanism is not an evolutionarily stable strategy, and justifying the defection can provide the potential routes to stabilize the cooperation and the leading eight rules of social norms can maintain the cooperation by the indirect reciprocity [19–21]. On the other hand, extensive experiments based on the laboratory and online social networks are also used to identify the impact of reputation mechanism and evaluation pattern on the cooperation within the human society, and it is found that the reputation mechanism provides a viable means to promote the level of collective cooperation [22,23], and even becomes a universal currency for human interactions within the populations [24–26].

This review is motivated to provide a comprehensive analysis of the evolution of cooperation favored by the reciprocity and reputation mechanism from the perspective of system modeling at the interface of physics and evolutionary game theory. In what follows, we first provide a clear presentation of the existing reputation-related researches through indexing the most recent published papers in the Web of Science database. This part accounts for the basic synopsis and classification of current reputation-related works to readers, and highlights two kinds of methods [26] (*i.e.*, theoretical modeling and real-world experiments) of reputation-related researches under the framework of evolutionary game theory. Since the modeling-based analysis is one of the most effective means for us to reveal the underlying evolution of cooperation during the process of conflict and interactions, this review then surveys the most frequently-used game models in the evolution of cooperation. After that, we will present the results on the theoretical modeling and numerical simulations in detail, which include the first-order, second-order and higher-order models used in the reputation evaluation. Thirdly, we will summarize the existing reciprocity and reputation-related evidences based on the real-world experiments, which are often adopted in the behavior economics and help to understand the decision motivation when confronting the strategy choice. Finally, we further provide some concluding remarks and point out some promising problems in this field, which aid in comprehending the role of reciprocity and reputation in the persistence and emergence of collective cooperation.

The rest of this review is organized as follows. Some basic concepts, key mechanisms and significant game models in the area of evolutionary game theory are firstly introduced in the following subsections. After that, Sec. 2 will describe the recent progresses in the theoretical modeling and simulations of the evolutionary cooperation based on the reciprocity and reputation in detail. Then, we provide some experimental evidences on the individual behavior decision during the game playing in the recent years in Sec. 3. Finally, some concluding remarks and illuminating outlooks will be summarized in Sec. 4.

1.1. Some basic concepts in evolutionary game theory

The theory of games can be considered as a new branch of modern mathematics and also a branch of operation researches, which aims to optimize the strategy setup and maximize the individual payoff when confronting the interaction or conflict between two or more agents. Among them, von Neumann proved the basic principle of games concerning two players in 1928, which declared that game theory was officially founded. In 1944, Von Neumann and Morgenstern wrote the seminal book named as *The Theory of Games and Economic Behavior* [27], which further generalized the 2-player game into the n-player game, and then systematically applied the game theory into the field of economics and laid the foundation and theoretical system of this discipline. In particular, the American mathematician John Nash [28] utilized the fixed point theorem to prove the existence of equilibrium points (*i.e.*, Nash equilibria), which provided a persuasive framework for the development of game theory. Afterwards, the game theory has been applied into many other areas such as politics, international relationship, computer science, engineering science and even biology.

Among them, the Nash equilibrium (NE) is a very important concept in the field of classical game theory, in which it is often supposed that any player owns the perfect rationality and recognizes this to be the common knowledge for all agents. During the process of gaming, any rational player will not deviate from the NE since he cannot enhance his payoff or fitness by means of unilaterally varying his own strategy, that is, the strategy under the equilibrium state is a strictly dominated one. At present, the concept of NE has become the fundamental starting point for us to understand the individual game behaviors under the circumstances with the static and perfect information, which has been further extended into the more complex scenarios under the dynamic or imperfect information.

It should be particularly noted that the evolutionary game theory (EGT) is an emerging field [29,30], where we often add some concepts (such as the strategy, player, payoff and so on) in game theory into the framework of biological dynamic evolution. Here, there exist a population of players or agents who hold their own strategy, and then they interact so as to earn payoffs. After that, the payoff is translated into the individual fitness to aid the strategy choice in the next game round, and hence the fraction of strategies within the population will vary over time accordingly. Thus, compared with the traditional game theory, it pays more attention to the strategy changes in the dynamic process of individual and ethnic evolution. Evolutionary game theory can successfully explain and complement the mutually beneficial behavior in Darwinian evolutionary theory. Economists, sociologists, anthropologists and even philosophers have gradually recognized the importance of evolutionary game theory and considered it as a powerful tool to perform the related studies.

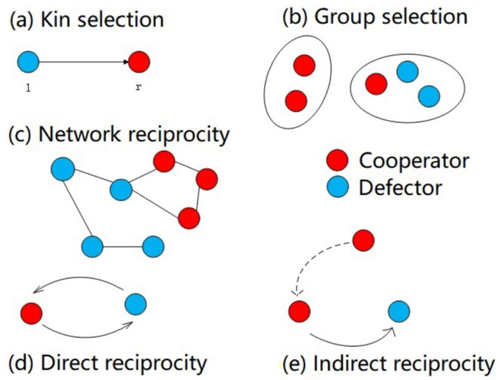

Fig. 1. Key mechanisms to favor the evolution of cooperation. (a) Kin selection emerges when the genetic relatedness exists between two individuals. (b) Group selection occurs provided that the competition happens between groups and between individuals. (c) Spatial or network reciprocity means the population structure to form the cooperative clusters. (d) Direct reciprocity applies when the repeated interaction takes place within the acquaintances, that is, the current action will influence what your parter will do in the future. (e) Indirect reciprocity is related with the individual reputation, that is, the current action relies on how you play in the previous round. Reproduced from [5].

Correspondingly, a significant notion in EGT is the evolutionarily stable strategy (ESS) firstly proposed by Smith and Price [31], which greatly generalizes the Darwinian theory of survival of the fittest and means that, if most of members within a population adopt it, there is no "mutant" strategy that would give higher reproductive fitness in the upcoming interactions, and thus the mutant strategy can not invade the population. That is, under the pressure of natural selection, the mutants can only have two choices: one is that they change their strategy into the ESS; the other is that they quit and disappear from the population. The ESS determines the means of cooperation or competition among individuals when they confront various resources, such as food, habitats or spouses and so on. Meanwhile, the ESS just defines the evolutionary stability of the population and it cannot characterize the dynamic evolutionary process to arrive at the stationary state [32,33]. In addition, the ESS is only a static concept describing the local attraction of systems [34], and it meets with the difficulty once several key assumptions are not satisfied: 1) the single population just takes one pure strategy; 2) the population size is infinite; 3) the mutant factors are not continuous or overlapped. Afterwards, for further dealing with these problems or assumptions, many scholars try to improve the definitions or conditions of ESS [35–37].

1.2. Several key mechanisms to support the cooperation

In the social dilemma, one challenging issue is that the rational player should adopt the defection strategy, which is often an NE one, to maximize the personal payoff, while the NE-dominant strategy for an individual is not necessarily the optimal one for the whole population, and thus the so-called social dilemma emerges although the defection may be very popular. However, the emergence of the collective cooperation has often arisen within the society of animals and human beings. Thus, as mentioned in [1,4], how to understand the universal phenomenon of cooperation has become a well-known scientific puzzle in the interdisciplinary area, which aroused the extensive interests of researchers from physics, biology, computer science and even humanity and social science.

Based on EGT and related progresses from multi-disciplinary perspectives, several common mechanisms have been summarized in Ref. [5] as the key rules to promote the evolution of cooperation, which include the kin selection, group selection, spatial or network reciprocity, direct and indirect reciprocity, as illustratively shown in Fig. 1. In addition, two or more schemes can be combined to further foster the emergence of altruistic behaviors between agents.

Among them, kin selection could be the first rule identified to facilitate the evolution of cooperation since we are often willing to help those related with our genes, such as parents, brothers, sisters or children and so on. At present, most of researches discussed the kin selection based on the notion of inclusive fitness [38], which is a specific measure to characterize the individual adaptation level to the new evolutionary environments. Generally, the individual fitness can be calculated as a sum of additive payoffs or factors obtained by a series of actions, but recently Nowak et al. [39] have tried to propose a more general mathematical method to formally describe the evolutionary dynamics of inclusive fitness. However, the traditional inclusive fitness usually avoids being a universal concept, and thus the corresponding proponents questioned these related mathematical analyses and results [40,41]. Anyway, a clearer comprehension of kin selection is necessary since the consensus on the inclusive fitness is still difficult to be reached at present.

Direct or indirect reciprocity are two key altruistic mechanisms in support for the evolution of cooperation. Direct reciprocity relies on the repeated interactions between the same pair of players, and hence they can conditionally make the strategy choice according to the previous game outcomes [42]. It should be noted that the cooperation could be continuously fostered if the probability for two players to interact in the next round is high enough. For examples, tit-for-tat (TFT) [43], Generous TFT (GTFT) [44] and WSLS(win-stay, lose-shift) [45] are three typical mechanisms characterized as the direct reciprocity. In the TFT [43], all players initially adopt the cooperating action, and then each player will take the action that his opponent has adopted at the previous round, as the current action at this game round. For the GTFT mechanism [44], each player cooperates on the first move, and then continues to cooperate as long as the other player does; If the other player defects, then the generous TFT player will still cooperate on the next move, but he will defect once his opponent defects for two continuous rounds. Regarding the WSLS [45], it is assumed that each player will keep the current action (cooperation or defection) if he can win the game, or else he will switch to the opposite action (defection or cooperation). Up to now, these three mechanisms are still successful ones in the experiments for the repeated prisoner's dilemma games.

However, indirect reciprocity does not require the same pair of opponents to repeatedly play the game, and it works only if the interaction between any two players within a specified population can be observed by a third party, whereby the information on these encounters can be spread and the reputation of the participants can be built [6,7]. Then, individuals will play the conditional strategy based on these available information. Thus, how to evaluate the individual action in the current game round and what kind of action will be adopted in the next game round are crucial to the success of indirect reciprocity [46], and the former issue is addressed by the social norm [21], while the latter one is determined by the action rule [47]. The indirect reciprocity could cultivate the cooperation provided that the information on individual reputations can be fully known to the interacting opponents.

Group selection [48] (also termed as multilevel selection) arises if the competition exists among individuals not only within one group, but also between more groups. That is, one defector may dominate the population of cooperators, but a group of defectors may be defeated by other groups of cooperators. As pointed out in [49], the group selection may favor the evolution of cooperation only if the ratio of cost-to-benefit for the donation game is larger than the specific threshold, which is determined by the maximum group size and the number of groups within the population.

Spatial [50] or network [51] reciprocity provides a brand new framework to foster the cooperation without further taking the strategic complexity into account. Under this framework, the population is not well-mixed, but rather structured, which means that each player can only interact with his nearest neighbors and accumulate the corresponding payoffs. Since the interaction neighborhood is confined, it is possible for cooperators to create the cooperative clusters to resist the invasion of defectors within the population, that is, the clustering effect leads to the individual assortment so that cooperators have a higher chance to interact with each other. Meanwhile, the population structure may take on a homogeneous (*e.g.*, regular lattice) or heterogeneous (*e.g.*, scale-free) topology, which determines the number and distribution of player's opponents, may greatly affect the evolutionary outcome for the cooperation. Recently, the evolutionary game on complex topology or networks, which may be static [8,12], dynamic [9,52] or multi-layered [13,53], has become an active topic and made a huge progress in this field.

Although the aforementioned rules are often investigated in separation from one specific angle, it will be a promising direction in the future provided that we can combine two or more rules to explore the evolution of cooperation. As an example, even in the modern society, many human individuals still need to repeat the interactions during our daily studies, lives and jobs; but we also frequently encounter with strangers and perform the one-time deal. Therefore, it is necessary and significant for us to consider the direct or indirect reciprocity under the framework of spatial or network structures [54,55]. Furthermore, Li et al. [56] recently proposes a novel long memory strategy named after cumulative reciprocity (CURE), where cumulative agents discriminate the exploitative opponent by roughly counting the imbalance of cooperation or "unfairness" across all their previous interactions and maintain cooperation as long as this cumulative unfairness does not exceed a given threshold of tolerance, and it is demonstrated numerically and analytically that CURE enforces fair outcome and sustains cooperation in noisy environments, even under hostile ones.

1.3. Game models in the collective cooperation

In this sub-section, we will briefly introduce the most commonly-used game models in the field of EGT, which include the 2-player game such as prisoner's dilemma game, snowdrift game, stag-hunt game and harmony game, the public goods game among multiple players, the donation game, the trust game, the ultimatum game and so on. We will illustrate the basic properties and main parameters of these models in the following paragraphs.

1.3.1. Pairwise games

In the evolutionary game theory, the simplest game between a pair of players is the 2-strategy game and can be characterized through the following payoff matrix,

$$\begin{array}{c} \\ C \\ D \end{array} \begin{array}{c} \begin{array}{cc} C & \quad D \end{array} \\ \begin{pmatrix} R, R & S, T \\ T, S & P, P \end{pmatrix} \end{array}, \tag{1}$$

where C and D denote the two distinct strategies: Cooperation (C) and Defection (D). After an encounter, the strategists will simultaneously make the strategy choice and obtain the corresponding payoffs, and the first element within each matrix entry denotes the payoff obtained by the row strategist, while the second one means the payoff acquired by the column strategist. Among them, two players will reap the benefits of reward (R) or punishment (P) if they choose to cooperate or defect at the same time. Nevertheless, if they select different strategies, the defective player will get the temptation (T) to defect while the cooperating strategist will only earn the sucker's (S) payoff. Considering the symmetry of game interactions, without loss of generality, we can just take the payoff of one of players into account and the payoff of the row player will be recorded in the payoff matrix as follows,

$$\begin{array}{c} \\ C \\ D \end{array} \begin{array}{c} \begin{array}{cc} C & \quad D \end{array} \\ \begin{pmatrix} R & S \\ T & P \end{pmatrix} \end{array}, \tag{2}$$

where R, T, S and P have the same meanings as Eq. (1). In particular, the game will take on the cooperative dilemma provided that (i) $R > P$, that is, the payoff obtained for the simultaneous cooperation will be higher than that for the simultaneous defection, yet (ii) there exists an incentive to defect for any player, which is categorized into three different scenarios: 1) $T > R$; 2) $P > S$; 3) $T > S$, denoting the fact that defection is a dominant strategy when playing against a cooperator, a defector and the encounter between a cooperative strategist and a defective one, respectively. Thus, the cooperation is dilemmatic if at least one of aforementioned conditions are fulfilled, otherwise the cooperation is encouraged and there is no dilemma.

To be remarkably noted, the prisoner's dilemma (PD) arises if all three conditions are satisfied, *i.e.*, $T > R > P > S$, which means that PD becomes the most stringent cooperation dilemma. Thus, the defection will dominate the population in the PD game (PDG) and the full defection is the equilibrium point, and the specific mechanism needs to be added into the game to foster the evolution of cooperation. According to the payoff ranking, other types of pairwise games can be easily implemented here, such as snowdrift (SD) game requiring the ranking $T > R > S > P$, the stag-hunt (SH) game meaning the order $R > T > P > S$, the coordination or harmony (H) game meeting the constraint $R > T > S > P$ and so on. In order to fully depict the evolution of cooperation, we sometimes fix two elements in the payoff matrix to be $R = 1$ and $P = 0$ such that we can only vary the values of T and S to examine the cooperation behaviors. At this case, the corresponding payoff matrix can be described as follows,

$$\begin{array}{c} \\ C \\ D \end{array} \begin{array}{c} \begin{array}{cc} C & \quad D \end{array} \\ \begin{pmatrix} 1 & S \\ T & 0 \end{pmatrix} \end{array}, \tag{3}$$

where T and S are two tunable parameters to be adapted to characterize the different games. Among them, T varies from 0 to 2, and S is changed from -1 to 1. Starting from this, several typical pairwise games are illustrated in Fig. 2, where four-quadrant areas represent the above-mentioned pairwise games and the red line between the first and fourth quadrant stands for the weak prisoner's dilemma game, which has been widely investigated in previous researches [50,57].

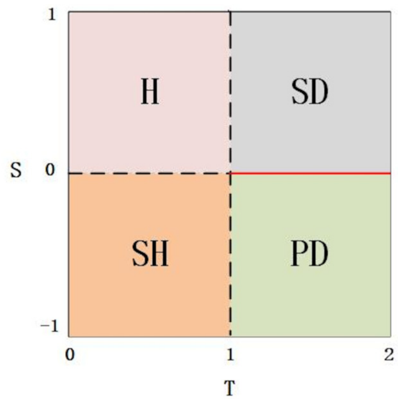

Fig. 2. Typical pairwise game models. Here, we fix the payoff for mutual cooperation and defection as $R = 1$ and $P = 0$. As T is varied from 0 to 2 and S increases from -1 to 1, four-quadrant areas are used to represent four typical pairwise games: prisoner's dilemma game (the fourth quadrant: $1 < T \leq 2$ and $-1 \leq S < 0$), stag-hunt game (the third quadrant: $0 \leq T < 1$ and $-1 \leq S < 0$), harmony game (the second quadrant: $0 \leq T < 1$ and $0 < S \leq 1$) and snowdrift game (the first quadrant: $1 < T \leq 2$ and $0 < S \leq 1$. In particular, the red line between the first and fourth quadrant denotes the weak PDG.

1.3.2. n-person game and public goods game

The pairwise games are often played by two agents, and can be further generalized to the scenario involving more than two persons (*i.e.*, n-person game or n-player game). P_i and Q_i are used to denote the payoffs of cooperators and defectors, respectively, where the population consists of i cooperators and $n - i$ defectors. It is obvious that the cooperation dilemma exists if two similar conditions hold as follows: (i) the fully cooperative population has a higher payoff than the fully defective group, that is, $P_n > Q_0$, yet (ii) the temptation or incentive to defect exists. Likewise, the temptation usually contains two different forms: 1) $P_i < Q_i$ for $i = 1, 2, ..., n - 1$; and 2) $P_i < Q_{i-1}$ for $i = 1, 2, ..., n$. The former condition means that the defective individual has an advantage over the cooperating agent within the well-mixing population, while the latter indicates that independently switching from cooperation to non-cooperation can result in the payoff increase of defectors. If some of the aforementioned conditions cannot be reached, the cooperation dilemma will be relaxed, to some extent, and the persistence of cooperation may emerge even without help of any specific mechanism, such as the volunteer's dilemma [58,59]. However, if all of these conditions hold, this n-person game is equivalent to the prisoner's dilemma for two players and it is usually termed as the public goods game (PGG) [60,61].

The traditional definition for the public goods game is prescribed in this way. For each game round, a population of n players will independently make the decision at the same time on whether they make an investment into a common pool or not, and then we will multiply the total contribution by a synergy coefficient and then evenly distribute these benefits over all participants within this group. As an example, at some game round, there are n_C cooperators among n players, and it is assumed that each cooperator will contribute a fixed cost c to the pool and then the collected contribution will be multiplied by one coefficient r larger than 1.0, which is named as the synergy factor $r > 1.0$. Finally, the net payoff or benefit for each cooperator or defector can be expressed as follows,

$$\begin{cases} P_D = \dfrac{r * c * n_C}{n} \\ P_C = P_D - c, \end{cases} \tag{4}$$

where P_C and P_D denote the net payoff of a cooperator or defector, respectively. It is obvious that there is an incentive to defect since P_D is always larger than P_C, while the defector's payoff P_D tends to be zero if all players do not invest any contribution into the common pool. Henceforth, as mentioned above, the dilemma arises and even the tragedy of commons emerges [60].

