PERSPECTIVE

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Perspective

Reputation evaluation and its impact on the human cooperation —A recent survey

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Abstract – In this survey, we briefly review some recent advances in the field of indirect reciprocity and reputation mechanism along the routes of theoretical modeling and behavior experiments. Firstly, various game models with reputation evaluation are proposed, and large quantities of numerical simulations demonstrate that introducing the reputation evaluation drastically enhances the level of collective cooperation within the population. In particular, the so-called leading eight rules are found to be evolutionarily stable strategies. Secondly, through extensive human experiments played in the laboratory or via the online labor market, it is validated that providing enough information on the individual strategy or reputation status will help players to select the cooperative partners or perform the rational decision, which eventually facilitates the evolution of cooperation, but some experiments also indicate that allowing the link rewiring may dominate the human cooperation. Finally, several potential and valuable directions are pointed out so as to further explore how the cooperation evolves within the real-world population.

Introduction. – How to comprehend the evolution and emergence of cooperation within the collective population is a challenging topic to be resolved urgently, which ranked among the 25 scientific puzzles voted by *Science* magazine in 2005 [1]. At present, exploring the potential mechanisms that promote the emergence of cooperation is conducive to explaining many unknown phenomena, such as the canceration of cells [2], the generation of languages [3] and the clustering of collective behaviors [4]; to addressing global problems we face, such as the tragedy of the commons [5], climate change [6] and resource depletion [7]; to speeding up the cracking of new problems we encounter inside the virtual world in the era of Internet and artificial intelligence, such as online fraud and other illegal and criminal behaviors [8]. Therefore, the design and analysis of mechanisms to greatly foster the evolution of cooperation are very pressing and significant for the development of contemporary human society.

In recent years, the evolutionary game theory (EGT) has offered a strongly mathematical tool to investigate the evolution of cooperation [9]. In 2006, Nowak [10] systematically summarized the mechanisms to favor the emergence of cooperation and believed that 5 classes of rules, which include kinship selection, direct reciprocity and indirect one, spatial or network reciprocity and multi-level selection (*i.e.*, group selection), are the most important means to foster the cooperation. Among them, the generation of languages, the formation of moral norms, the division of social labors, the improvement of public relations and the development of brains are usually related with the indirect reciprocity, where building, maintaining and diffusing the individual reputation are the core mechanisms for it to function in the evolution of cooperation [11–17]. Furthermore, with the globalization and rapid development of digital economics and trades, the trading frequency between strange agents is greatly increased, and the single transactions between strangers will gradually replace the repeated interactions among acquaintances, which relies on the individual reputation and trust with each other to a large extent [18,19]. Thus, the availability of individual reputation and identity information becomes the cornerstone of online e-business platforms, such as eBay, Amazon, Jingdong and Alibaba [20,21].

At the same time, the reputation and credibility of agents are also very important for financial systems [22]. For example, business banks can utilize these pieces of information to identify the individuals and institutions who lose the credit, and then bad loans or debts can be greatly

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reduced; also, with the help of related credibility information, banks can discover the potential clients who have the good status of reputation so that they can further expand the credit scale, optimize the resource allocation and even improve the profit level. Afterwards, by reshaping the reputation rules and moral mechanisms in the market and social sectors on a large scale, we can curb the diffusion of opportunism and speculation, stimulate rational subjects to make effective decisions in decentralized trading scenarios and then build an efficient social credit system, which can aid government departments to largely cut down the cost of direct intervention and thus greatly improve the level of social public governance.

Henceforth, it is of utmost importance to systematically summarize the recent progresses in the area of indirect reciprocity and reputation modeling so that the role of reputation in the human population can be further revealed along the aforementioned theoretical routes. In addition, beyond the assumption of rational agents, the real-world behavior experiments can help to identify some crucial factors to influence the individual decision during the gaming process. To this end, we will here provide a recent survey on how the reputation assessment can affect the evolution of cooperation from the following two perspectives: the theoretical analyses and experimental evidences.