1.3.3. Donation game

In order to explore the impact of indirect reciprocity on the evolution of cooperation, the interaction between any pair of players can be described as a donation game. First of all, a pair of players will be chosen simultaneously at each game round, in which one player is selected as a donor while the other one is called the recipient. Then, the donor will decide whether he will make the donation to the recipient or not, which is determined by the specific rule. If he donates, the donor will pay the cost c and the recipient will obtain the benefit b, in where $b > c$ is hypothesized to highlight the reciprocity since the net benefit $b - c > 0$ for two players); If not, the donor pays nothing and the recipient can only receive zero benefit. Although the donation does not give any direct benefit to donors, some actors are still willing to make the donation so as to accumulate a good image within the population and hope to get the help from others in the future. Thus, the donation game is often chosen as the standard game model to explore the role of indirect reciprocity.

1.3.4. Trust game

The trust game (TG) originates from the economics [62,63], and thus it is also termed as the investment game. In essence, the trust game is a sequential game since the truster or investor must decide at first whether he will believe the trustee. After the truster's positive decision, the trustee needs to determine whether he is trustworthy or not, that is, he will make up his mind whether he will send the partial benefit back to the truster or not. Traditionally, there are two types of trust games in economic experiments, known as TG1 and TG2, which are both nonzero-sum games. In the version of TG1, if the truster does not trust the trustee, their payoffs are both 5 dollars. If the truster does, the trustee will decide whether he will be trustworthy or not. Provided that he cooperates (*i.e.*, being trustworthy), the trustee and truster will receive \$15 and \$10, respectively. Once he decides not to cooperate (*i.e.*, being untrustworthy), the trustee will keep the total benefit \$25 and the truster gets nothing.

In the version of TG2, both players are endowed with an initial fund \$12. Then, the truster first decides to how much money, say $X \in [0, 12]$ will be transferred to the trustee. The amount of money sent to trustee will be tripled, and then he will decide to send some amount of money, say Y, back to the truster. Finally, the net benefit for the truster will be $12 - X + Y$, while the trustee's balance will become $12 + 3X - Y$. Taking together, a strict social dilemma does not exist in TG1 or TG2 since only if the truster trusts the trustee, the total benefit for both players is \$25 in TG1 and $24 + 2X$ in TG2, irrespective of the final choice of the trustee.

As a further step, the 2-player trust game is generalized to the n-player one in recent years, which has been investigated within the well-mixing and networked populations. Abbass et al. [63] explored the evolution of trust within the well-mixing population and found that the untrustworthy behaviors will become the dominant ones in the whole population even if there are only a few untrustworthy agents introduced. After that, beyond the well-mixing assumption, Chica et al. [64] investigated the evolution of trust among the networked population, and demonstrated that the trust and credibility can be elevated into a higher level when the N-player game is played on heterogeneous social networks.

1.3.5. Ultimatum game

The ultimatum game is often used by two players to make an agreement on how to distribute a sum of money between them. In this game, one player is stochastically selected to make a proposal on the distribution of this money, and the other one can only accept or reject this proposal. Here, the former one is often called the proposer, while the latter is named as the responder. If the responder accepts the offer, they can share this sum of money based on the proposer's scheme. Nevertheless, if the responder rejects it, both parties will not obtain any amount of money. In the single shot game, the action for any rational responder should accept it if the proposer provides any positive offer to him, but correspondingly the proposer should offer the money as low as possible [30]. However, in most human experiments based on the laboratory, most proposers are willing to share 40% to 50% of the total amount with their partners, but the responders usually reject the proposal if the shared amount is lower than 30%, and this human behavior has been reproduced under the framework of evolutionary game theory [65–67].

1.3.6. Other models

In addition to these commonly used game models, there also exist some other models to characterize the competitions and conflicts between stake holders. For example, the hawk-dove game, which is often applied into the biological and political sciences, denotes the scenarios where animals or individuals almost have the identical properties except their aggressiveness when they interact with other ones. This behavior trait can only exhibit two types which are called Hawk (aggressive) and Dove (cooperative), respectively. Whenever two individuals meet together for the same resources, they will evenly share them if both individuals are doves, but they will fiercely fight otherwise, and then one side be seriously injured while the other takes all the resources if they are both hawks; Meanwhile, they have different behavior traits, the hawk will obtain all these resources without fighting, and the dove escapes and gets nothing. In fact, the hawk-dove game is mathematically equivalent to the pairwise snowdrift game, and also termed as the Chicken game in economics.

Another typical n-player game is the minority game, where n is odd and all agents need to make the choice between possible options at the same time. Here, the successful action is defined to be the one adopted by the minority, and the related situations can be often observed in the financial markets, where agents need to choose between buying and selling operations that determine the pricing tendency of products or assets. This game model is originally proposed by Arthur [68], and then investigated by Challet and Zhang [69,70] under the evolutionary game-based framework.

The models mentioned above own only two pure strategies, the game with multiple pure strategies is also studied in the field of biology and ecology. Among them, the rock-scissors-paper game is a typical 2-person and 3-strategy zero-sum game, where each strategy (rock, scissors or paper) wins over the other one but fails when confronting the third strategy, that is, rock defeats scissors and then defeats paper, but finally paper defeats rock and finally the cyclic dominance can be exhibited [71,72]. This kind of game with multiple pure strategies can be further extended in the future, and several recent generalizations have been coined and popularly played over the world [73].

2. Theoretical modeling and simulations

In this section, we will review the recent advances in the field of theoretical modeling and simulations on the reciprocity and reputation dynamics, and in detail introduce the models related with the reputation building and evaluation.

2.1. Reciprocity and reputation dynamics

As declared in the introduction, the reciprocity is the key mechanisms to foster the evolution of cooperation. Among them, the direct reciprocity requires the repeated interaction between two players, while the indirect reciprocity does not demand the players to repeatedly interact with each other and the evolution of cooperation is built on the individual reputation within the population. Moreover, beyond the well-mixing topology, the network reciprocity limits the interacting opponents within the nearest neighbors, and then renders the cooperators to hold the possibility to organize into cooperative clusters so that they are not invaded by the defectors, which thus provides a new framework to favor the evolution of cooperation.

2.1.1. Definitions of reciprocity

On the one hand, it is obvious that direct reciprocity can facilitate the emergence of altruistic acts since the mutual cooperation can create the net positive benefits between the same pair of players. Taking the simplest donation game as an example, the donor confers a benefit b to the recipient at a cost c when two players encounter, without loss of generality, b is assumed to be greater than c and then both players will experience a net gain $(b - c) > 0$ if either of them makes the donation to the other one. Thus, this kind of game can be viewed as a particular instance of the famous PDG, without any doubt, the simultaneous cooperation leads to the better outcomes than the mutual defection as $(b - c) > 0$. Nevertheless, a unilateral defecting recipient will earn the highest payoff b, and the exploited donor will obtain the negative benefit $(-c)$ by paying the cost of cooperation. Henceforth, the defection is the optimal strategy for one single round, but the scenario will change if the repeated interactions between the same pair of players have been allowed for multiple game rounds. The famous folk theorem [74] indicates that the cooperation can emerge for the repeated game by means of the so-called trigger strategy provided that the possibility for two agents to continuously play the game is sufficiently high in future rounds, that is, a rational player will not sacrifice the long-term benefit by only harvesting once during the period of multiple game rounds.

On the other hand, in the case of indirect reciprocity, any two players are prohibited to repeatedly interact with each other, that is, each player can participate in the game for many rounds, but never interact with the identical opponent twice. Accordingly, the defecting recipient can not be retaliated by the exploited donor, and then direct return between them is excluded. Another edition of indirect reciprocity allows two participants to play the game multiple times, but one player is always selected for the donor, the other always for the recipient, which renders the direct return impossible. Here, the explicit trigger strategy can still guarantee the Nash equilibrium for the cooperating action since no participants are willing to deviate it if all players adopt the triggering mechanism. However, from the perspective

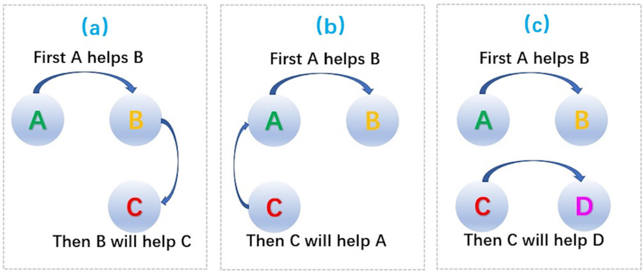

Fig. 3. Three different types of indirect reciprocity. (a) upstream reciprocity means that player *A* first helps another one *B*, and then player *B* will help the player *C*; (b) downstream reciprocity indicates that player *A* helps his partner *B*, which is observed by the third player *C*, and then *C* will help *A* in the future; (c) generalized reciprocity implies that player *A* helps *B* at first, which is rightly observed by player *C*, then player *C* is affected by this action and decides to help another player *D*. Reproduced from [7].

of strategic thinking, pursuing the payoff maximization is the individual target for the game, and why not defect if one participant can obtain the higher payoff by exploiting the opponent? Once the defection is experienced by an individual, then the defection is adopted and spread, but it may take many game rounds to find the original defector, which will hurt many innocents and cause a havoc. Clearly, any retaliation should aim at the original cheater rather than the whole game group, which requires more specific information to discern the origin of defection. That is, we need to design the more detailed mechanism or rule to ensure the persistence of cooperation between unrelated agents.

As the persuasive reciprocity takes places among agents without any genetic relatedness or direct benefit, deeply understanding the role of indirect reciprocity in the human or animal society is much more significant for us to explore the evolution of cooperation. Thus, without lacking the generality, we will mainly focus on the impact of indirect reciprocity on the evolution of cooperation in what follows.

Under the framework of EGT, the indirect reciprocity is often divided into three types: upstream, downstream and generalized reciprocity, which is shown in Fig. 3. Among them, upstream reciprocity [Fig. 3(a)] means that player *A* first helps another one *B*, then B experiences the benefit of reciprocity and thus decides to help the third party *C*. In downstream reciprocity [Fig. 3(b)], since player *A* helps his partner *B* at first, the third player *C* rightly observes this helping process and will help *A* in the upcoming rounds, that is, the altruistic act of player *A* in the previous round provides a good image and catalyzes the decision of *C* in later rounds. For the generalized reciprocity [Fig. 3(c)], player *A* helps *B* at first, which is rightly observed by player *C*, and then he will decide to help the fourth agent *D* in the following rounds. In particular, upstream reciprocity can only promote the emergence of cooperation when combined with direct or network reciprocity, but downstream and generalized reciprocity can separately enhance the emergence of cooperation.

Up to now, most researches related with indirect reciprocity mainly concentrate on the downstream reciprocity, which relies on the reputation building and evaluation, we will review the recent progresses in more detail in the following sections. However, there are also some fewer works to involve the upstream indirect reciprocity [79] or generalized reciprocity [80,81]. As an example, van Doorn and Taborsky [82] indicated that the so-called generalized reciprocity or upstream indirect reciprocity can be viewed as a minimal mechanism to favor the evolution of cooperation. Remarkably, they further discussed the impact of heterogeneous interaction patterns between individuals on the generalized reciprocity, and found that the average connectivity of social networks can greatly influence the spread of altruistic acts and sparse networks are more conducive to the clustering of cooperators, and especially emphasized that the community structure hidden the population can protect the altruists from being exploited. In fact, the spareness and communities [83] are two widespread traits of social interactions inside many real-world vertebrate biological systems including the fish, birds and even primates, and thus this finding is highly beneficial for us to understand the emergence of cooperation.

2.1.2. Reputation dynamics

As what mentioned before, the indirect reciprocity can favor the evolution of cooperation with the help of reputation dynamics. Among them, the key for the reputation dynamics to play the role involves whether it can effectively evaluate the individual goodness or badness during the strategy game, that is, how to construct the evaluation rule or model is the core of reputation dynamics. At present, the commonly used rules include the first-order, second-order

Table 1
The rules for various order reputation evaluations. According to the difference of information needed by the reputation evaluation, four typical rules are defined, which include the First-, Second-, Third- and Fourth-order ones, respectively. In addition, *Number* column indicates the number of all possible rules with the same order.

Evaluation rule	Definitions	Number	Typical examples	References
First-order	just consider the action of donor	4	Image scoring	[6]
Second-order	simultaneously consider the action of donor and the status of recipient	16	Stern judging Simple standing	[20,75,76]
Third-order	simultaneously consider the action and status of donor, and the status of recipient	256	The leading eight rules	[21,47]
Fourth-order	simultaneously consider the action and status of donor, and the action and status of recipient	65536	Kandori's rule	[77,78]

and even higher-order models, which are based on the image or action for a pair of players at the specific game round, and their main properties for various reputation dynamics are summarized in Table 1. In what follows, we will introduce the key advances for these reputation dynamics in the recent years.

2.2. First-order reputation models

In this subsection, we will first introduce the main characteristics of first-order reputation evaluation based on the well-mixed population; Then, we review the recent progresses of first-order reputation evaluation, where the reputation mechanism is embedded into the structured population.

2.2.1. Well-mixed population

The first-order rule is the simplest reputation model to judge the goodness or badness of players, which is just based on the individual action (that is, cooperation or defection) at the last game round, that is, the donor will be evaluated as being good if he cooperates, or being bad if he defects. In particular, based on the well-mixing population, Nowak and Sigmund [6] seminally proposed an image scoring mechanism to explore the role of indirect reciprocity in the evolution of cooperation. In this model, a pair of players are randomly picked up and then the one is assigned as a donor while the other one is viewed as a recipient. The donor can decide to help the recipient with a fixed cost (c) or not, and the recipient will receive a higher benefit b ($> c$) if the donor cooperates or both parties will receive nothing if the donor defects. Meanwhile, the image score s for every individual participating in the donation game is recorded and publicly made within the whole population. Then, after each pair of interactions, the image score of each donor will be decreased or increased by one unit if he defects or cooperates, while the recipient will keep the score unchanged. Regarding whether the donor will donate to the recipient for each encounter between a pair of players, Nowak and Sigmund designed one typical strategy, which is determined by one specific number k, and the donor can only decide to cooperate only if the recipient's image score is equal or higher than this number k. Based on the well-mixed topology, computer simulations and simplified theoretical analysis indicate that the indirect reciprocity can only take effect in the evolution of cooperation as follows: the donors have the opportunity to decide whether to make the donation to help another player with some cost c or not; for the donor, refusing to help can avoid the cost of cooperation and create the higher payoff in the short term, while in the long term, the helping act can accumulate the good image for donors and may therefore increase their opportunities to obtain the benefit as a recipient in the upcoming encounter. Furthermore, the discriminators who refuse to help the low-score players will pay a price by rendering their own scores to be reduced, which further creates the so-called social dilemma. Nevertheless, this type of altruistic punishment promotes the cooperation within the well-mixed population, which is also demonstrated to be plausible under other gaming scenarios including public goods game [84], ultimatum game [85] and trust game [86].

2.2.2. Structured population

As mentioned earlier, although the first-order model is very simple and direct, the promotion of cooperation is fairly obvious. Thus, it is interesting if we can further probe into the evolution of cooperation beyond the well-mixing topology. In fact, a variety of works explored the evolution of cooperation in static spatial or complex networks, where numerical simulations verified that heterogeneous scale-free networks can promote the cooperation to a higher level [6,7]. Also, some previous works discussed the evolution of cooperation on adaptive networks, where the links could be broken up and reconnected, which can characterize the interactions between individuals more realistically [87–89]. Although reputation is inevitably involved within the human relationship, reputation-based games in adaptive social networks receive the little concern. To this end, Fu et al. [90] proposed a novel prisoner's dilemma game model by considering the reputation effect, in which the links between nodes can be rewired so as to avoid the averse partner with lower reputation within the nearest neighborhood. In this model, they hypothesized that any player can obtain the reputation of his nearest and next-nearest neighbors. Meanwhile, it is also assumed that all participants of PDG can change their strategies by mimicking their nearest neighbors, or switching their partners to connect another player. In particular, the partner switching process can be defined in the following two ways: on the one hand, with the probability p, the focal player cuts down the link from one of nearest neighbors with the lowest reputation to one next-nearest neighbor, who has the highest reputation and is selected from his neighbors' neighbors; on the other hand, with the complementary probability $(1-p)$, the focal one reconnects the link from the lowest-reputation neighbor to a partner randomly chosen from the whole population, which excludes their nearest and next-nearest neighbors. Through extensive numerical simulations, it is demonstrated that the stable and persistent cooperation can be accomplished in the networked PDG with the help of reputation-based partner switching process. In addition, it is also found that the denser networks of agents and the higher temptation to defect often lead to the more partner switchings, which is possible for players to keep the high reputation and then likely for the population to arrive at a higher level of cooperation. However, when the reputation is not considered in the partner switching process, the cooperation is usually less favored than the scenarios with reputation mechanism. All these results point out the pronounced role of reputation (*i.e.*, indirect reciprocity) in the promotion of cooperation when individuals have a chance to dynamically adjust his partners, that is, the reputation or indirect reciprocity provides a feasible means to foster the cooperation.

However, it is often a little more expensive for us to obtain the accurate information about the individual reputation status, and then it is difficult to endow each individual with a completely cognitive power due to the cost or error of information transmission. Henceforth, it is significant to further explore the impact of incomplete reputation or indirect reciprocity information on the collective cooperation within the structured population. In Ref. [54], Wang et al. introduced a reputation inferring approach into the choice of potential strategy imitators, and found that this novel mechanism can powerfully promote the level of cooperation on multiple foundational networks and different evolutionary game models. In this work, it is assumed that each player can have the identical reputation inferring ability p during the game, which means that the focal agent deterministically selects the neighbor of the highest reputation with the probability p or randomly chooses one neighbor with the probability $(1-p)$ to perform the strategy update. Firstly, each player will calculate the game payoff by playing the game with the nearest neighbors according to the model of social dilemma, which includes the PDG and SD game (SDG) models. Then, the focal player will update his or her current strategy based on the evolutionary rule, that is, choose one neighbor to learn on the basis of reputation inferring. Here, all players have the same reputation 1 at the initial step and then perform the reputation update at the following steps according to the first-order assessment, which implies that the cooperation leads to the increment of individual reputation, while the defection makes the reputation unchanged. Finally, the focal player tries to imitate the strategy of chosen neighbor with the Fermi-like update dynamics. In terms of large quantities of numerical simulations, the current inferring reputation can greatly enhance the level of cooperation within the networked PDG or SDG population. Taking an example, in the weak PDG model (*i.e.*, $T=b$, $R=1$, $P=S=0$), the density of cooperators (ρ_C) at the stationary state can be substantially elevated when the inferring reputation mechanism (IRM) is added into the networked population, whether the topology is the regular lattice, small world or random regular graph, as shown in Fig. 4. Furthermore, the proposed limited reputation is also incorporated into the snowdrift game and it is also found that the stationary cooperation level under the IRM will be enhanced a little higher when compared to the traditional SDG model as pointed out in [54].

As a further step, based on the first-order image scoring rule, Chen et al. [91] proposed an adaptive assortment mechanism to explore the evolution of cooperation for the spatial public goods game, and they found that this kind of assortment will substantially promote the public cooperation level at the steady state. In this study, the whole population is divided into two classes according to the specified reputation threshold: influential and non-influential agents, where the influential players will be assumed to own the higher strategy spreading ability. Initially, each player will be assigned as the cooperative or defective ones with the equal probability, and also be endowed with a specific reputation uniformly distributed within an interval $[1, R_{max}]$. After that, each player will accumulate their payoffs according to the PGG model, and then perform the strategy update with the following Ferm-like dynamics,

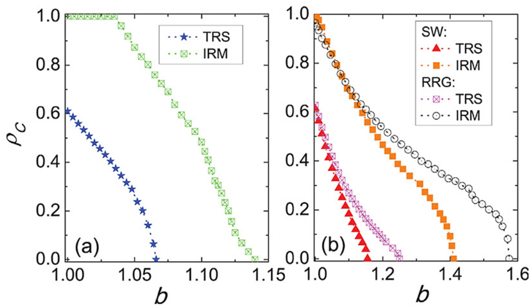

Fig. 4. Stationary density of cooperators (ρ_C) as a function of the temptation to defect (b) in the weak PDG model on different networks: (a) Regular lattice; (b) Small world (SW) networks with the rewiring probability 0.1 and Random Regular Graph (RRG). It can be observed that, in comparison with the results of traditionally spatial version (TRS), the proposed inferring reputation mechanism (IRM) can foster cooperators and even the cooperation can prevail at a larger value of b. Related parameters are set to be $L = 300$ (Lattice size), $K = 0.1$ (amplitude of noise), $MCS = 2 \times 10^5$ (MCS time steps) and $p = 0.5$ (reputation inferring probability). Reproduced from [54].

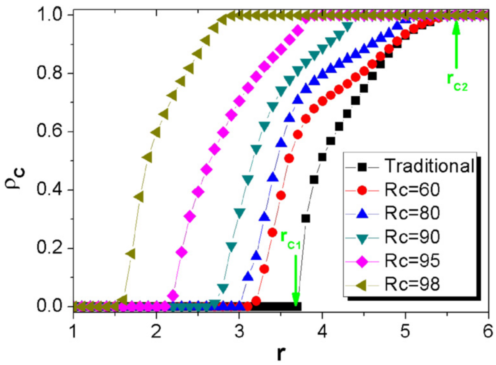

Fig. 5. Stationary density of cooperators (ρ_C) as a function of the synergy factor (r) in the PGG model on the spatially regular lattices. It is shown that the proposed reputation assortment can greatly enhance the cooperation level of PGG when compared to the traditional PGG. Within the moderate ranges of r, the more reputation assortment threshold (R_c), the large the value of ρ_C. Related parameters are set to be $w_y = 0.001$ (multiplicative imitation coefficient of non-influential players), $L = 200$ (Lattice size), $R_{max} = 100$ (Maximum value of reputation), $MCS = 5 \times 10^4$ (MCS time steps) and $K = 0.5$ (amplitude of noise). Reproduced from [91].

$$Prob(s_x \leftarrow s_y) = w_y \frac{1}{1 + e^{\frac{(\Pi_x - \Pi_y)}{K}}} \tag{5}$$

where Π_x and Π_y represent the cumulative payoffs of player x and y, and K means the strategy selection strength, while w_y denotes the multiplicative coefficient determined by the reputation value R_y of player y. A specific threshold R_{th} is used to judge whether player y is influential or non-influential, and player y is influential if $R_y \geq R_{th}$, or else player y is non-influential. Henceforth, they set w_y to be 1.0 for the influential player y, but to be $w \in (0, 1)$ for the non-influential player y. At the same time, each player will increase or decrease their reputation by one unit if he cooperates or defects at this game round, and also $R_x \in [1, R_{max}]$ is always kept in this model. Lots of numerical simulations indicate that the level of public cooperation will be largely elevated, and typical results are depicted in Fig. 5. It can be observed that the introduction of reputation mechanism will enhance the density of cooperators within the population at the stationary state under the identical synergy factor r, to be specific, the minimum r leading to the appearance of cooperators or full cooperation will decrease little by little as the reputation threshold increases. In order to further scrutinize the role of adaptive reputation assortment in the spatial PGG model, interacting patterns between two different strategies on the lattice can be illustrated as Fig. 6, where panel (a) denotes the distribution of cooperators (blue) and defectors (red) at the initial time step ($MCS = 0$) and there does not present any characteristic clustering patterns, the following panels [from panel (b) to (f)] all evolve from panel (a) and the cooperative clusters can be effectively exhibited here as the reputation threshold R_{th} increases. In particular, many high-reputation cooperators are often organized into giant clusters surrounded by a few low reputation cooperators so that they can ensure the survival of cooperators by creating the hierarchical structure from cooperators to defectors; while for defectors, the low

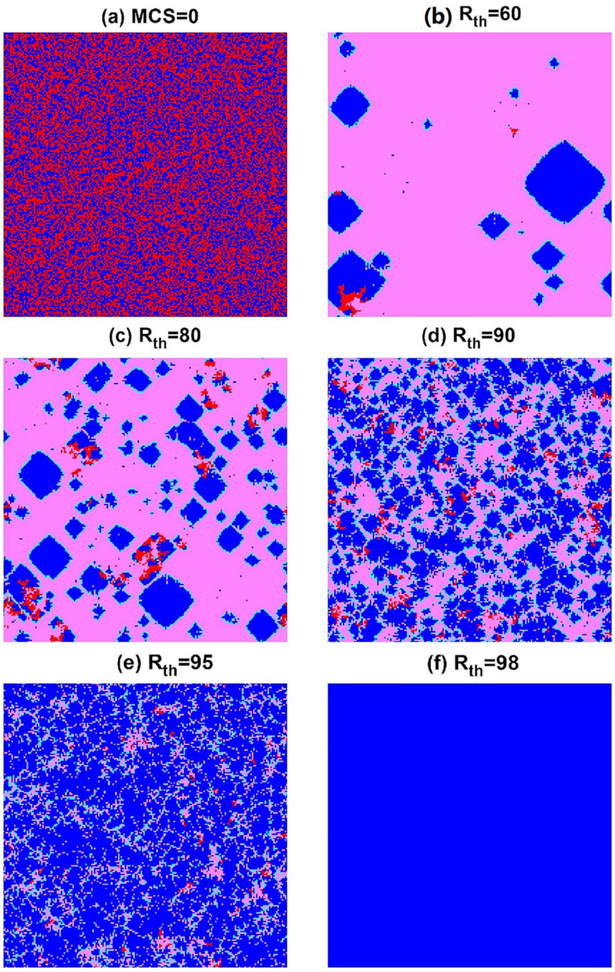

Fig. 6. Characteristic snapshots between cooperators and defectors with different values of reputation at (a) $MCS = 0$ and (b-f) $MCS = 5 \times 10^4$ on the spatially regular lattices. In panel (a), all players are randomly distributed onto the lattice, where red dots are defectors and blue dots denote cooperators; Meanwhile, each one takes a random reputation value from the interval [1, 100]. From panel (b) to (f), as R_{th} increases from 60 to 98, snapshots of cooperators and defectors at the stationary state are pictured, where red ($R \geq R_C$) and pink ($R < R_C$) dots denote defectors, while blue ($R \geq R_C$) and cyan ($R < R_C$) dots represent cooperators. Among them, the synergy factor of PGG is set to be $r = 3.3$ and other model parameters are identical with those in Fig. 5. Reproduced from [91].

reputation agents can dominate the population and develop into a very giant cluster, but cannot devour all cooperators although some defective agents have penetrated into the cooperative clusters. As R_{th} increases, the size of cooperative clusters will also become larger and larger, and even fully dominate the whole population when R_{th} is equal to 98, as displayed in Fig. 6.

Very recently, we further introduce the first-order reputation dynamics into the trust game modeling inside the structured population, and propose a novel trust game model with an adaptive reputation adjustment [92], in which investors, trustworthy trustees and untrustworthy trustees compete for assets subject to a third-party evaluation system that oversees and modifies each individual reputation. When compared to the standard trust game in heterogeneous social networks [64], the introduction of reputation further boosts the proliferation of trust between individuals, and the trust level can be maintained at a high level even if the social dilemma is quite hard in the trust game. As illustrated in Fig. 7, we plot the average number of final agents and global wealth as a function of the ratio of temptation to defect r_{UT} for different values of the degree of rationality α. It can be clearly seen that $\alpha = 0$ leads to the completely irrational trust between individuals and then creates the dramatic drop for the investors, trustworthy trustees and global wealth when the temptation to defect is augmented, which is almost same as the standard case in [64]. As α increases, the introduction of reputation effect substantially promotes the evolution of trust, where the mutual benefit between

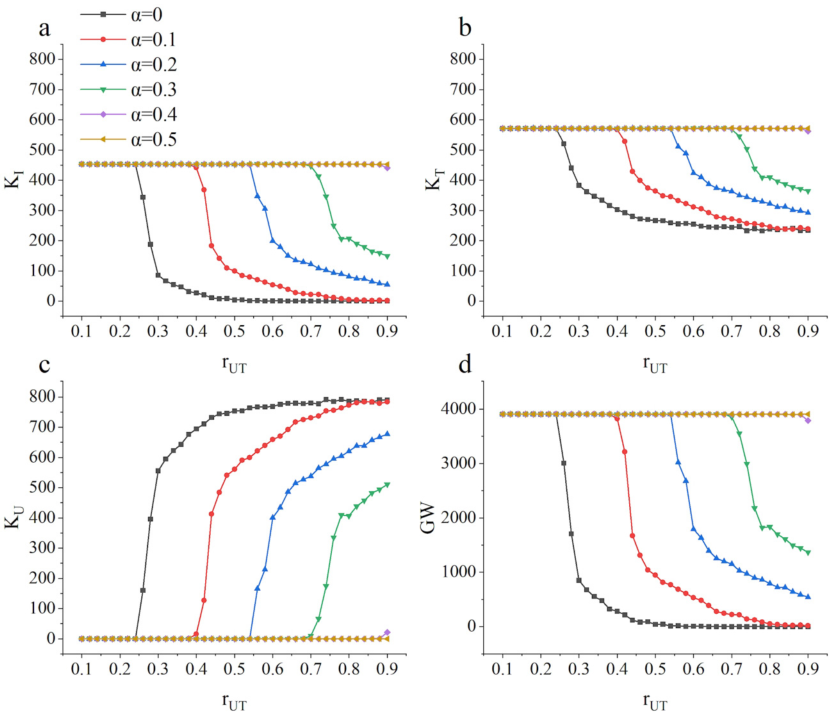

Fig. 7. The evolution of trust behaviors for different values of the degree of rationality α on a scale-free network with the average degree 6. From panel (a) to (d), the average number of final agents (investors K_I, trustworthy trustees K_T, untrustworthy trustees K_U) and global wealth (GW) are plotted as a function of the temptation to defect (r_{UT}) here. It can be clearly shown that, when compared to the traditional trust game $(\alpha = 0)$, and trust level [panels (a), (b) and (d)] is greatly increased as α increases from 0.1 to 0.5, but the untrustworthy behavior [panel (c)] is largely inhibited. For each value of α, the ratio of temptation to defect r_{UT} increases from 0.1 to 0.9 with the step size 0.02. Other model parameters include the reputation threshold $R_C = 3.0$, trustworthy gaining factor $R_T = 6$, while the proportion of various types of agents Pro_I, Pro_T and Pro_U are initialized to be 0.3, 0.3 and 0.4, respectively. Reproduced from [92].

investors and trustworthy trustees becomes more stable and persistent, and then renders that the trust and cooperation can be kept even under a harder social dilemma. Meanwhile, the ranges of untrustworthy trustees are further squeezed in the improved trust game model. Afterwards, we take the cost of reputation building into account and explore how the heterogeneous reputation cost for each individual affects the evolution of trust and cooperation [93], and it is again revealed that trust and trustworthiness could still emerge and persist even if reputation building is costly.

2.3. *Higher-order reputation models*

Under some realistic cases, first-order evaluation is not enough to perform the objective assessment, and thus higher-order rules are necessary. Here, we will first introduce the higher-order reputation rules up to the fourth-order within the well-mixed population. Then, higher-order reputation is added into the structured population, and we will review the related works in detail.

2.3.1. *Well-mixed population*

The first-order rule points out the impact of reputation dynamics on the evolution of cooperation, but what really matters is how to define the goodness or badness for a player's action. As cooperating with a bad player can elevate, or defecting with a good one can reduce the image score of the current mover, the player's kind action can be easily exploited by free riders, which may lead to the demise of cooperators. Thus, just considering the action or move of a player during the game is not sufficient to maintain the stable cooperation, and further mining the hidden mechanism behind a specific action is significant to build a reasonable evaluation regime.

To be particularly mentioned, Kandori [77] seminally investigated the social norms by the game theory, and found that the cooperative and individually rational strategy could be sustained with the help of reputation information, where the reputation update rule generally relies on four types of information including: (i) the current reputation of a focal player, (ii) the current reputation of his opponent, (iii) the action of a focal player, and (iv) the action of his opponent. Henceforth, the fourth-order evaluation is reached if the above-mentioned factors are all considered, such as [78]. On the contrary, in the work of Nowak and Sigmund [6], the discriminator just made the evaluation on the focal player based on (iii), and then it is called the first-order evaluation, as illustrated in the previous section. Meanwhile, Takahashi and Mashima [94] performed the evaluation according to (ii) and (iii), which is then called the second-order evaluation, and several typical rules, which include stern judging, simple standing, shunning and even image scoring, can also come down to this category.

As a further step, Ohtsuki and Iwasa [21,47] systematically investigated the reputation dynamics and discovered that eight main rules, named after the leading eight, can lead to the evolutionarily stable state, which uncovered the role of reputation dynamics in the evolution of cooperation to the full. In their model, each player will be evaluated as a binary score, named after the H-score, to be 1 (good) or 0 (bad) based on the criteria (i), (ii) and (iii), that is, the third-order evaluation. To be specific, the reputation dynamics d is characterized as (d_{ijX}), where $i, j = 1$ (good) or 0 (bad), X denotes the behavior strategy of the focal player, cooperating (C) or defecting (D), and each element is recorded to be 1 or 0 meaning the goodness or badness. That is, for a social population adopting the reputation dynamics d, the H-score of the focal player (say, $F1$) will be assigned to be d_{ijX} if (1) H-score of $F1$ is i, (2) H-score of $F1$'s opponent (*e.g.*, $F2$) is j, and (3) the action or move of $F1$ towards $F2$ is X. Taking an example, reputation dynamics $d = (d_{00D}, d_{00C}, d_{01D}, d_{01C}, d_{10D}, d_{10C}, d_{11D}, d_{11C}) = (0, 1, 0, 1, 0, 1, 0, 1)$ prescribes that just H-score of those who take the cooperating action will be 1 and will be abbreviated as $d =$ **IMAGE** (*i.e.*, image scoring rule [6]). Likewise, reputation dynamics $d = (d_{00D}, d_{00C}, d_{01D}, d_{01C}, d_{10D}, d_{10C}, d_{11D}, d_{11C}) = (0, 1, 0, 1, 1, 1, 0, 1)$ means the standing rule, which is usually written as $d =$ **STAND** for short. It is quite clear that **IMAGE** rule evaluates the focal agent as good or bad just by checking his action to be cooperative or defective, while the **STAND** norm needs to simultaneously consider their action and reputation status, and the only difference between these two rules is d_{10D}. Thus, the method of distinguishing them is to check the reputation status of the good player if he defects a bad opponent, which is good for the **STAND** rule, but it is bad for the **IMAGE** one. Considering all possible combinations of (i, j, X), it can be inferred that we can have 2^8 different reputation dynamics as demonstrated by Ohtsuki and Iwasa [21,47]. Among them, eight kinds of reputation dynamics, that is, the leading eight, have been proved to evolutionarily stable through theoretical analyses and extensive numerical simulations, and hold the following common features

$$d(*, 1, C) = 1, d(*, 1, D) = 0, d(1, 0, D) = 1 \tag{6}$$

where 1 and 0 stand for the H-Score of corresponding players, and the asterisk (*) denotes a wild card. Eq. (6) implies that (1) a player who cooperates with another high H-Score opponent will be evaluated as good (*i.e.*, H-Score = 1) in the subsequent round, but the player defecting against the good opponent will be thought to be bad (*i.e.*, H-Score = 0) at the next round; (3) a good player's defection against the bad opponent will be justified, that is, he still holds the good reputation (H-Score = 1) next time. Thus, the main characteristics can be outlined in the upper region of Table 2.

After the reputation dynamics are well defined, the behavior strategy (p) is also important to maintain the ESS dynamics. As shown in the lower region of Table 2, corresponding to the good status in the upper part, there are three elements common to the leading eight as follows

$$p(1, 1) = C, \quad p(1, 0) = D, \quad \text{and } p(0, 1) = C. \tag{7}$$

But the action strategy can be either C or D when two agents with bad reputation meet together, shown as the fourth element ($**$) in the lower table of Table 2. However, once the specific reputation dynamics is fixed, $p(0, 0)$ is specified to be C or D for each strategy pair (d, p). In fact, after thoroughly checking the properties of all possible pairs of reputation dynamics and behavior strategies (in total $2^8 * 2^4 = 4096$), Ohtsuki and Iwasa [21,47] showed that the condition for the leading eight pairs of (d, p) is rightly the desirable social norm since the population can maintain the non-trivial level of cooperation even under small errors.

Recently, by means of donation game and binary reputation, Santos et al. [19] further explore the role of social norms and action rule in the evolution of cooperation within the well-mixed population, and up to the fourth-order social norms regarding the reputation evaluation are exhaustively searched. Different from Kandori [77], they build the fourth-order model of reputation dynamics, which incorporate the current reputation and action of the donor, and the past and current reputation status of the recipient. Meanwhile, they proposed a complexity index κ, which ranges from 0 to 32, to characterize the performance of social norms on the basis of logical reduction of Karnaugh map,

Table 2
The common features of the leading eight social norms. The upper table: the reputation dynamics d defines the reputation of a focal player at the next round. Four columns denote the different reputation pairs between the focal player and his opponent. 1 or 0 inside the table means good or bad, respectively, and 11, 10, 01 and 00 at the top are the possible combinations of reputations for the focal player (the first digit) and his opponent (the second digit). C or D in the left indicates the action of the focal agent, *i.e.*, C or D implies the cooperation or defection. Asterisk (*) is a wild card, which means that 1 and 0 are both possible in the leading eight. The lower table: the behavior strategy p prescribes the action of the agent. Three elements labeled as C or D mean that they are common to the leading eight social norms. The double asterisks (**) could be C or D, which is dependent on the adopted norms. It is C provided that $d(00, C) = 1$ and $d(00, D) = 0$, otherwise it is D. Reproduced from [47].

d:	11	10	01	00
C	**1**	*	**1**	*
D	**0**	**1**	**0**	*
p:	**C**	**D**	**C**	**

found that social norms of the same order can hold distinct complexity index κ. Large quantities of simulations and theoretical analyses demonstrate that the optimal social norm leading to the highest cooperation level ($> 90\%$) has often the lower index κ, and its performance becomes even more evident when we take a complexity cost $\gamma \in [0, 1]$ into account during the decision process. Also, the results indicate that simple moral principle based on the lower complexity index κ can induce the prevailing of cooperation even under the very complex environments.