Theoretical modelling and simulations. – In order to discuss the role of indirect reciprocity and reputation under the framework of EGT, it is necessary to utilize some traditional game models to characterize the interactions among agents [23], where the most frequently used game models are pairwise games including the donation game, prisoner's dilemma game (PDG) or snowdrift game (SDG), and the group games including the trust game [24] and public goods game (PGG). Taking the 2-player pairwise game as an example, the corresponding game payoffs can be calculated via the following matrix:

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

where C and D denote the corresponding actions or strategies of a pair of players, Cooperation (C) and Defection (D), and R, S, T and P represent the payoffs obtained by a row player during a game, that is, for a C-strategist, he will get the payoffs of reward R and sucker S when he encounters with a cooperator and a defector, respectively; similarly, if a D-strategist meets with a cooperator and a defector, he will receive the payoffs of temptation to defect (T) and punishment (P), respectively. Based on the relative ranking of these payoffs, different types of games can be presented, as an example, PDG appears if $T > R > P > S$ and SDG is present when $T > R > S > P$. In addition, PGG can be considered as a multi-player edition of PDG if multiple players participate in a group game, where each player can simultaneously and independently determine whether he will contribute to the common pool. Furthermore, the donation game is often used to illustrate the function of indirect reciprocity and reputation. In this game, a pair of players are selected to play the game at each game round, where two players are viewed as the donor and the recipient, respectively. The recipient will obtain the payoff $b > c$ provided that the donor is willing to pay the cost c; otherwise, the recipient will get the payoff 0.

Well-mixed population. Originally, large quantities of works focus on the role of indirect reciprocity and explore whether indirect reciprocity and the reputation can foster the cooperation within the well-mixed population. As an example, Nowak and Sigmund [25] constructed a novel indirect reciprocity game model based on the donation game and proposed the "Image Score (IS)" mechanism to evaluate the game player, where the cooperation results in the good reputation and the defection leads to the bad reputation. Through extensive numerical simulations, they found that this evaluation rule can considerably enhance the overall ratio of cooperators at the stationary state, but may give rise to the collapse of cooperation once the noise is introduced into the individual action or reputation assessment, that is, IS is not the evolutionarily stable strategy. Nevertheless, the player is still evaluated to be bad in this rule even if he does not cooperate with a bad opponent, which may allow the existence of free-riders that cooperate with others to improve their reputation status. To resolve this issue, some researches [26] presented another rule to justify this kind of defection, namely, defection against the bad player will be evaluated to be good, which is termed as the standing rule, and numerical simulations indicate that this standing rule can avoid the free-riding behavior and become the evolutionarily stable strategy. As a further step, the individual action and evaluation rules are thoroughly investigated and extended to other pairwise and multi-player game models [27,28], it is declared that eight leading rules are found to be evolutionarily stable ones, and it is also found that the standing rules are generally more successful than the IS scheme.

Additionally, the success of indirect reciprocity or reputation usually relies on the social norms, which prescribe what kind of action is the good or bad one and thus offer a morality standard for the evaluation [29]. By use of the donation game and simple binary reputation (Good or Bad), Santos *et al.* [30] systematically investigated the impact of various social norms on the cooperative capacity within a well-mixed population, where a large number of cognitive complexities and up to fourth-order social norms are taken into account. Among them, the fourth-order norms encompass the current action and reputation of the donor, and the past and present reputations of the recipient, which can be represented as a 16-bit tuple, and the corresponding strategies are also characterized as a 8-bit tuple. Based on the optimal logical expressions, they define the complexity index κ, denoting the number of

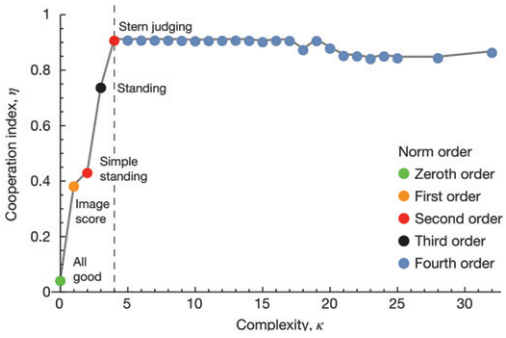

Fig. 1: Impact of social norm complexity (κ) on the cooperation index (η). The highest cooperation level ($\eta > 90\%$) is obtained under the classical stern judging norm ($\kappa = 4$), while the more complex norms ($\kappa > 4$) do not generate the higher ratio of cooperators within the population. This figure is reproduced from [30].