So far, most works focus on the assumption that the individual reputation is evaluated by the third-party observer and publicly available, that is, the reputation status is based on the indirect observation and perfectly synchronized so that all players will have the same image on the donor's action. However, under some realistic conditions, some individuals may often make the judgment or evaluation according to their own interactions or experiences, leading to the distinct opinion or assessment on the identical action or individual. To this end, Hilbe et al. [95] investigate the indirect reciprocity when reputation information is private, noisy and even incomplete, and they systematically explore the evolutionarily stable performance of leading eight social norms. They demonstrate that the leading eight strategies may lose the advantages in the evolution of cooperation when the related information is erroneous or noisy. As an example, the stern judging strategy is highly successful and even leads to the full cooperation under the publicly available information, but may inaccurately make the judgment and result in the full defection when the information is private or incomplete. Thus, their results point out the importance of reliable information transmission and synchronized reputation to foster the cooperation and build the moral evaluation systems.

To be particularly mentioned, the building of reputation system relies on the individual reporting when the interaction between two opponents can be reported in time, it is worth being explored when the reputation building involves the reporting cost [96], which may impede the diffusion of reputation. In addition, the reputation evaluation can be also combined with the reward or incentive [97] and punishment [98–100] to further comprehend the role of reputation in the evolution of altruistic behaviors.

2.3.2. *Structured population*

Although the reputation dynamics and behavior strategy have been explored in depth, the interacting topology is often assumed to be well-mixed, that is, any pair of players can directly encounter with each other or the topology is fully connected. However, the underlying topology among the population, in real-world systems, is far from the well-mixing topology, but exhibits the structured properties, which include the homogeneous mixing, small-world effects [101,102] or scale-free characteristics [103,104]. Thus, it is significant to explore the cooperative behaviors with reputation assessment within the structured population.

Along with the work of Chen et al. [91], Dong et al. [105] further investigated the impact of second-order reputation evaluation on the cooperation behaviors in the spatial prisoner's dilemma game, in which the underlying topology

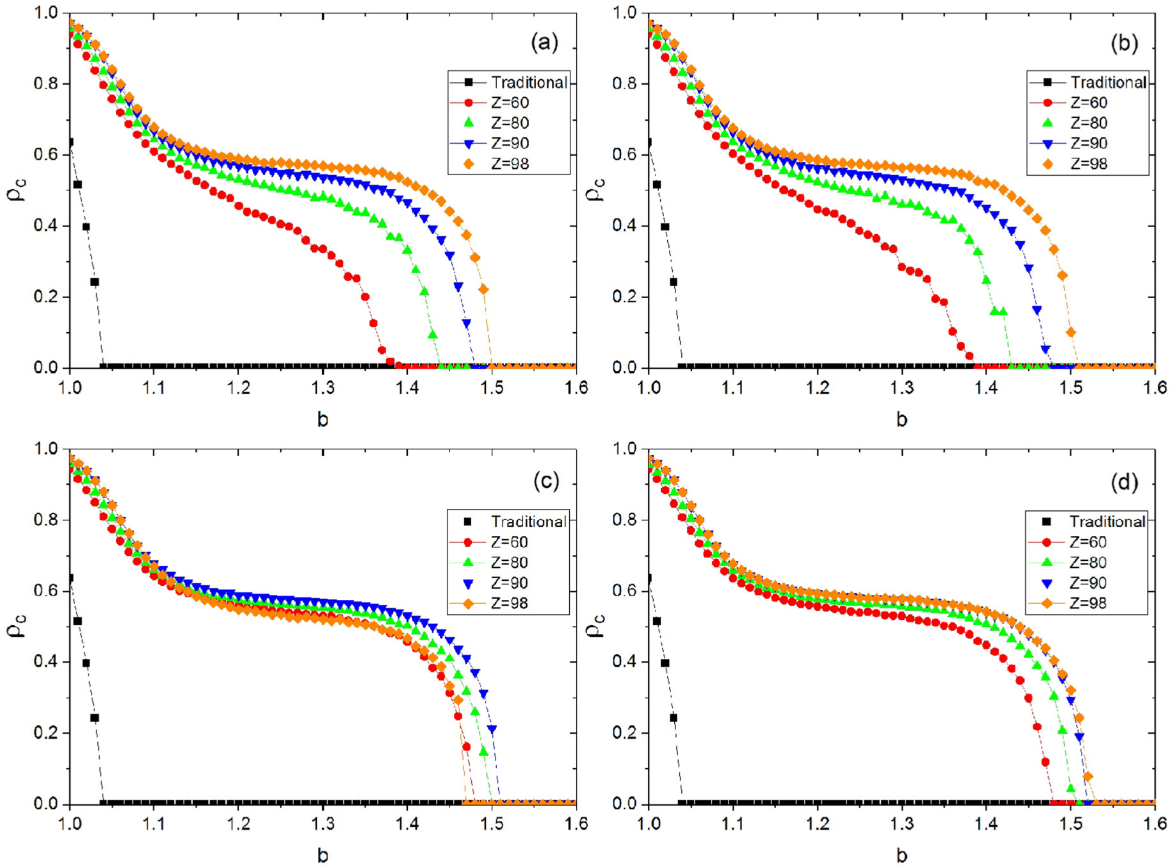

Fig. 8. Density of cooperators ρ_C at the stationary state as a function of temptation to defect b for 4 second-order evaluation rules. From panel (a) to (d), the second-order evaluation rules are set to be stern judging, simple standing, shunning and image scoring, respectively. It can be observed that the second-order evaluation rule can obviously affect the cooperation behaviors among agents, and ρ_C can be tremendously augmented in comparison with the traditional case without any reputation mechanism. Regarding the model parameters, strategy update pre-factor ω_j is set to be 0.05, Monte Carlo step MCS is 50000, reputation step p is 5 and lattice size L is 100. Reproduced from [105].

is not well-mixed, but the regular lattice with Von-Neumann neighborhood (*i.e.*, each player will have just 4 nearest neighbors and its degree is fixed to be 4). In this work, built on four pragmatic second-order reputation rules including the shunning, stern judging, image scoring and simple standing, an adaptive reputation update mechanism is constructed, where the different reputation increment is exerted when a central player takes the different action against the good or bad partner. Meanwhile, a specific reputation threshold Z is introduced to divide players into two classes: good or bad ones, that is, the player i will become good and hold the highly influential power during the behavior strategy update if his reputation value R_i is larger than or equal to Z, or bad otherwise. Fig. 8 illustrates the density of cooperators ρ_C at the stationary state as a function of temptation to defect b for 4 second-order evaluation rules. It is clearly shown that the introduction of reputation can highly promote the collective cooperation within the structured population under 4 second-order evaluation rules, when compared to the traditional prisoner's dilemma game model. Moreover, from panel (a) to (d), the solid squares with the black line stand for the results of the traditional PDG model, where no reputation effect is considered, and other colored symbols denote the results for various reputation thresholds, where Z is varied from 60 to 98, and ρ_C is usually larger when Z is higher. However, to be mentioned particularly, in panel (c), the shunning rule is adopted and it is difficult for good players to have a chance to interact with each other when Z is very high. Furthermore, the cooperation tends to be extinct for the traditional PDG model when b approaches around 1.04, but the maximum value leading to the extinction of cooperation (b_c) has been greatly increased under the second-order reputation dynamics, which means that the introduction of reputation assessment has significantly fostered the cooperation; Also, we can also find that b_c becomes larger and larger as the reputation

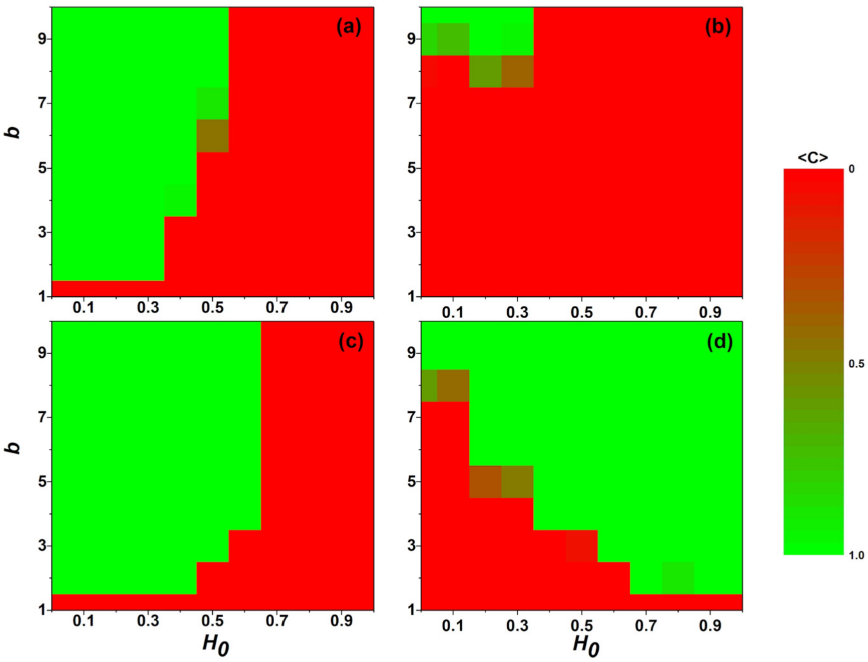

Fig. 9. Fraction of cooperating actions $< C >$ at the stationary state as a function of donation benefit b and intolerance threshold H_0 for 4 second-order evaluation rules. From panel (a) to (d), the second-order evaluation rules are set to be shunning, stern judging, image scoring and simple standing, respectively. Similar to Fig. 8, second-order evaluation rules immensely determine the fate of cooperation, where the stern judging greatly suppresses the evolution of cooperation, but other three rules foster cooperators within the large range of parameters. Model parameters are set to be $N = 2500$, $M = 5$, $c = 1$, $h = 0.5$, $K = 1$ and $w = 0.165$. Reproduced from [115].

threshold Z is increased. As a further step, the third-order evaluation rule is carried out in the spatial public goods game [106], and the fourth-order assessment is to be explored in the future.

Furthermore, the aforementioned theoretical works just carry out the reputation assessment according to the recent action and reputation status of players [107–109]. At the same time, the tit-for-tat (TFT) [110] and win-stay-lose-shift (WSLS) [111] can be also viewed as the classical memory-one behavior strategy. However, some historical information more than one step (*e.g.*, the action strategy or reputation status in the recent several game rounds) could be beneficial for actors to make the optimal strategy choice in the upcoming game rounds [112–114]. To this end, Xia et al. [115] proposed a new second-order reputation evaluation model with memory in the spatial donation game to further illustrate the evolution of cooperation within the structured population. In their model, the donation game is used to characterize the interplay between agents, who are placed on the square lattice with Moore neighborhood (*i.e.*, each agent has 8 nearest neighbors) and stochastically initialized as the unconditional cooperators ($ALLC$), unconditional defectors ($ALLD$) and discriminators ($DISC$) with the equal probability. The system evolution proceeds according to the generation, which is divided into the fine-grained periods. During each period, the donor with $DISC$ strategy will perform the weighted assessment on the basis of past actions of the recipient in accordance with 4 classical second-order rules, which include the shunning, stern judging, image scoring and simple standing ones. After that, the intolerance threshold (H_0) is introduced to determine whether the donor will give the donation to the recipient. At end of each generation, all individuals have the opportunities to synchronously update their current strategy according to the Fermi-like dynamics. In Fig. 9, for 4 different second-order evaluation rules, we depict the average fraction of cooperating actions at the stationary state as the donation benefit b to the recipient and the intolerance threshold are varied. From panel (a) to (d), the assessment rule corresponds to the shunning (a), stern judging (b), image scoring (c) and simple standing (d), respectively. It can be generally observed that, on the one hand, a very low donation benefit $b \sim 1$ does not mean the altruistic donation since the incentive is not high enough; on the other hand, for the higher values of $b > 1$, the level of cooperation hinges on the combination of b and H_0 in different ways under 4 distinct evaluation rules. In panels (a) and (b), low H_0 encourages the donation behavior, but high H_0 hinders the persistence of donation, while in panel (d), the converse phenomenon is displayed, that is, high H_0 leads to the better situation when compared to the case of low H_0. To our surprise, in panel (b), the cooperation is very hard to maintain provided that the stern judging rule is adopted, which is different from some previous works without any memory or intolerance effect [19,47,95].

3. Experimental evidences

As is well-known, the evolutionary game theory provides a unified framework to explore the persistence or emergence of cooperation, and also the related theoretical researches offer the profound insights into the evolution of cooperation. However, in order to carefully scrutinize the evolutionary decision process of cooperation within the human population, the laboratory-based experiments are commonly used to validate the aforementioned mechanisms to foster the cooperative behaviors. Among them, the theoretical researches often propose some mechanisms, quantities or indexes, and then explain the reasons being conducive to the cooperation; Nevertheless, the experiments illustrate the human cooperation from two directions, one is to examine what kind of phenomena can emerge when the specific incentive mechanism and interaction structure are preset within the human subjects, and the other is to explore the internal mental decision or cognitive procedure influenced by some mechanisms in sociology or psychology.

Here, firstly, we will review the recent experimental progresses regarding the role of reciprocal mechanisms and reputation effects in the evolution of cooperation, and the interacting topologies inside the population are usually not considered at this time. Then, we introduce the advances of network reciprocity based on the laboratory or online Internet experiments so that the impact of interaction topologies on the human cooperation can be further examined.

3.1. Reciprocal mechanisms

In general, reciprocal mechanisms include the direct and indirect reciprocity. In this subsection, we will first outline some results based on the experiments to discuss the role of direct reciprocity. After that, combined with the reputation effect, we will present some experimental works on indirect reciprocity, which further contribute to the understanding of altruistic behaviors among the human population.

Direct reciprocity involves the repetitions between two players, and then repeated game models, such as repeated PDG, are frequently used to conduct the experiments within multiple human subjects. A basic consensus is that agents tend to adopt the cooperation strategy [44] provided that the interaction will happen with a higher probability in the future, where the probability indicating a pair of players to interact with each other is typically fixed in many experiments. Even if errors are introduced [116] during the strategy evolution (*i.e.*, performing the move or imitation), the repetition still favors the cooperation, which well agrees with the theoretical predictions in Ref. [117]. Meanwhile, as pointed out by Axelrod [1], TFT is a simple yet successful strategy to win the high level of cooperation in the repeated PDG without any noise. Under the noisy environments, Nowak et al. further developed the Generous TFT [44] or WSLS [45] schemes to effectively enhance the altruistic behaviors among players performing the repeated games, which are also successfully observed in several other experiments [23,118,119].

Although the repetition has been proved to be effective in the 2-person pairwise PDG, the situation may become much more complex when multiple players are involved within the interaction simultaneously and repeatedly. In the framework of EGT, we utilize the public goods game (PGG) to characterize such group interaction, which is called another form of n-person PDG and has been fully outlined in Sec. 1. Here, we need to mention that the targeted interactions within the group are impossible, that is, if one player donates a higher amount to the common pool than another one, one third-party group member cannot selectively reward the former or punish the latter. Henceforth, any third-party member can only reward or punish both of them at the same time by donating a higher or lower endowment, which then renders the cooperation not to thrive in the repeated PGGs in the laboratory experiments [81,84,120]. Therefore, in order to stabilize the evolution of cooperation, the pairwise reward and punishment are usually introduced into the repeated PGG so that the cooperation can be effectively promoted [121,122]. In addition, some recent experiments [123,124] also demonstrated that antisocial punishment can occur in the cross-cultural environments, which prevents the evolution of cooperation and indicates that targeted interactions need to be applied properly.

All in all, the related experiments probing into the connection between the 2-person and n-person repeated games point out the high power of direct reciprocity to enhance the level of cooperation within the human groups. In fact, the results in the repeated PGG have also manifested that direct reciprocity is inevitable to correlate with indirect reciprocity since punishing a low contributor not only receives the following reciprocation, but also does harm to the image score of other members within the same group (*i.e.*, indirect reciprocity). Therefore, as pointed out in [23], developing theoretical models to explore the interplay between direct and indirect reciprocity is a very promising direction in the field of EGT, and then the related human experiments can be further devised to validate them.

3.2. Reputation effect

As the aforementioned theoretical studies have demonstrated, indirect reciprocity is a powerful means to promote the evolution of cooperation among human subjects without direct and repeated interactions, which often requires the help of reputation mechanism [22,23]. Thus, extensive experiments based on the laboratory or online platform are conducted to further explore the role of reputation or indirect reciprocity in the emergence and persistence of cooperation [24–26].

The basic experimental setup is deployed as follows. In order to test the indirect reciprocity, a group of human subjects anonymously enrolled at the laboratory or on Internet are endowed with an initial capital, and then performed the game for a series of rounds according to the specified game model and rule. Meanwhile, face-to-face contacts are prohibited to eliminate the confounding effects and some historical information related with past actions are provided to assist the decision of players at the current game round. Finally, the eventual scoring points at the end of game experiments are changed into the actual cashes in terms of the specific requirements stated in advance. For various given experiments, many parameters can be modified to reflect the purpose of experiments, such as the ratio of cost-to-benefit, the number of game rounds, the size of the population, the size of interacting neighbors, the richness degree of information of past actions and even the social and cultural backgrounds of players.

Based on the donation game, where the donor will pay the cost c for the benefit b ($> c$) of his recipient, many experiments have found that a substantial fraction of donors are willing to make the donation during the game evolution, in particular for the lower cost-to-benefit (c/b) and larger initial endowment, that is, indirect reciprocity is often persuasive within the population. Meanwhile, several works [22,125,126] have indicated that players who frequently donated previously, especially towards opponents who are also cooperative, will receive much more help in the upcoming rounds, that is, having a good reputation is valuable and past cooperating actions will help to build a good reputation within the population, which in turn attracts the benefits in the future. In Fig. 10, the repeated PD game is played within different human subjects, and it can be observed that considering the reputation can greatly enhance the level of cooperation when compared to the case without any reputation mechanism. Meanwhile, if the value of reputation can be quantified and traded [22], the trading of reputation may create a positive or negative impact on the level of cooperation within the human population, which is dependent on how the game is set up and the reputation is evaluated. Although the reputation trading promotes the cooperation when compared to the scenarios without any reputation information, allowing the trading of reputation has undermined the cooperation and reputation to a certain extent.

Cuesta et al. [127] carried out 24 experiments involving 243 participants in the laboratory to demonstrate the role of reputation in the cooperative behavior and network formation inside human groups. In their work, human subjects played an iterated weak prisoner's dilemma on a dynamic network, where the cooperative players can be allowed to cut links with their defective neighbors with bad reputation. The experiments indicate that the implicit punishment mechanism needs the reputation information of partners to play as a cooperating actor, and then the reputation of cooperative players drives the reconfiguration of the underlying network. In addition, they also reveal that the memory plays a substantial role in the evolution of cooperation and network formation process. Meanwhile, of particular significance, the experiments provide a convincing evidence that the reputation can be quantified with a weighted score between the average fraction of cooperating actions and the last action conducted, which is greatly important to develop some potential applications in the commercial practice, as illustrated in Fig. 11. After that, they [128] further assume that the individual reputation can be faked or modified by paying a cost, and it is found that the cooperation can still be maintained at the expense of honest human subjects, who are cheated by dishonest participants.

Indirect reciprocity is even embedded into the PGG so as to resolve the tragedy of the commons [129]. Fig. 12 depicts the evolution of public cooperation under the game experiments, where the PGG may be played alternately with indirect reciprocity game (IRG) or not. It can be observed that, in the first 16 game rounds, the cooperation can be always maintained at a higher level if the PGG is alternated with IRG, as shown in the blue circles; however, when PPG and IRG are conducted respectively, the level of cooperation will be decreased continuously within 8 PGG rounds,

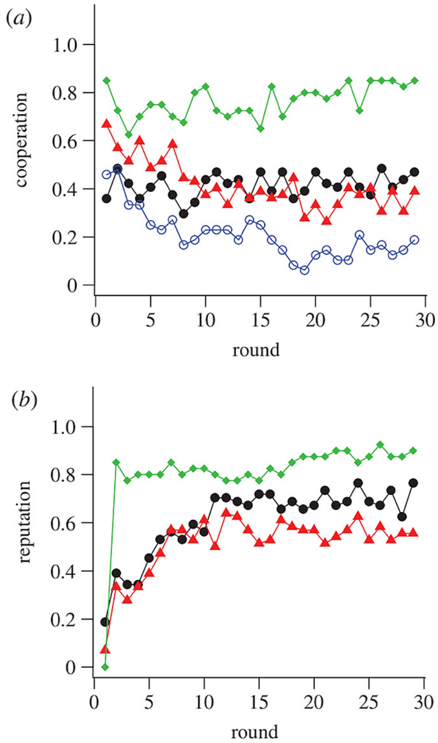

Fig. 10. The evolution of cooperation with different game setup and reputation assessment. Here, repeated PD game is played within distinct human subjects. From top to bottom, the experiments are carried out under the standing assessment without trading (Green diamonds), the standing assessment with trading (Red triangle), the alternative assessment with trading (Black solid circle) and the control without any reputation information (Blue open circle), respectively. For the standing or alternative assessment rule, one of the leading eight, cooperating with a good player or defecting against a bad one is evaluated as good, on the contrary, defecting against a good player or cooperating with a bad one is thought to be bad, where two players have different reputation status or both have a good position. However, if two bad players meet together, two rules have different assignments: in the standing rule, the cooperating action leads to the good reputation, but the defecting action creates the bad reputation; while for the alternative assessment rule, the cooperation creates the bad reputation, and the defection results in the good one. It is obvious that introducing the reputation has greatly enhanced the level of cooperation within the population, but allowing the trading of reputation (*i.e.*, buying or selling for the good reputation) undermined the total cooperation and reputation when compared to the reputation setup without any trading. Reproduced from [22].

afterwards the cooperation will be greatly enhanced as 8 continuous IRG rounds are performed. In the last 4 game rounds, only PGGs are carried out within human subjects, and the cooperation can be sustained at the higher level if the human subjects are not informed in advance. Nevertheless, if we publicly announced that IRG is not performed and PGG is played until the end of the experiments, the cooperation will quickly drop to zero since subjects lack the motivation to maintain the reputation. Hence, the indirect reciprocity—“first give and you will receive the benefits in the future”, is built on the basis of individual reputation, which can aid to greatly enhance the level of cooperation, and the experimental results in [129] demonstrated that alternating rounds of PGG and IRG, which needs to maintain the reputation, contributes to the common pool at a higher level and creates the larger profits for all participants.

As mentioned above, indirect reciprocity could be successful only if the individual reputation information can be effectively and reliably propagated within the population. However, the direct observation or assessment between any two players is not realistic, and gossip could be used as a potential tool to indirectly transmit the reputation information between players although each person may maintain a private list of the reputation of other ones [130]. Among them, Sommerfeld et al. [131] made some empirical studies to explore the role of gossip about the social reputation in the games of indirect reciprocity, and found that the gossip has a strong impact on the resulting behavior even though players can simultaneously access the original information and the related gossip. Furthermore, they also showed that gossip about cooperators is often more positive than that for defectors and gossip comments will transmit the social information successfully, and the tendency of cooperation becomes higher when participants meet with the

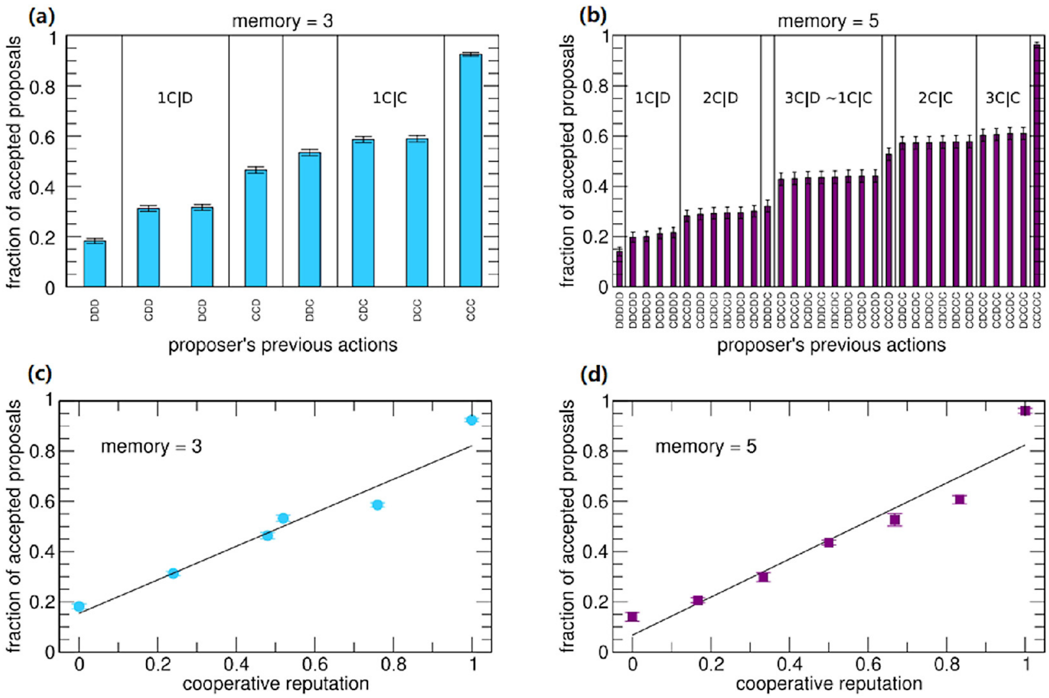

Fig. 11. Reputation is depicted as a weighted score between the average fraction of cooperating actions and the last action strategy. If the order of actions in the past rounds is sorted in ascending order, those corresponding relationships between the last action and fraction of cooperating actions can not be distinguished statistically, which hold both for the memory length m to be 3 (a) and 5 (b). Also, the fitting formula can be characterized as a typical linear relationship $r = wC_{last} + (1 - w)\bar{C}$, and the weight w could be 0.280 for $m = 3$ (c) or 0.165 for $m = 5$ (d). Reproduced from [127].

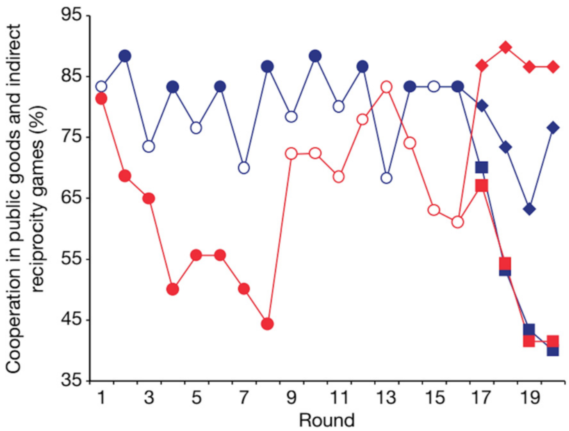

Fig. 12. The evolution of cooperation driven by the alternate game between PGG and indirect reciprocity game (IRG), the abscissa depicts the game round (total 20 rounds) and the ordinate means the fraction of cooperating actions within each group of 6 persons. In the first 16 rounds, the solid symbols denote the PGG and empty ones stand for the IRG; on the one hand, PGG is alternated with IRG, which is shown in blue symbols; on the other hand, continuous 8 PGG rounds are played at first and then 8 IRG rounds are performed. For rounds 17 − 20, groups under the above-mentioned scenarios will both play the PGG, in which human subjects are informed, only PGG is played from now on until the end (red squares) or not informed (red diamonds). Reproduced from [129].

positive gossip, not the negative one. As a further step, they still demonstrated [132] that multiple types of gossip about the same information provides a better description of personal behaviors, and thus fake or inaccurate gossip is non-influential only if it is not in the majority. Meanwhile, it is also found that the reciprocity is positively correlated with trust and reputations transmitted via gossip, and then rendered the level of cooperation to be further promoted.

Besides this traditional form of reputation diffusion, Internet has dramatically enhanced our ability to build large-scale reputation systems among strange agents. Taking an example, online electronic markets (such as eBay [133], Jingdong and Taobao) and even third-party websites (such as Yelp.com and dianping.com) have constructed the specialized reputation systems, which provide online platforms for buyers to rate sellers, and thus hold the great economic values to have a good reputation. On the one hand, these online reputation systems can prompt the sellers to keep the good image in order to attract more customers in the future; on the other hand, they can aid the clients without local information or experiences to reliably buy the high-quality products or services. Henceforth, the online rating systems will create huge economic incentives for various businesses to earn good reputations.

In particular, the reciprocity may be discovered for agents between different species, for example, capuchin monkeys can observe the behavior of humans around them and will not accept food from those who has not provided help to the third parties [134]. Also, humans are extremely sensitive to the possibility of being observed by any third party, and humans become more pro-social even if they are watched by a robot without true eyes or the desktop background of a computer is furnished with a pair of stylized eye-spots [135].

Meanwhile, another challenge for IRG is the ability to justify the defection of participants against ones with a bad reputation, which involves the complex reputation rules to evaluate the action of players. Since the defective players accumulate the lower reputation values, why do the participants need to cooperate with them? Also, the defection against these players should not tarnish your name. Thus, beyond the first-order rule [136], building the higher-order reputation models based on the individual action and their goodness status is necessary, and the corresponding experimental evidences are still absent, which deserve the further trials in the future.

In addition, how to understand the underlying mechanism of reciprocity or pro-social behavior is an intriguing topic from the perspectives of social cognition [137]. Among them, the reciprocity between individuals receives the concern in the field of child psychology, and explores the emergence of pro-social behaviors among children through some field experiments. As an example, Geraci and Surian [138] have shown that 16-month-old infants can own the ability to identify the fair donor in a manual choice task. To be similar, Schmidt and Sommerville [139] have found that there exists a strong correlation between the longer looking times at unfair distributing actions and the tendency to share a toy under an unfamiliar condition for 15-month-old infants. After that, Meristo and Surian [140] further demonstrated that 10-month-old babies anticipate the third parties to take the positive action towards those fair donors who have evenly allocated attractive resources among recipients, not for unfair donors, that is, even the infants are able to evaluate the action of participants based on their distributing behaviors and create the expectation towards the third-party behaviors. As a further step, many works [141–143] are devoted to the studies on the psychological mechanisms to promote the emergence of pro-social behaviors within young children, which involve the positive social emotion, behavior imitation, moral assessment and individual cognitive ability. Furthermore, Beeler-Duden and Vaish [144] performed the experiments among 3-year and 4-year old children to explore the development and emergence of children's upstream reciprocity, found that it were 4-year old children to present the evidences of upstream reciprocity, but not for 3-year old ones. Meanwhile, among 4-year old children, the gratitude-like mechanism was found to support the persistence of upstream reciprocity, that is, those children who received help will assess their donors actively and maintain this form of reciprocity. Taking together, the infants can perceive and evaluate the direct or indirect reciprocity, which may provide some intriguing evidences for reciprocal mechanisms to function in the evolution of cooperation within the rational population.

3.3. Network reciprocity

Most previous works [8,9,12–15] related with the evolution of cooperation often assume that the population is well mixed, especially for large-scale groups, which means that the population structure is neglected and participants are difficult to group into clusters to avoid the demise of cooperation. In fact, many real-world systems usually exhibit the spatial or networked structure characteristics to some extent, that is, beyond the well-mixing topology hypothesis, human subjects will be placed on spatial or complex networks during the experiments, where the structure may be fixed or dynamically evolved, and we will here review the recent advances from these two perspectives.

3.3.1. Experiments on static networks

Experiments performed on static (*i.e.*, fixed) networks typically distribute agents or subjects onto nodes or vertexes within a network, and then make them play the game repeatedly with their nearest neighbors. After that, the

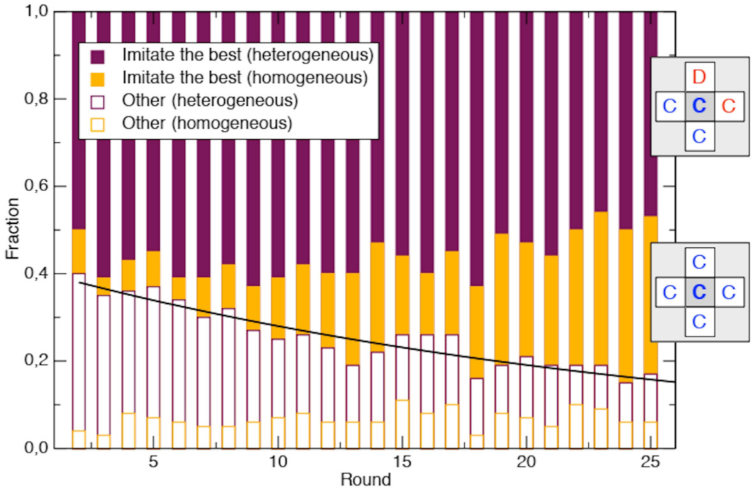

Fig. 13. Prisoner's dilemma game is played on a lattice with a fixed Von-Neumann interaction neighborhood, in which each agent plays with 4 nearest neighbors. It can be observed that most players perform the strategy update (*i.e.*, change the strategy) according to the rule of "imitating the best" (full bar), that is, the focal player will switch to the best available strategy in a heterogeneous (brown) or homogeneous (orange) environment. However, there are still a substantial fraction of strategy updates, which cannot be explained by the imitation rule (open orange bars), and these include either spontaneous strategy update without role model (open orange bars) or random choice of one different neighboring strategy (open brown bars). Reproduced from [145].

cooperation behavior is compared with a controlled experiment in a well-mixed population with the same network size, where the game partners in the network are reshuffled at each round. Although the network reciprocity [51,146] has theoretically indicated that agents in the network can effectively organize into cooperative clusters to resist the exploitation of defectors and then foster the emergence of cooperation, recent experiments do show that the level of cooperation under the networked environment is no higher than that in the well-mixed population, and we will present several examples as follows.

Trausen et al. [145,148] investigated the impact of strategy update rule and population structure on the evolution of cooperation, where the subjects are placed on the spatial lattice and play the PDG. In their studies, total 400 subjects are enrolled and divided into 25 groups (*i.e.*, 16 subjects within each group), among which 15 groups are used to perform the networked experiments and other 10 groups are control groups. In the networked experiment, 16 subjects are placed onto the intersection of 4×4 lattice and their interaction relationships are not changed during the whole game rounds; while for the control groups, subjects are randomly placed onto the lattice at each game round so that the fixed neighborhood or network structure is removed. As shown in Fig. 13, the results reveal that the strategy update rule adopted by human subjects is dynamically varied, and around 60% of subjects adopt the strategy of "imitating the best" at the initial stage and then this fraction increases by 4% at each round, which is different from the theoretical prediction on the imitation rule being kept as constant. In addition, they also observe that the spatial structure does not promote the evolution of cooperation, when compared to the well-mixed population, that is, the cooperation induced by population structure inside human subjects is not as obvious as that under the theoretical models.

Meanwhile, several other works also demonstrated that the introduction of network structure can not lead to the emergence of cooperation within the structured population. Grujić et al. [149] devised an experiment based on the PDG on a network consisting of 169 subjects, who are placed onto a lattice with Moore neighborhood, and they found that the cooperation level is degraded into an asymptotic state with low but nonzero value, where the population is made up of fewer cooperators, a group of conditional cooperators and a very high fraction of defectors. As a further step, Gracia-Lázaro et al. [147] conducted large quantities of experiments participated by 1229 human subjects who played the PDG on a virtual lattice (625 nodes) and scale-free network (604 nodes), and they also reported that the observed level of cooperation is almost the same regardless of the network structure, even comparable to ones in the smaller size or well-mixing population. In Fig. 14, it can be discovered that around 60% of subjects choose the cooperating actions and then decline until 30% is arrived at, which is also similar to the control group, that is, the contact network created by the human subjects has no little impact on the final fraction of cooperative actions. Meanwhile, by analyzing the distribution of frequency of cooperating actions, the normal distribution is exhibited

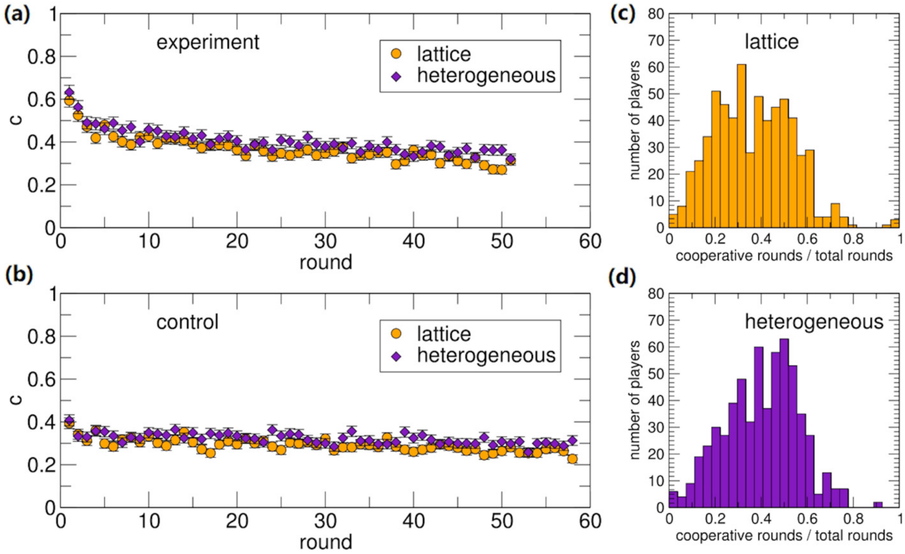

Fig. 14. The fractions of cooperating actions are plotted as a function of game rounds in panel (a) (experiment) and (b) (control), and the histograms of cooperative actions are presented in panel (c) (lattice) and (d) (scale-free network). It can be observed that, on the one hand, a lower level of cooperation is finally reached and unrelated with the contact networks created by human subjects, where the circle and diamond symbols represent the fraction of cooperating actions in a lattice and scale-free network, respectively; on the other hand, the difference between experimental results and those from control group is not obvious. Reproduced from [147].

in a lattice or a heterogeneous network, where most players adopt the cooperative actions and fewer ones select the defective actions. Meanwhile, they also demonstrated that human subjects perform the strategy choice in a reciprocal manner, that is, being more possible to cooperate provided that most of their neighbors do really cooperate in the previous game round, which further implies that human agents do not rely on the neighbor's payoff, but their actions when they make the decision in the experiments of prisoner's dilemma game.