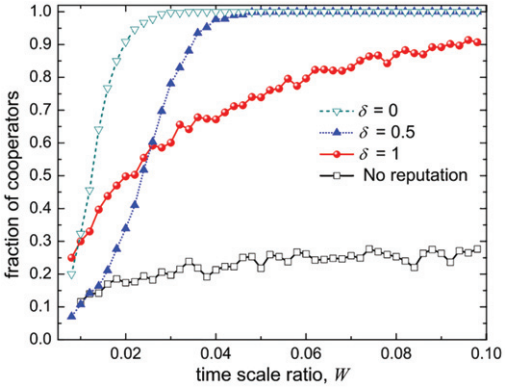

Fig. 2: Impact of reputation on the cooperating behaviors in the partner switching process. It is clearly shown that the introduction of reputation can enhance the evolution of cooperation. This figure is reproduced from [33].

literals in the most simplified logical expressions, to depict the capability for individuals to acquire a new concept. Through extensive computations and simulations, they find the optimal pattern of social norms and the necessary prerequisites to highly elevate the promotion. Figure 1 plots the impact of social norm complexity (κ) on the cooperation index (η) leading to the maximum cooperation, and it is demonstrated that the highest cooperation level is obtained under the classical stern judging norm with the complexity index $\kappa = 4$; while for $\kappa > 4$, only fourth-order norms can lead to the maximization of cooperation level although the complexity index can vary substantially for the same order norms.

Besides, punishment is a potential and significant mechanism to stabilize the cooperation, but it also results in the dilemma of second-order free rider. Henceforth, the reputation can be introduced to help punishers to obtain benefits in future interactions, which can greatly resolve the second-order free rider problem [31,32].

Structured population. Although striking advance has been made, many works are based on the well-mixed population, where it is assumed that each individual can play with any other one. However, this assumption is far from the reality, and then increasing works combine the reputation effect with more realistically spatial lattices or complex networks so that the role of reputation in the cooperation within the structured population can be explored in depth. As an example, Fu *et al.* [33] explored the influence of individual reputation on the choice of game partners, and found that allowing the switch of interacting neighbors based on the individual reputation can foster the prevalence of cooperators over defectors, as shown in fig. 2. Obviously, when compared to the original model without involving any reputation effect, the cooperation can be greatly enhanced with the help of reputation in a different way. To be particularly mentioned, if individuals tend to frequently switch their game partners, discounting of individual reputation can lead to a higher level of cooperation since defectors are possibly disconnected by the focal agent and then experience the decreasing partnership as a result of the lower reputation score, where individuals are inclined to make the prompt partner switching (*i.e.*, the larger time scale ratio W) only determined by the present reputation score (as $\delta = 0$ in fig. 2), rather than the accumulated scores (like $\delta = 1$ in fig. 2). In addition, the cooperation may be inhibited by the decaying memory effect if the partner switching process is slower, namely, the smaller $W < 0.02$ for $\delta = 0.5$.

Meanwhile, as the individual heterogeneity exists and accurately sensing the reputation information of others is usually difficult, Wang *et al.* [34] proposed a novel reputation referring mechanism, which is used to choose a potential neighbor to imitate his strategy. At the beginning, each player is endowed with a specified probability p denoting his ability to precisely infer the reputation of his neighbors, and the value of p is kept to be constant during the whole game. At each time step, each player can only own one chance to perform the strategy update by imitating one of his neighbors, which is chosen as the neighbor of the highest reputation with the probability p or selected as a random neighbor with the probability $(1 - p)$. It can be found that this novel reputation referring mechanism universally enhances the level of cooperation at the stationary state for the PDG or SDG, whether the game is carried out on the regular lattice or on the small-world network and random regular graph. Figure 3 illustrates how the reputation referring influences the stationary cooperation level (ρ_C) in the PDG for different networks, it can be clearly indicated that this novel mechanism can greatly foster the collective cooperation within the population when it is compared to the traditional spatial PDG. Also, the introduction of reputation inferring into the SDG will have a similar effect [34], but the extent of ρ_C being increased is not obvious as that in the PDG. After that, Chen *et al.* [35] put forward a novel spatial PGG model with the adaptive reputation assortment,