The aforementioned experimental results exhibited the disappointing conclusions that the network reciprocity does not favor the emergence of cooperation, which contradicts with the predictions of many theoretical models and numerical simulations. As Helbing and Yu [150] has remarked, the disparity of cooperation between experiments and theories could be caused by the fact that the theoretical results are often obtained under the imitation dynamics, while human subjects in the experiment may not utilize the imitation rule to perform the strategy update, and they usually make the decision based on the fraction of actions around their nearest neighbors.

Furthermore, Ohtsuki et al. [151] have theoretically verified that for the networked donation game, the collective cooperation will prevail in the network if the ratio of benefit-to-cost (r) is larger than the average degree (k), that is, $r = b/c > k$. Does this theoretical prediction hold for the experiments of human subjects? Rand et al. [152] performed extensive experiments to validate this conclusion. Firstly, they enrolled 109 university undergraduate students to carry out the experiments, and they found that the relationship between r and k determines the cooperative behavior on random networks and ring lattices, which are created temporally among human subjects during the experiments. Then, they enrolled 1163 online volunteers from the Amazon Mechanical Turks platform to further investigate the impact of relationship between r and k on the cooperation. As Fig. 15 illustrates, the cooperation can be maintained at a higher level [panel (a)] if $r > k$, but tend to decline when $r < k$, especially for the final game round [panel (b)], which implies that the static network structure can stabilize the cooperation of human subjects in the donation game if the ratio of benefit-to-cost is higher enough.

3.3.2. Experiments on dynamic networks

In the real world, the contacts between individuals or agents are often dynamic or temporal, where some links may be severed or created as time proceeds. Thus, exploring the cooperation behavior among human subjects on dynamical networks is significant to understand the evolution of cooperation. To this end, in what follows, we will introduce several typical and important works to present some recent advancements and then perform the further open discussions.

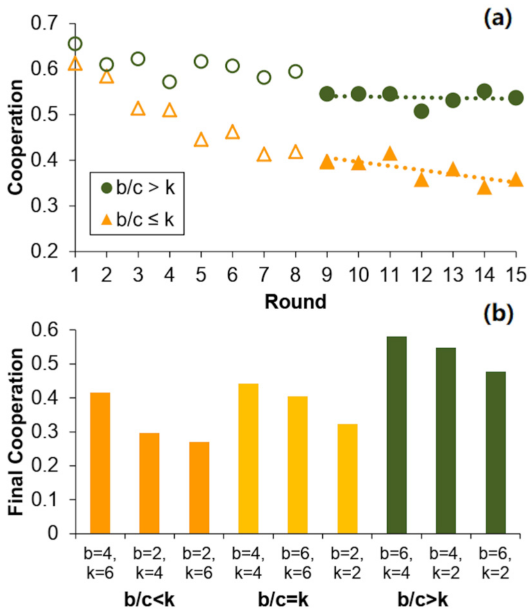

Fig. 15. Donation game is played on a lattice with the different number of nearest neighbors, and the stable cooperation emerges when $r = b/c > k$, but not for $r \leq k$. In panel (a), the fraction of cooperators at each round is plotted for $r > k$ (green circles) and $r \leq k$ (orange triangles); Panel (b) depicts the fraction of cooperators at the final round for different combinations of b/c and k, where c is always fixed to be 1 for all experiments. It is obvious that cooperation can only be maintained for larger values of r. Reproduced from [152].

Fehl et al. [153] recruited 200 students (including 90 male and 110 female students) from the University of Göttingen to play the iterated prisoner's dilemma game in the laboratory, which took place in the fall of 2009, and all subjects can only interact with each other through computers and any other type of communication was prohibited. They run the experiments on two networks: a static network and a dynamic one, where the initial network topology is a regular one composed of 10 agents and each player has three neighbors. The topology keeps constant in the static network, but the links could be rewired in terms of the active-link breaking mechanism in the dynamic network. Their primary result is that the average level of cooperation in the dynamic network can be greatly enhanced when compared to the static one, which can be shown in the panel (a) of Fig. 16. Meanwhile, they also uncover that the link duration will be significantly longer provided that paired participants both cooperate at their first encounter than that if one of them takes the defecting action at that game round, as observed in panel (b) of Fig. 16. In particular, they explored the role of link-breaking mechanism in the structural evolution of dynamic networks, and the resulting higher degree of clustering indicated that the interaction between the player's behavior in PDG and link-breaking decision may lead to the self-organized assortment process, which could be the major reason for the enhancement of cooperation within human experiments beyond the direct and indirect reciprocity.

Rand et al. [154] enrolled 785 participants to play a repeated cooperative dilemma game on an artificial social network virtually created in the laboratory, where the average network size is 19.6 and the standard deviation is 6.4. In the experiments, four kinds of network scenarios are considered: random, fixed, viscous and fluid dynamic link updating. In the random link condition, all links are randomly reconnected after each round and the well-mixed population is created. In the fixed condition, the structure is static and the network hold the initial setup during the whole game rounds. While for the viscous and fluid dynamic link updating, the network is dynamic and the connections will be constantly rewired after each round, where 10% and 30% percentage of all node pairs will be randomly chosen and then rewired in the latter two cases. The experimental results are presented in Fig. 17, and the high level of cooperation can only be maintained on the fluid dynamic networks, where the network updates much more frequently than those in the viscous conditions. However, the cooperation will not be sustained if the network connections are randomly reshuffled at each round. In addition, the static or fixed networks do not favor the cooperation in the experiments for human subjects. Anyway, the experiments demonstrate that rapid network updating can support the cooperation, but too fast or low updates may not result in the optimal cooperation.

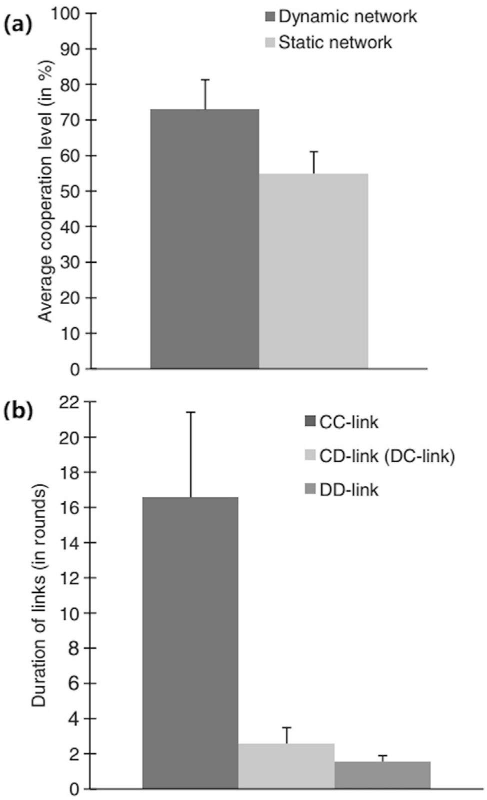

Fig. 16. Evolution of cooperation in the static and dynamic networks. Panel (a) means the average level of cooperation for 30 game rounds of prisoner's dilemma game, which shows that the dynamic network favors the evolution of cooperation; Panel (b) plots the duration of links in the dynamic network, and bars stand for the mean duration of links between paired participants if they decide to adopt the cooperation or defection in their first round of PDG, which indicates that the link duration will become much longer if paired participants both cooperate in their first encounter and $C - C$ links facilitate the existence of cooperating actions within the population. Reproduced from [153].

Although the extensive experiments demonstrate that dynamic networks do foster the cooperation within the human population, costs associated with dynamism including the time, space and available resources to discover and build the links with new and potential opponents, have been ignored in most earlier works. To address this challenge, Bednarik et al. [155] performed the experiments in the laboratory to further demonstrate the role of cost to build new links in the evolution of network structure and cooperation behavior. They found that human subjects are not easy to cut the old link and create the new one once the cost is involved, and even the network is nearly static provided that the costs are high. In particular, the level of cooperation in the PDG is almost not influenced by the decreasing dynamism of networks, as illustrated in Fig. 18, where the rate of cooperation can be promoted to a higher level if there exists the link rewiring cost. Thus, they concluded that the mere possible threat to rewire the link in networks is sufficient to maintain the high level of cooperation, but the impact of self-structured or clustered process inside social networks is not obvious.

However, most prior works focus on the role of network structure or reputation information in the emergence of cooperation on model networks or human social networks, but the existing studies on networked evolutionary game cooperation often conflate reputations and dynamics, that is, they are not simultaneously considered. Melamed et al. [156] performed a large-scale experiment involving total 2675 participants to further disentangle the effects of dynamics and reputations, and experimentally demonstrated that dynamic networks lead to a very high level of cooperation even if the reputation information, whether it is local or global, is not available. In the experiments, based on the iterated prisoner's dilemma game, the participants are placed onto random or clustered networks with different levels of reputation information, which are static or dynamic. As expected, the results in Fig. 19 indicate that static networks do not support the sustenance of cooperation, but dynamic ones favor it, which is similar to those reported on dynamic networks in Ref. [157]. Moreover, the very high level of cooperation can be arrived at for

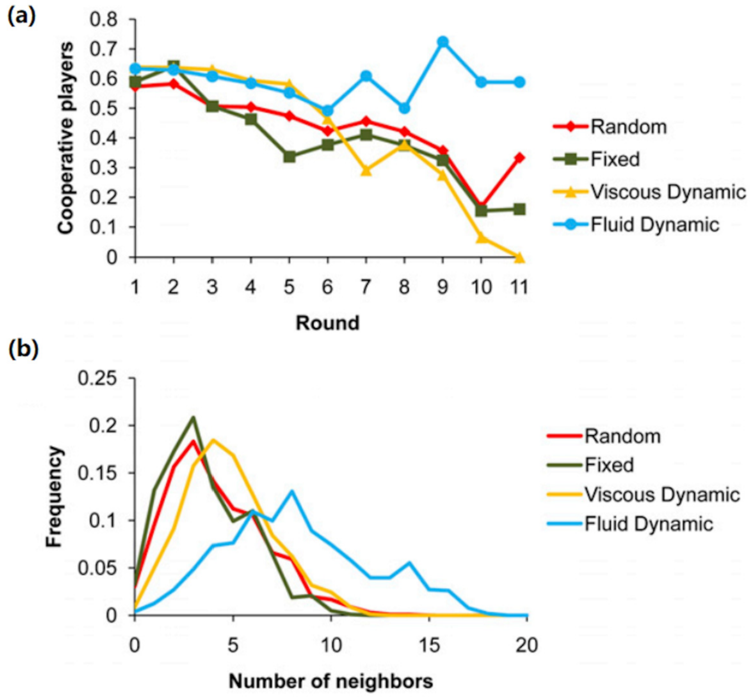

Fig. 17. Impact of different network configuration conditions on the cooperation dilemmas. Panel (a) plots the fraction of cooperative players as the game round evolves, and the higher level of cooperation can be only maintained on the fluid dynamic networks, where the network updates much more frequently; Panel (b) depicts the distribution of nearest neighbors, and as expected, the greater variation for the focal player to own the number of nearest neighbors is observed here. Reproduced from [154].

varying ranges of reputations, and it appears that reputations do not matter for the evolution of cooperation, that is, the rate of cooperation under the conditions with reputation being acquired is akin to that under the conditions without reputation knowledge. Yet, the existence of threat to rewire the link from defectors to cooperators is significant and enough to maintain the stable cooperation. In addition, although the clustering effect can promote the cooperation in static networks [*cf.* panels (a) and (b)], it seems that this structural property has no effect on the cooperation behavior in dynamic networks [by comparing the panels (c), (e), (g) and (d), (f), (h), respectively], and the cooperation is high only provided that the underlying topology is malleable, which enables the defective partners to be cooperative, or else they will become isolated from the whole population.

To be mentioned particularly, they still explored whether the player's decisions are specific to each opponent or applicable to all opponents at the same time. Here, they called the former strategy to be targeted, where each player will adopt the distinct actions for his different neighbors, while the latter is said to be diffused, which is identical with the traditional conditions and each participant will take the same action for all opponents. As shown in Fig. 20, the targeted or diffused strategies do not influence the cooperation on dynamic networks as observed in panels (b) and (d), which can be attributed to the fact that the participants are able to cut the links with the defectors as a punishment. However, for static networks, it can be found that targeted choices can keep the fraction of cooperating actions up to 90%, but the cooperation gradually declines in the diffused ones as the game round evolves, as illustrated in panels (a) and (c). Thus, the rules governing whether the players adopt the targeted or diffused strategies, have a great impact on the cooperation behavior in the experiments for human subjects.

Nevertheless, most of recent works did not vary reputation information or other peers' past actions during the experiments, which has usually been identified as an important element to favor the evolution of cooperation. Also, these works assumed that human subjects did not know about the global structure or social knowledge, or information about who is linked with whom within the group. Thus, it is unknown about how social and reputation information fosters the cooperation on dynamic networks independently or by uniting together. For this purpose, Gallo and Yan [158] designed the large-scale experiments, where they recruited 364 human subjects based on the online Amazon Mechanical Turk (AMT) platform, to further explore the influence of reputational and social knowledge on the cooperation

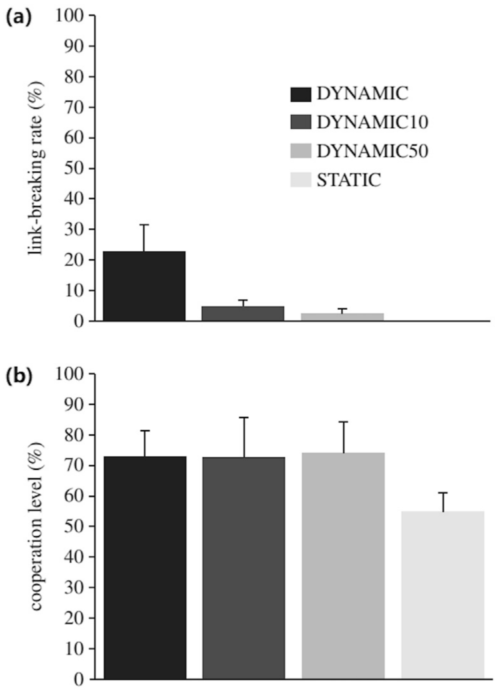

Fig. 18. Impact of network dynamism on the evolution of cooperation within the human population. (a) Average rates of rewired links and (b) Average level of cooperation in the PDG are plotted here. The underlying networks for human participants to play the game could be static (STATIC) or dynamic. After each round, old links could be broken and new links could be built with zero cost (DYNAMIC), low cost of 0.1€ (DYNAMIC10) or high cost of 0.5€ (DYNAMIC50), in which the link-breaking rates will be largely reduced as the breaking and building cost becomes higher and higher; Meanwhile, the cooperation level is just elevated a little as the cost increases. Reproduced from [155].

within subjects. They devise four treatments to discuss the relative significance of these two classes of knowledge in the evolution of cooperation and networks, which include the baseline (B), reputation (R), network (N) and simultaneous consideration of reputation and network (RN) treatments, respectively. The experimental results are presented in Fig. 21, and they found that the global reputation information is pivotal to sustain a high level of cooperation and welfare, but the global social knowledge has no influence on the collective cooperation. As a further step, the community analysis reveals that cooperation is often correlated with the appearance of densely clustered networks with cooperative hubs, inside which cooperators are easy to organize into separate communities achieving a higher level cooperation than that of defectors, and then members of cooperative communities will obtain the higher payoff from interactions within the cooperative community than that from the interplays with members of defective community.

As Nowak has declared in [5], aside from the aforementioned reciprocity mechanism, the kin selection and multilevel or group selection are also two important approaches to favor the evolution of cooperation. Among them, the least-studied mechanism in the experiments for human subjects could be the kin selection so far, and nearly all experiments focus on the genetically unrelated individuals. On the one hand, this is partially because cooperation between related individuals is considered to be anticipated and uninteresting; On the other hand, the relatedness and reciprocity are usually inexorably intertwined and not easily teased apart, which may lead to the situation that it is difficult to measure the effect of kinship on the cooperation behavior. Even so, it is very important for us to comprehend the role of kin selection in the context of human population, and more studies in this field are required, especially for the development of experiments to disentangle the role of kinship and reciprocity in the evolution of cooperation. In particular, it would be greatly helpful if we can combine the recent progresses in evolutionary game theory [1,29] and population genetics [39] to perform the theoretical predictions and experimental design.

Regarding the multilevel or group selection [49], it is often implemented by using the interacting systems, within which each component characterizes one group and they compete with each other to maximize their group benefits. Recently, multiple experiments [159,160] have shown that the inter-group competition greatly encourages the cooperation among intra-group members, and even just depicting the interaction as an inter-group competition is sufficient

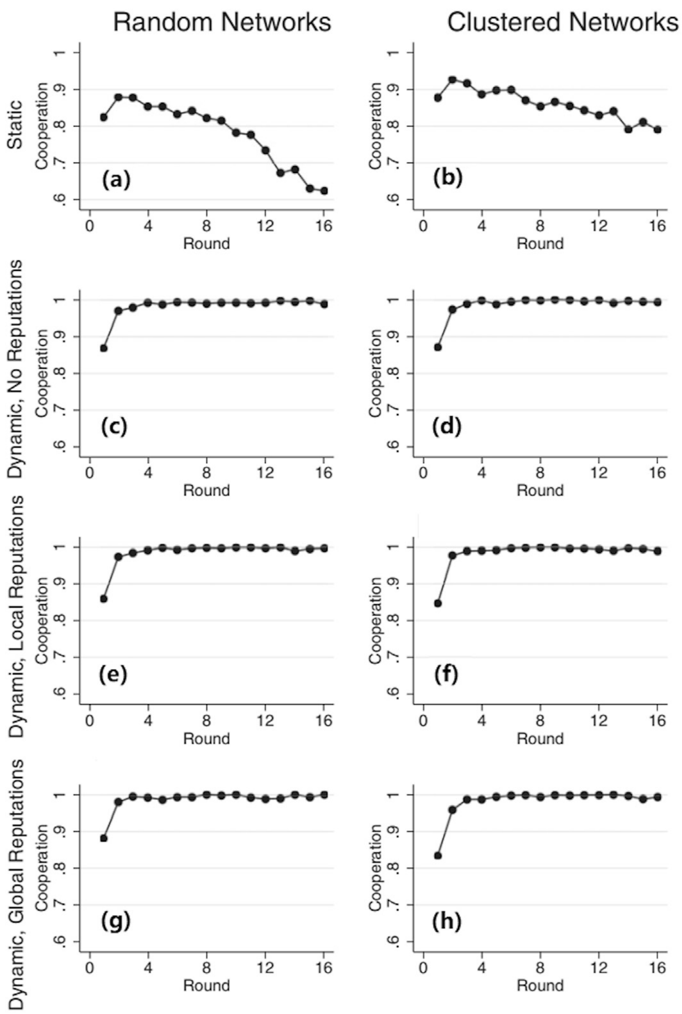

Fig. 19. Level of cooperation on random and clustered networks as a function of game round. Panels (a) and (b) depict the cooperation on static networks, and other panels plot the cooperation on dynamic networks. Among them, panels (c) and (d) describe the conditions without any reputation information, panels (e) and (f) represent the cases where only the local reputation is available, and panels (g) and (h) stand for the scenarios where the global reputation can be accessed. From panel (c) to (f), it can be observed that the dynamic networks are enough to foster the evolution of cooperation, while the reputation knowledge could not be important for the persistence of cooperation at this case. Meanwhile, on static networks, the clustered topology will more favor the cooperation than the random topology. Reproduced from [156].

to put the emergence of cooperation into a higher level, where any monetary prize to win could be absent [161,162]. Taking together, the multilevel or group selection provides a viable means to promote the intra-group cooperation through the inter-group competition.