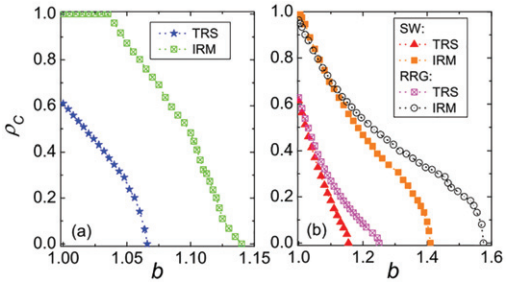

Fig. 3: Impact of reputation referring on the stationary cooperation level in the PDG for different networks. In panel (a), the fraction of cooperators (ρ_C) at the stationary state is illustrated for different values of the PDG parameter b under the traditional spatial version (TRS) and inferring reputation mechanism (IRM), where the underlying topology is the regular lattice. In panel (b), ρ_C is obtained on the small-world and random regular networks. This figure is reproduced from [34].

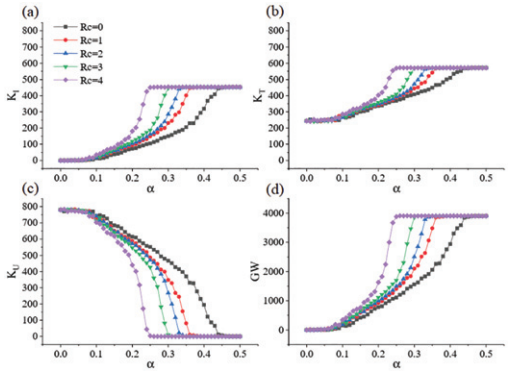

Fig. 4: Role of rationality degree and reputation effect in the networked trust game on the scale-free network, where K_I, K_U, K_T and GW denote the final number of investors (panel (a)), trustworthy trustees (panel (b)), untrustworthy trustees (panel (c)) and the global wealth (panel (d)) in a network with size $N = 1024$. This figure is reproduced from [38].

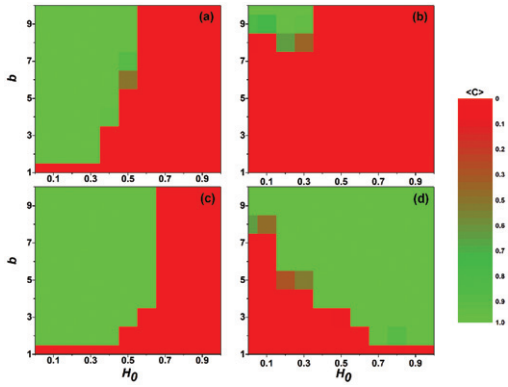

Fig. 5: Impact of reputation evaluation rules and intolerance on the cooperation. Here, the proportion of cooperating actions is recorded at the stationary state on a regular network with the population size $N = 2500$, and four typical second-order reputation assessment rules, which include the shunning (a), stern judging (b), image scoring (c) and simple standing (d), are explored. This figure is reproduced from [39].

where players with the higher reputation hold the stronger strategy spreading ability, and the results indicate that, with the help of reputation assortment, the level of public cooperation on the regular lattice can be effectively enhanced. In addition, the diversity of strategists, adaptive link weight adjustment and individual mobility are also combined with the reputation so as to increase the collective cooperation to a higher level [36,37].

As a further step, Hu *et al.* [38] take the electronic commerce as the background and investigate the evolution of trust between investors and trustees from the perspective of return on investment, and then they present a new networked trust game model to consider the individual rationality and the dynamically adaptive reputation update, where players are classified into three types: investors, trustworthy trustees and untrustworthy trustees. The results demonstrate that, based on regular lattice and heterogeneous scale-free network, the degree of individual rationality is found to be the key factor to dominate the evolution of trust on the basis of the proposed reputation rule; even under irrational conditions, the reputation mechanism can significantly reduce the risk of investors being cheated in the process of cooperative evolution and then promote the maintenance of trust within structured groups. As depicted in fig. 4, as the degree of individual rationality ($\alpha \leq 0.5$) is increased for a fixed reputation threshold, the final number of untrustworthy trustees is gradually reduced until they are extinct within the population; on the contrary, the number of investors and trustworthy trustees, and the global wealth grow little by little until they are saturated. At the same time, when α is fixed and lower than a specific value, the trust among agents will be enhanced as the reputation threshold R_c is increased. Nevertheless, the role of reputation in the cooperation can be ignored when α is greater than 0.5.

However, the above-mentioned works focus on the first-order reputation evaluation within the structured population, second-order or higher-order rules are worthy of being further explored. Very recently, Xia *et al.* [39] started from the donation game and proposed a new second-order reputation model considering the memory effect, where four typical second-order rules are taken into account and the reputation evaluation is performed in accordance with the recent M actions of a focal agent. The mean-field approximations well predict the Monte Carlo simulation results, which indicate that the intolerance threshold of reputation scores may determine the fate of cooperation, and it can be found that intolerance may foster the cooperation under the simple standing rule, but hinder the cooperation for most other assessment rules. In addition, provided that the memory effect is introduced, the stern judging rule leads to the lower level of cooperation, while the stricter rule such as shunning one can foster the higher cooperation level. As pictured in

fig. 5, the proportions of cooperating actions are recorded at the stationary state, which are obtained by averaging over 20 independent runs on a regular lattice with size $N = 2500$ and the Moore neighborhood. The simulation results clearly reveal that the cooperation can be greatly varied when the second-order assessment and memory effect are introduced into the structured population, which may be different from those in the well-mixed case.

Experimental evidences. – In reality, the individual decisions may be influenced by some realistic factors such as the moral or cultural differences, but the aforementioned theoretical advances regarding the reputation or indirect reciprocity often rely on some given hypotheses, such as pursuing the individual payoff maximization. To this end, substantial works try to utilize the human experiments (inside the laboratory or via the online labor market such as Amazon Mechanic Turkey) to explore the relevant factors in the human cooperation. It is uncovered that the reputation is a powerful means to enhance the collective cooperation or social image [40], and even the reputation can be viewed as a universal currency for human social interactions [41].

Several representative researches are presented here for references. Wedekind and Milinski [42] performed the donation game experiments among Swiss students, and the results indicate that the image score of recipients is key to donor's decisions and the score of recipients who get the donation is much higher than those who do not obtain the donation, as shown in fig. 6, where the solid bars mean that the donor gives something to recipients, but the open bars mean that the donor does not donate anything to them. Moreover, in order to compare the difference between the image scoring and simple standing rules, Milinski *et al.* [43] provided some comparisons about the cooperation level in fig. 7, where a NO-player is secretly inserted into the group and never gives help to others. After refusing to help such a NO-player, the donor will be punished under the image scoring rule, but will not be penalized since the defection is justified in the standing rule. It can be observed in fig. 7 that those donors for NO-players are punished nearly with the predicted probabilities in the scoring rule, but much higher than those in the standing rule, that is, the game players prefer to choose the scoring rule when they decide to make the donation or not. Meanwhile, it is found that providing much information to players seems to have no obvious effect on the donor's strategy choice, which could be attributed to the fact that all players that participated in the experiments can directly observe their interactions among them.