4. Conclusions and outlooks

How to profoundly comprehend the emergence and evolution of cooperation within the population including the humans and animals has been a significant and open scientific puzzle within the academia, which was ranked as one of the most crucial 25 issues publicized by *Science* magazine in 2005 [4]. The related researches help to shed light on the widespread cooperation, which leads to one of foundations of human existence as an advanced social species. Meanwhile, these studies also provide some specific evidences or cues for individuals, organizations, regions and even countries and the whole society of human beings, and then pursue the potential and consistent actions to cope with the global crisis, such as the climate change [163], pandemic epidemics [164,165] and even global poverty [166].

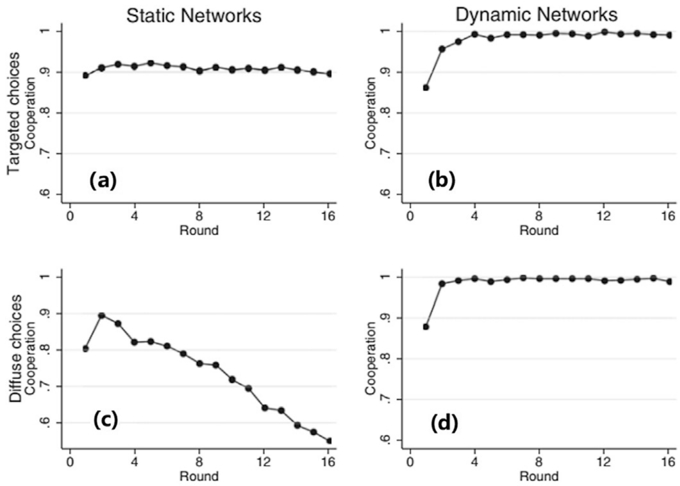

Fig. 20. Level of cooperation on static and dynamic networks as a function of game round. Panels (a) and (c) depict the cooperation on static networks, where the participant takes the targeted and diffused strategies, respectively; Panels (b) and (d) describe the cooperation on dynamic networks, and the targeted and diffused strategies are adopted here. It can be clearly shown that the targeted or diffused strategies do not influence the cooperation on dynamic networks, but the difference in the cooperation level is very obvious on static networks, where the targeted mechanism can lead to a higher ratio of cooperation when compared to the diffused scheme. Reproduced from [156].

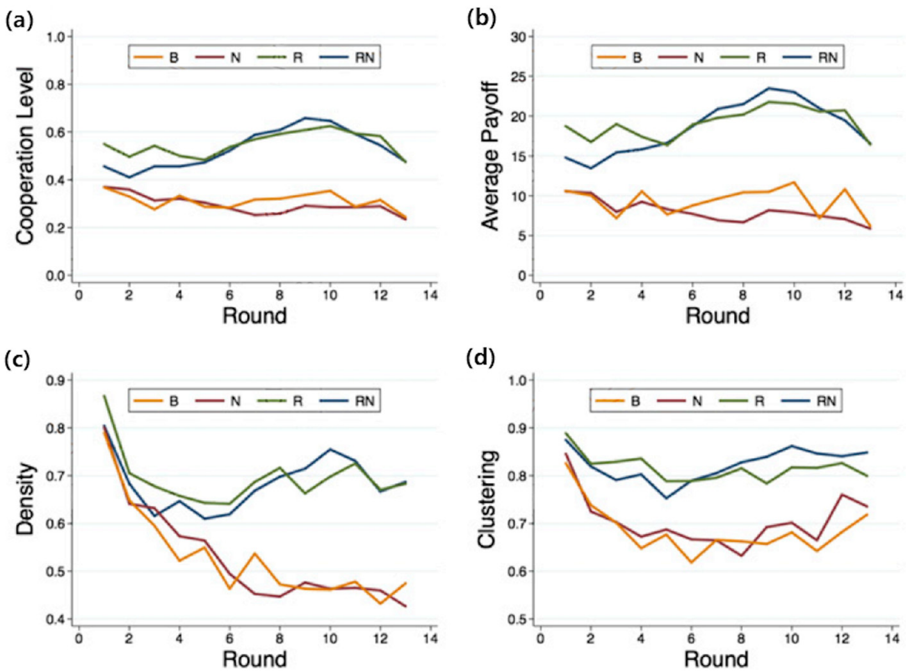

Fig. 21. Impact of four experimental treatments on the cooperation and network structure. Panels (a), (b), (c) and (d) depict the level of cooperation, average payoff, density and clustering coefficients over 13 game rounds. Among them, the yellow lines mean the baseline (B) treatment, and subjects can only obtain the local reputation information just including the last five actions chosen by a list of their current immediate neighbors; the green curves depict the reputation (R) treatment, where they can see the last five actions of each subject and local social knowledge; the red lines stand for the network (N) treatment, in which subjects can know the global social knowledge, that is, the connections among all subjects within the whole group are known, but they can only access the local reputation information; the blue curves represent the reputation and network (RN) treatment, where the global social knowledge is known and the last five actions of all subjects are also exhibited. Reproduced from [158].

In this review, under the framework of evolutionary game theory, we theoretically and experimentally outlined the evolution of cooperation induced by the reputation and various reciprocal mechanisms, including the direct, indirect and network reciprocity, which are identified as three means to promote the coordinating behavior within the population. Also, some contradictions between the theoretical and experimental results are pointed out. As an example, the static network was deemed theoretically to favor the evolution of cooperation through the strategy imitation to form the cooperative clusters, while the experimental works found no convincing evidences to support the cooperation, which could be attributed to the fact that human subjects update the strategy just according to the behaviors of himself and nearest neighbors, not in terms of their payoffs.

Although great advances on the reciprocal mechanism in the role of cooperation [23,167,168] have been made in the recent years, based on our own experiences, the explorations along with several potential directions are still important and valuable for us to understand the ubiquitous cooperation behavior as follows.

- In the condition of direct reciprocity, reward and punishment are the key means to promote the evolution of cooperation. Although many theoretical and experimental evidences have validated that punishing the free-riding defectors is beneficial to foster the emergence of cooperation, the punishment incurs the cost and triggers the second-order free-riding problem [169]. Among them, Sigmund et al. [170] proposed the novel punishing scheme to address this issue, where the peer punishment is replaced by the pool punishment in the public goods game, so that the long-term and stable cooperation can be sustained. Meanwhile, Chen et al. [171] put forward the rule of "First carrot, then stick" to combine the reward and punishment to enhance the cooperation with a lower cost. Thus, it will become a very promising direction to design the experiments carried out by human subjects, which is harnessed to demonstrate the role of reward and punishment in the evolution of cooperation. Moreover, as declared in the previous sections, combining the direct and indirect reciprocities to design the theoretical or experimental schemes is also worth exploring in depth in the future.
- Under the context of indirect reciprocity, what kind of incentives can be used to encourage the players to provide the honest knowledge about the actions and reputation status of their opponents and others, and why are players willing to take the risk of their own good reputation being undermined to defect against those with the bad reputation? Thus, how to construct the effective and reliable reputation assessment mechanism has become a hard task. On the one hand, although the first and second-order evaluation models have been investigated in depth, the third or higher-order and even multi-dimensional evaluation ones are not widely explored yet; On the other hand, in the laboratory and real-world conditions, there still lack the large-scale experiments conducted by human subjects to demonstrate the role of second or higher order reputation models. In addition, gossip is often utilized as an effective means to propagate the information including the reputation, and then building a robust reputation diffusion system to resist the noise and lies is of paramount significance to understand the cooperation behavior induced by the indirect reciprocity.
- For the situation of network reciprocity, how to objectively assess the role of network structure (*i.e.*, the interaction topology between players within the population) through large quantities of human experiments is a vital topic in the field of evolutionary game theory. Although the overwhelming evidences have theoretically verified that complex network structures provide a viable route to promote the cooperation, where the cooperative hub nodes may dominate the cooperation of the whole population, numerous human experiments on static networks revealed that the cooperation is not substantially improved when compared to the well-mixed population. Meanwhile, the experiments on dynamic networks do really present the inclination to support the human cooperation. Thus, devising the experiments to further disentangle the role of network structure in the human population is an intriguing research direction in the future. Furthermore, the real-world contacts among individuals within the population may break through the pairwise interaction [172], and then investigating the evolutionary cooperation dynamics on networks with non-pairwise interaction pattern is a brand new topic in the area of network reciprocity.
- Regarding the design of experimental mechanisms, most existing works arrived at their conclusions on the basis of the specific assumption, and what kind of these results can be explained and extended into the wider context? At present, many experiments are conducted by human subjects under the anonymous settings, but considerable decisions are often made in the environment of onymity [173], how to account for the individual decisions under the onymity is an interesting topic in the field of human cooperation. Moreover, the current evolutionary game models usually focus on the individual actions, and the reciprocal mechanisms just make the response to the actions of game participants. Nevertheless, during the game process, we not only keep a watchful eye on the

individual actions, but also need to understand the intentions behind these public actions and then take the corresponding modifications. Therefore, modeling the interactions between individual intentions and game outcomes may help to provide the deeper insights into the evolution of cooperation.

- On the applicability of experimental results, how to generalize the current conclusions and mechanisms obtained in the laboratory or the online labor AMT into the real-world scenarios is of utmost importance to the inter-disciplinary fields. On the one hand, the evolutionary models can be further modified and optimized on the basis of extensive experiments; on the other hand, the related mechanisms and models can be used to promote the collective cooperation within the humans and gregarious animals, and then increase the social welfare across the region, country and even the global world. At the same time, how to apply the acquired typical results into the engineering systems is also vital in practice. As an example, P2P (Peer to Peer) network has been widely applied into real-world Internet environments, where nodes or peers will share their own hardware or software resources and allow other peers to directly visit them, and then enhancing the widespread cooperation and trust among peers is a great challenge to build a reliable file sharing system [174].
- From the perspective of inter-disciplinary research, the reciprocal mechanisms and models attract the attention of scientists from biology, economics, physics, behavior and even engineering sciences. Thus, how to perform the theoretical predictions and experimental validations in the human population from the multi-disciplinary view is worthy of being further explored in the future. Since the simplified strategy space does not characterize the sophistication of individual psychology and decision making, considering more psychological factors in evolutionary models and human experiments may provide the subtle insights into the human cooperation. Besides, the progress in the cognitive science and technology offers new means for our understanding of individual decisions, where we can observe and record the activity process of human brains during the game decision. Henceforth, by organizing the large-scale human experiments, how to model the interplay between the game decision, psychological factors and brain activity is an extremely valuable topic in the upcoming years [175].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Axelrod R. The evolution of cooperation. New York: Basic Books; 1984.
[2] Nowak MA, Sigmund K. Bacterial game dynamics. Nature 2002;418:138–9.
[3] Nowak MA, Sigmund K. Evolutionary dynamics of biological games. Science 2004;303:793–9.
[4] Pennisi E. How did cooperative behavior evolve. Science 2005;309:93.
[5] Nowak MA. Five rules for the evolution of cooperation. Science 2006;314:1560–3.
[6] Nowak MA, Sigmund K. Evolution of indirect reciprocity by image scoring. Nature 1998;393:573–7.
[7] Nowak MA, Sigmund K. Evolution of indirect reciprocity. Nature 2005;437:1291–8.
[8] Roca CP, Cuesta JA, Sánchez A. Evolutionary game theory: temporal and spatial effects beyond replicator dynamics. Phys Life Rev 2009;6:208–49.
[9] Perc M, Szolnoki A. Coevolutionary games – a mini review. Biosystems 2010;99:109–25.
[10] Yan B, Ahmadi A, Mehrabbeik M, Rajagopal K, He S, Jafari S. Expanding the duopoly Stackelberg game with marginal costs into a multipoly game with lowering the burden of mathematical calculations: a numerical analysis. Chaos Solitons Fractals 2022;164:112645.
[11] Moafi M, Ardeshiri RR, Mudiyanselage MW, Marzband M, Abusorrah A, Rawa M, et al. Optimal coalition formation and maximum profit allocation for distributed energy resources in smart grids based on cooperative game theory. Int J Electr Power Energy Syst 2023;144:108492.

[12] Szabó G, Fáth G. Evolutionary games on graphs. Phys Rep 2007;446:97–216.
[13] Wang Z, Wang L, Szolnoki A, Perc M. Evolutionary games on multilayer networks: a colloquium. Eur Phys J B 2015;88:124.
[14] Perc M, Jordan JJ, Rand DG, Wang Z, Boccaletti S, Szolnoki A. Statistical physics of human cooperation. Phys Rep 2017;687:1–51.
[15] Van der Laan G, Tieman X. Evolutionary game theory and the modeling of economic behavior. Economist 1998;146:59–89.
[16] Shu Y, Dai Y, Ma Z. Evolutionary game theory analysis of supply chain with fairness concerns of retailers. J Ind Manag Optim 2023;19:3560–8.
[17] Gutierrez J, Kowara S, Kraus S, Steeples T, Wooldridge M. Cooperative concurrent games. Artif Intell 2023;314:103806.
[18] Han W, Zhang Z, Sun J, Xia C. Role of reputation constraints in the spatial public goods game with second-order reputation evaluation. Chaos Solitons Fractals 2022;161:112385.
[19] Santos FP, Santos FC, Pacheco JM. Social norm complexity and past reputations in the evolution of cooperation. Nature 2018;555:242.
[20] Panchanathan K, Boyd R. A tale of two defectors: the importance of standing for evolution of indirect reciprocity. J Theor Biol 2003;224:115–26.
[21] Ohtsuki H, Iwasa Y. How should we define goodness? – reputation dynamics in indirect reciprocity. J Theor Biol 2004;231:107–20.
[22] Pfeiffer T, Tran L, Krumme C, Rand DG. The value of reputation. J R Soc Interface 2012;9:2791–7.
[23] Rand DG, Nowak MA. Human cooperation. Trends Cogn Sci 2013;17:413–25.
[24] Milinski M. Reputation, a universal currency for human social interactions. Philos Trans R Soc B 2016;371:20150100.
[25] Marsh C. Indirect reciprocity and reputation management interdisciplinary findings from evolutionary biology and economics. Public Relat Rev 2018;44:463–70.
[26] Wang J, Xia C. Reputation evaluation and its impact on the human cooperation – a recent survey. Europhys Lett 2023;141:21001.
[27] von Neumann J, Morgenstern O. Theory of games and economic behaviour. Princeton, NJ: Princeton University Press; 1944.
[28] Nash J. Equilibrium points in n-person games. Proc Natl Acad Sci USA 1950;36:48–9.
[29] Nowak MA. Evolutionary dynamics. Cambridge, MA: Harvard University Press; 2006.
[30] Gintis H. Game theory evolving. Princeton: Princeton University Press; 2000.
[31] Maynard Smith J, Price GR. The logic of animal conflict. Nature 1973;246:15–8.
[32] Maynard Smith J. Evolution and the theory of games. Cambridge, UK: Cambridge University Press; 1982.
[33] Sigmund K. Games of life: exploration in ecology, evolution and behavior. Oxford, UK: Oxford University Press; 1993.
[34] Maynard Smith J, Szathmáry E. The major transitions in evolution. Oxford: W. H. Freeman & Co; 1995.
[35] Foster KR. The Phoenix effect. Nature 2006;441:291–2.
[36] Garay J, Varga Z. Survivor's dilemma: defend the group or flee? Theor Popul Biol 2011;80:217–25.
[37] Feldman M. Life models. Nature 2011;476:396.
[38] Hamilton WD. Genetical evolution of social behavior I & II. J Theor Biol 1964;7:1–52.
[39] Nowak MA, Tarnita CE, Wilson EO. The evolution of eusociality. Nature 2010;466:1057–62.
[40] Abbot P, et al. Inclusive fitness theory and eusociality. Nature 2011;471:E1–2.
[41] Nowak MA, Tarnita CE, Wilson Nowak EO, et al. Reply. Nature 2011;471:E9–10.
[42] Trivers RL. The evolution of reciprocal altruism. Q Rev Biol 1971;46:35–57.
[43] Axelrod R. The evolution of strategies in the iterated prisoner's dilemma. In: Davis L, editor. Genetic algorithms and simulated annealing. London: Pitman; 1987. p. 32–41.
[44] Nowak MA, Sigmund K. Tit for tat in heterogeneous population. Nature 1992;355:250–3.
[45] Nowak MA, Sigmund K. A strategy of win-stay, lose-shift that outperforms tit-for-tat in the prisoner's dilemma game. Nature 1993;364:56–8.
[46] Brandt H, Sigmund K. The good, the bad and the discriminator – errors in direct and indirect reciprocity. J Theor Biol 2006;239:183–94.
[47] Ohtsuki H, Iwasa Y. The leading eight: social norms that can maintain cooperation by indirect reciprocity. J Theor Biol 2006;239:435–44.
[48] Boyd R, Richerson PJ. Group selection among alternative evolutionarily stable strategies. J Theor Biol 1990;145:331–42.
[49] Traulsen A, Nowak MA. Evolution of cooperation by multilevel selection. Proc Natl Acad Sci USA 2006;103:10952–5.
[50] Nowak MA, May RM. Evolutionary games and spatial chaos. Nature 1992;359:826–9.
[51] Santos FC, Pacheco JM. Scale-free networks provide a unifying framework for the emergence of cooperation. Phys Rev Lett 2005;95:098104.
[52] Su Q, McAvoy A, Wang L, Nowak MA. Evolutionary dynamics with game transitions. Proc Natl Acad Sci USA 2019;116:25398–404.
[53] Wang C, Wang L, Sun S, Xia C. Inferring the reputation enhances the cooperation in the public goods game on interdependent lattices. Appl Math Comput 2017;293:18–29.
[54] Wang Z, Wang L, Yin Z, Xia C. Inferring reputation promotes the evolution of cooperation in spatial social dilemma games. PLoS ONE 2012;7:e40218.
[55] Li A, Zhou L, Su Q, Cornelius SP, Liu Y, Wang L, et al. Evolution of cooperation on temporal networks. Nat Commun 2020;11:2259.
[56] Li J, Zhao X, Li B, Rossetti CS, Hilbe C, Xia H. Evolution of cooperation through cumulative reciprocity. Nat Comput Sci 2022;2:677–86.
[57] Xia C, Ma Z, Wang Y, Wang J, Chen Z. Enhancement of cooperation in prisoner's dilemma game on weighted lattices. Physica A 2011;390:4602–9.
[58] Archetti M. Cooperation as a volunteer's dilemma and the strategy of conflict in public goods games. J Evol Biol 2009;22:2192–200.
[59] Li X, Wang H, Xia C, Perc M. Effects of reciprocal rewarding on the evolution of cooperation in voluntary social dilemmas. Front Phys 2018;7:125 (1–12).
[60] Hardin G. The tragedy of the commons. Science 1968;162:1243–8.
[61] Xia C, Meloni S, Moreno Y. Effects of environment knowledge on agglomeration and cooperation in spatial public goods games. Adv Complex Syst 2012;15:1250056.
[62] Güth W, Ockenfels P, Wendel M. Cooperation based on trust – an experimental investigation. J Econ Psychol 1997;18(1):15–43.
[63] Abbas H, Greenwood G, Petraki E. The n-player trust game and its replicator dynamics. IEEE Trans Evol Comput 2016;20(3):470–4.