Furthermore, Bolton *et al.* [44] discovered through experiments that providing more information including the first- and second-order one does not necessarily affect the donor's strategy or increase the level of cooperation, and also the information cost can obviously influence the cooperation level. As depicted in fig. 8, before the donors decide to make the donation, they will be provided without

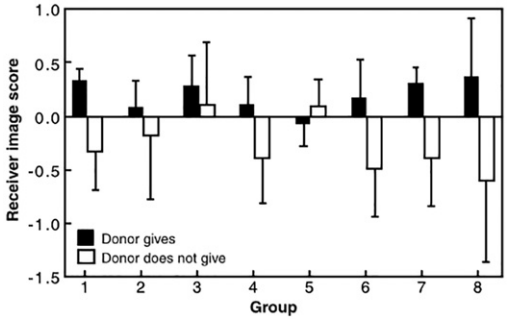

Fig. 6: Reputation or image score of recipients is a determinant factor for donors to donate or not. The solid bars mean that the donor gives something to recipients, but the open bars mean that the donor does not provide anything to them. This figure is reproduced from [42].

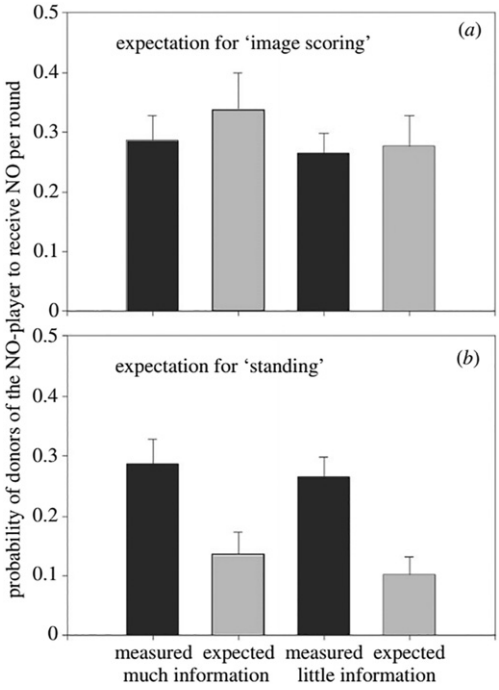

Fig. 7: Comparison of reputation rules between image scoring and standing. Panel (a) compares the measured probabilities (black bars) with expected ones (gray bars) for the image scoring rule; while panel (b) provides the comparison between the measured probabilities (black bars) with expected ones (gray bars) for the standing rule. This figure is reproduced from [43].

any information (zero), or with the first-order and second-order information. For the higher cost ($c = 0.75$), the cooperation will be unambiguously promoted when more information is provided, but the cooperation is not increased for the lower cost ($c = 0.25$), especially for the scenario where only the first-order information is available.

In addition, Swakman *et al.* [45] deeply discussed how the first- or second-order information is utilized during the game decision through extensive human experiments, and found that the donors often request the second-order information of recipients to know the motivation of their

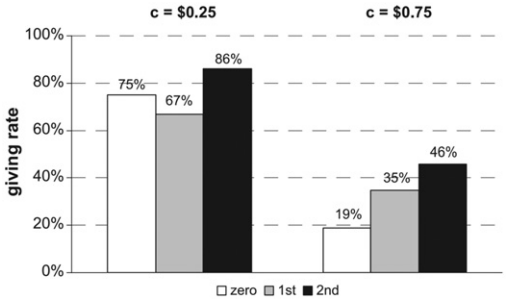

Fig. 8: Impact of provided information and giving cost on the cooperation. The open, grey and black bars denote the zero, first-order and second-order information, respectively. This figure is reproduced from [44].