[64] Chica M, Chiong R, Kirley M, Ishibuchi H. A networked n-player trust game and its evolutionary dynamics. IEEE Trans Evol Comput 2018;22(6):866–78.
[65] Nowak MA, Sigmund K. Cooperation with competition. Financ Anal J 2000;56:13–22.
[66] Sánchez A, Cuesta JA. Altruism may arise from individual selection. J Theor Biol 2005;235:233–40.
[67] Page KM, Nowak MA. A generalized adaptive dynamics framework can describe the evolutionary ultimatum game. J Theor Biol 2000;209:173–9.
[68] Arthur WB. Inductive reasoning and bounded rationality. Am Econ Rev 1994;84:406–11.
[69] Challet D, Marsili M, Zhang Y-C. Minority games: interacting agents in financial markets. Oxford: Oxford University Press; 2004.
[70] Challet D, Zhang Y. Emergence of cooperation and organization in an evolutionary game. Physica A 1997;246:407–18.
[71] Szolnoki A, Szabó G. Phase transitions for rock-scissors-paper game on different networks. Phys Rev E 2004;70:037102.
[72] Szabó G, Szolnoki A, Izsák R. Rock-scissors-paper game on regular small-world networks. J Phys A, Math Gen 2004;37:2599–609.
[73] Szolnoki A, Mobilia M, Jiang L-L, Szczesny B, Rucklidge AM, Perc M. Cyclic dominance in evolutionary games: a review. J R Soc Interface 2014;11:20140735.
[74] Friedman J. A non-cooperative equilibrium for supergames. Rev Econ Stud 1971;38:1–12.
[75] Leimar O, Hammerstein P. Evolution of cooperation through indirect reciprocity. Proc R Soc Lond B 2001;268:745–53.
[76] Sugden R. The economics of rights, co-operation and welfare. New York: Springer; 2004.
[77] Kandori M. Social norms and community enforcement. Rev Econ Stud 1992;59:63–80.
[78] Brandt H, Sigmund K. The logic of reprobation: assessment and action rules for indirect reciprocity. J Theor Biol 2004;231:475–86.
[79] Nowak MA, Roch S. Upstream reciprocity and the evolution of gratitude. Proc R Soc B 2007;274:605–10.
[80] Fowler JH, Christakis NA. Cooperative behavior cascades in human social networks. Proc Natl Acad Sci USA 2010;107:5334–8.
[81] Boyd R, Richerson P. The evolution of reciprocity in sizable groups. J Theor Biol 1988;132:337–56.
[82] van Doorn GS, Taborsky M. The evolution of generalized reciprocity on social interaction networks. Evolution 2014;66(3):651–4.
[83] Newman MEJ. Complex systems: a survey. Am J Phys 2011;79:800–10.
[84] Fehr E, Gächter S. Cooperation and punishment in public goods experiments. Am Econ Rev 2000;90:980–94.
[85] Fehr E, Fischbacher U. The nature of human altruism. Nature 2003;425:785–91.
[86] Fehr E, Fischbacher U. Social norms and human cooperation. Trends Cogn Sci 2004;8:784–90.
[87] Equíluz VM, Zimmermann MG, Cela-Conde CJ, Miguel MS. Cooperation and the emergence of role differentiation in the dynamics of social networks. Am J Sociol 2005;110:977–1008.
[88] Hanaki N, Peterhansl A, Dodds PS, Watts DJ. Cooperation in evolving social networks. Manag Sci 2007;53(7):1036–50.
[89] Equíluz VM, Tessone C. Critical behavior in an evolutionary ultimatum game with social structure. Adv Complex Syst 2009;12:221–32.
[90] Fu F, Hauert C, Nowak MA, Wang L. Reputation-based partner choice promotes cooperation in social networks. Phys Rev E 2008;78:026117.
[91] Chen M, Wang L, Sun S, Wang J, Xia C. Evolution of cooperation in the spatial public goods game with adaptive reputation assortment. Phys Lett A 2016;380:40–7.
[92] Hu Z, Li X, Wang J, Xia C, Wang Z, Perc M. Adaptive reputation promotes trust in social networks. IEEE Trans Netw Sci Eng 2021;8:3087–98.
[93] Xia C, Hu Z, Zhao D. Costly reputation building still promotes the collective trust within the networked population. New J Phys 2022;24:083041.
[94] Takahashi N, Mashima R. The importance of subjectivity in perceptual errors on the emergence of indirect reciprocity. J Theor Biol 2006;243:418–36.
[95] Hilbe C, Schimd L, Tkadlec J, Chatterjee K, Nowak MA. Indirect reciprocity with private, noisy, and incomplete information. Proc Natl Acad Sci USA 2018;115:12241–6.
[96] Santos FP, Pacheco JM, Santos FC. Social norms of cooperation with costly reputation building. In: Proc. of the thirty-second AAAI conference on artificial intelligence; 2018. p. 4727–34.
[97] Andreoni J, Harbaugh WT, Vesterlund L. The carrot or the stick: rewards, punishments and cooperation. Am Econ Rev 2003;93:893–902.
[98] Kurzban R, DeScioli P, O'Brien E. Audience effects on moralistic punishment. Evol Hum Behav 2007;28:75–84.
[99] Barclay P. Reputational benefits for altruistic punishment. Evol Hum Behav 2006;27:325–44.
[100] Xu C, Ji M, Yap YJ, Zheng DF, Hui PM. Costly punishment and cooperation in evolutionary snowdrift game. Physica A 2011;390:1607–14.
[101] Watts DJ. Small worlds. Princeton, NJ: Princeton University Press; 1999.
[102] Watts DJ, Strogatz SH. Collective dynamics of 'small world' networks. Nature 1998;393:440–2.
[103] Barabási A-L. Network science. Cambridge: Cambridge University Press; 2015.
[104] Barabási A-L, Albert R. Emergence of scaling in random networks. Science 1999;286:509–12.
[105] Dong Y, Sun S, Xia C, Perc M. Second-order reputation promotes cooperation in the spatial prisoner's dilemma game. IEEE Access 2019;7:82532–40.
[106] Yang W, Wang J, Xia C. Evolution of cooperation in the spatial public goods game with the third-order reputation evaluation. Phys Lett A 2019;383:125826.
[107] Wang W, Ren J, Chen G, Wang B. Memory-based snowdrift game on networks. Phys Rev E 2006;74:056113.
[108] Wang J, Liu L, Dong E, Wang L. An improved fitness evaluation mechanism with memory in spatial prisoner's dilemma game on regular lattices. Commun Theor Phys 2013;59:257–62.
[109] Wakiyama M, Tanimoto J. Reciprocity phase in various 2×2 games by agents equipped with 2-memory length strategy encouraged by grouping for interaction and adaptation. Biosystems 2011;103:93–104.
[110] Wedekind C, Milinski M. Human cooperation in the simultaneous and alternating prisoner's dilemma: Pavlov versus tit-for-tat strategies. Proc Natl Acad Sci USA 1996;93:2686–98.

[111] Imhof LA, Fudenberg D, Nowak MA. Tit-for-tat or win-stay, lose-shift? J Theor Biol 2007;247:574–80.
[112] Alonso-Sanz R, Martín M. Memory boosts cooperation. Int J Mod Phys C 2006;17:841–52.
[113] Liu Y, Li Z, Chen X, Wang L. Memory-based prisoner's dilemma on square lattices. Physica A 2010;389:2390–6.
[114] Milinski M, Wedekind C. Working memory constrains human cooperation in the prisoner's dilemma. Proc Natl Acad Sci USA 1998;95:13755–8.
[115] Xia C, Gracia-Lázaro C, Moreno Y. Effect of memory, intolerance, and second-order reputation on cooperation. Chaos 2020;30:063122.
[116] Funderberg D, Rand DG, Dreber A. Slow to anger and fast to forgive: cooperation in an uncertain world. Am Econ Rev 2012;102:720–49.
[117] Funderberg D, Maskin E. Evolution and cooperation in noisy repeated games. Am Econ Rev 1990;80:274–9.
[118] Rand DG, Ohtsuki H, Nowak MA. Direct reciprocity with costly punishment: generous tit-for-tat prevails. J Theor Biol 2009;256:45–57.
[119] Rand DG, Nowak MA. Evolutionary dynamics in finite populations can explain the full range of cooperative behaviors observed in the centipede game. J Theor Biol 2012;300:212–21.
[120] Rand DG, Dreber A, Ellingsen T, Fudenberg D, Nowak MA. Positive interactions promote public cooperation. Science 2009;325:1272–5.
[121] Sefton M, Schupp O, Walker JM. The effect of rewards and sanctions in provision of public goods. Econ Inq 2007;45:671–90.
[122] Choi J, Ahn T. Strategic reward and altruistic punishment support cooperation in a public goods game experiments. J Econ Psychol 2013;37:17–30.
[123] Gächter S, Herrmann B. Reciprocity, culture and human cooperation: previous insights and a new cross-cultural experiment. Philos Trans R Soc B 2009;364:791–806.
[124] Gächter S, Herrmann B. The limits of self-governance when cooperators get punished: experimental evidence from urban and rural Russia. Eur Econ Rev 2011;55:193–210.
[125] Wedekind C, Milinski M. Cooperation through image scoring in humans. Science 2000;288:850–2.
[126] Semmann D, Krambeck H-J, Milinski M. Strategic investment in reputation. Behav Ecol Sociobiol 2004;56:248–52.
[127] Cuesta JA, Gracia-Lázaro C, Ferrer A, Moreno Y, Sánchez A. Reputation drives cooperative behavior and network formation in human groups. Sci Rep 2015;5:7843.
[128] Lozano P, Antonioni A, Tomassini M, Sánchez A. Cooperation on dynamic networks within an uncertain reputation environment. Sci Rep 2018;8:9093.
[129] Milinski M, Semmann D, Krambeck H-J. Reputation helps to solve the 'tragedy of the commons'. Nature 2002;415:424–6.
[130] Nakamura M, Masuda N. Indirect reciprocity under incomplete observation. PLoS Comput Biol 2011;7:e1002113.
[131] Sommerfeld RD, Krambeck H-J, Semmann D, Milinski M. Gossip as an alternative for direct observation in games of indirect reciprocity. Proc Natl Acad Sci USA 2007;104:17435–40.
[132] Sommerfeld RD, Krambeck H-J, Milinski M. Multiple gossip statements and their effect on reputation and trustworthiness. Proc R Soc B 2008;275:2529–36.
[133] Resnick P, Zeckhauser R, Swanson J, Lockwood K. The value of reputation on eBay: a controlled experiment. Exp Econ 2006;9:79–101.
[134] Anderson JR, Kuroshima H, Takimoto A, Fujita K. Third-party social evaluation of humans by monkeys. Nat Commun 2013;4:1561.
[135] Haley KJ, Fessler DMT. Nobody's watching? Subtle cues affect generosity in an anonymous economic game. Evol Hum Behav 2005;26:245–56.
[136] Nowak MA, Sigmund K. The dynamics of indirect reciprocity. J Theor Biol 1998;191:561–74.
[137] Leimgruber K. The developmental emergence of direct reciprocity and its influence on prosocial behavior. Curr Opin Psychol 2018;20:122–6.
[138] Geraci A, Surian L. The developmental roots of fairness: infants' reactions to equal and unequal distributions of resources. Dev Sci 2011;14:1012–20.
[139] Schmidt M, Sommerville J. Fairness expectations and altruistic sharing in 15-month-old human infants. PLoS ONE 2011;6:e23223.
[140] Meristo M, Surian L. Do infants detect indirect reciprocity? Cognition 2013;129:102–13.
[141] Colman AM, Pulford BD. Problems and pseudo-problems in understanding cooperation in social dilemmas. Psychol Inq 2012;23:39–47.
[142] Kadota H, Nakajima Y, Miyazaki M, Sekiguchi H, Kohno Y, Kansaku K. Anterior prefrontal cortex activities during the inhibition of stereotyped responses in a neuropsychological rock-paper-scissors task. Neurosci Lett 2009;453:1–5.
[143] Kerr NL. Can social projection solve social dilemmas (any better than social normative models)? Psychol Inq 2012;23:55–65.
[144] Beeler-Duden S, Vaish A. Paying it forward: the development and underlying mechanisms of upstream reciprocity. J Exp Child Psychol 2020;192:104785.
[145] Traulsen A, Semmann D, Sommerfeld RD, Krambeck H-J, Milinski M. Human strategy updating in evolutionary games. Proc Natl Acad Sci USA 2010;107:2962–6.
[146] Santos FC, Pacheco JM, Lenaerts T. Evolutionary dynamics of social dilemmas in structured heterogeneous populations. Proc Natl Acad Sci USA 2006;103:3490–4.
[147] Gracia-Lázaro C, Ferrer A, Ruiz G, Tarancón A, Cuesta J, Sánchez A, et al. Heterogeneous networks do not promote cooperation when humans play a prisoner's dilemma. Proc Natl Acad Sci USA 2012;109:12922–6.
[148] Grujić J, Röhl T, Semmann D, Milinksi M, Traulsen A. Consistent strategy updating in spatial and non-spatial behavioral experiments does not promote cooperation in social networks. PLoS ONE 2012;7:e47718.
[149] Grujić J, Fosco C, Araujo L, Cuesta JA, Sánchez A. Social experiments in the mesoscale: humans playing a spatial prisoner's dilemma. PLoS ONE 2010;5:e13749.
[150] Helbing D, Yu W. The future of social experimenting. Proc Natl Acad Sci USA 2010;107:5265–6.
[151] Ohtsuki H, Hauert C, Lieberman E, Nowak MA. A simple rule for the evolution of cooperation on graphs and social networks. Nature 2006;441:502–5.
[152] Rand DG, Nowak MA, Fowler JH, Christakis NA. Static network structure can stabilize human cooperation. Proc Natl Acad Sci USA 2014;111:17093–8.

[153] Fehl K, van der Post DJ, Semmann D. Co-evolution of behaviour and social network structure promotes human cooperation. Ecol Lett 2011;14:546–51.
[154] Rand DG, Arbesman S, Christakis NA. Dynamic social networks promote cooperation in experiments with humans. Proc Natl Acad Sci USA 2011;108:19193–8.
[155] Bednarik P, Fehl K, Semmann D. Costs for switching partners reduce network dynamics but not cooperative behaviour. Proc R Soc B 2014;281:20141661.
[156] Melamed D, Harrell A, Simpson B. Cooperation, clustering, and assortative mixing in dynamic networks. Proc Natl Acad Sci USA 2018;115:951–6.
[157] Wang J, Suri S, Watts D. Cooperation and assortativity with dynamic partner updating. Proc Natl Acad Sci USA 2012;109:14363–8.
[158] Gallo E, Yan C. The effects of reputational and social knowledge on cooperation. Proc Natl Acad Sci USA 2015;112:3647–52.
[159] Puurtinen M, Mappes T. Between group competition and human cooperation. Proc R Soc B 2009;276:355–60.
[160] Sääksvuori L, Mappes T, Puurtinen M. Costly punishment prevails in intergroup conflict. Proc R Soc B 2011;278:3428–36.
[161] Gneezy A, Fessler DMT. Conflict, sticks and carrots: war increases prosocial punishments and rewards. Proc R Soc B 2012;279:219–23.
[162] Böhm R, Rockenbach B. The inter-group comparison – intra-group cooperation hypothesis: comparisons between groups increase efficiency in public goods provision. PLoS ONE 2013;8:e56152.
[163] Pacheco JM, Vasconcelos VV, Santos FC. Climate change governance, cooperation and self-organization. Phys Life Rev 2014;11:573–86.
[164] Wang Z, Moreno Y, Boccaletti S, Perc M. Vaccination and epidemics in networked populations – an introduction. Chaos Solitons Fractals 2017;103:177–83.
[165] Nicola M, Alsafi Z, Sohrabi C, Kerwan A, Al-Jabir A, Iosifidis C, et al. The socio-economic implications of the coronavirus pandemic (COVID-19): a review. Int J Surg 2020;78:185–93.
[166] Li Y, Wu W, Wang Y. Global poverty dynamics and resilience building for sustainable poverty reduction. J Geogr Sci 2021;31(8):1159–70.
[167] Zhang Y, Liu A, Sun C. Development of several studies on indirect reciprocity and the evolution of cooperation. Acta Autom Sin 2018;44:1–12.
[168] Rong Z, Xu X, Wu Z. Experiment research on the evolution of cooperation and network game theory. Sci Sin Phys Mech Astron 2020;50:010508.
[169] Fehr E, Rockenbach B. Detrimental effects of sanctions on human altruism. Nature 2003;422:137–40.
[170] Sigmund K, De Silva H, Traulsen A, Hauert C. Social learning promotes institutions for governing the commons. Nature 2010;466:861–3.
[171] Chen X, Sasaki T, Brännström A, Dieckmann U. First carrot, then stick: how the adaptive hybridization of incentives promotes cooperation. J R Soc Interface 2015;12:20140935.
[172] Battison F, Cencetti G, Iacopini I, Vito Latora ML, Patnia A, Young J-G, et al. Networks beyond pairwise interactions: structure and dynamics. Phys Rep 2020;874:1–92.
[173] Wang Z, Jusup M, Wang R, Shi L, Iwasa Y, Moreno Y, et al. Onymity promotes cooperation in social dilemma experiments. Sci Adv 2017;3(3):e1601444.
[174] Lu K, Wang J, Li M. An eigentrust dynamics evolutionary model in P2P file sharing systems. Peer-to-Peer Netw Appl 2016;9:599–612.
[175] Wang Z, Jusup M, Guo H, Shi L, Gecek S, Anand M, et al. Communicating sentiment and outlook reverses inaction against collective risks. Proc Natl Acad Sci USA 2020;117:17650–5.