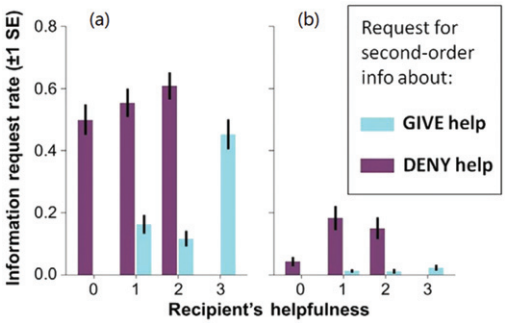

Fig. 9: Frequency of donors' requests for the second-order information to justify the defection, where the request is free (a) or costly (b). The horizontal axis denotes the number of GIVE actions presented to the donor over the past three decisions for the recipients. The purple and blue bars represent the average request rate for DENY and GIVE actions, respectively. This figure is reproduced from [45].

refusals to help others, which then contributes to justify some defections, as illustrated in fig. 9, particularly when the request is free and the recipient conducts the DENY action. However, detailed analyses manifest that a large number of players make the decision just based on the first-order information, but there is also a considerable proportion of donors who perform the game decision after the second-order information of recipients is considered. As an example, fig. 10 pictures the strategy diversity of players in the reputation-based experiments, and it can be shown that the most common strategies are the first-order cooperators, where the donors decide to only help those recipients who helped others in the past, but there exist a substantial fraction of donors who seek the second-order information to make the donation or not.

Recently, the game subjects are often organized into the specified network topology to deeply explore the influential factors of collective cooperation, that is, the role of network reciprocity is carefully checked through human experiments [46]. Although the theoretical works powerfully demonstrated that the heterogeneous scale-free topology highly promotes the cooperation, Gracia-Lázaro *et al.* [47] found through extensive human experiments

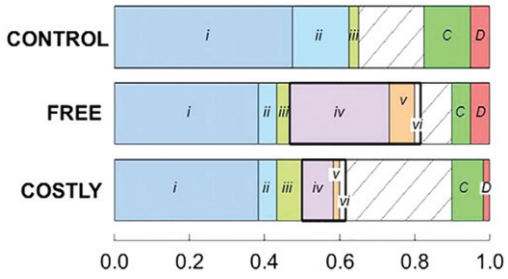

Fig. 10: Strategy diversity in the reputation-based behavior experiments. Bars represent the proportion of various strategies. Among them, blue bars refer to the strategies that just condition the cooperation on the first-order information, green bars are those strategies that make the decision only according to the behaviors of donors, thick black boxes denote the strategies that use the second-order information of recipients, hatched areas mean those strategies that cannot be categorized, C and D stand for those that always cooperate or defect, respectively. This figure is reproduced from [45].

that heterogeneous networks do not increase the level of cooperation in comparison with other regular or random ones. To be notably mentioned, Melamed *et al.* [48] conducted the large-scale online experiments, which enrolled up to 2675 agents to play the games, and they deployed the participants onto random or clustered networks that are static or dynamic, where individual reputation information could be accessed by any game player. The experimental results demonstrate that initially clustered networks may help to predict the cooperation on static networks, but not dynamic ones, meanwhile proving that reputation information is conducive to selecting the cooperative partners, but the promotion of cooperation is primarily attributed to the dynamic switching of links between players.

Conclusions and outlooks. – This brief survey outlines the recent advances in the field of reputation modeling and behavior experiments. Theoretically, it is clearly found that introducing the reputation mechanism will substantially foster the evolutionary cooperation within the population, and various reputation models including the first-order, second-order and even higher-order evaluations are built to comprehend the impact of reputation on the cooperative behaviors. Experimentally, when the game is played, providing enough information on the individual strategy and reputation status can help players to make the rational decision, which eventually leads to the considerable increase of the level of cooperation, especially in static networks.

Although current works greatly promote the understanding of reputation or indirect reciprocity in the evolution of cooperation, there are also some valuable and potential directions to be further explored in the future. On the one hand, an open and hard task is to devise the effective and reliable reputation evaluation rules, which powerfully contribute to perform the strategy choice for

any rational player. On the other hand, reputation as an important means of indirect reciprocity, is combined with other reciprocal mechanisms, such as direct or network reciprocity, to disentangle the role of different reciprocity mechanisms in the human cooperation, that is, constructing the theoretical models or designing experimental schemes considering multiple reciprocity is an interesting topic, which is worthy of being probed in depth.

Data availability statement: No new data were created or analysed in this study.

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