Punishment diminishes the benefits of network reciprocity in social dilemma experiments

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Network reciprocity has been widely advertised in theoretical studies as one of the basic cooperation-promoting mechanisms, but experimental evidence favoring this type of reciprocity was published only recently. When organized in an unchanging network of social contacts, human subjects cooperate provided the following strict condition is satisfied: The benefit of cooperation must outweigh the total cost of cooperating with all neighbors. In an attempt to relax this condition, we perform social dilemma experiments wherein network reciprocity is aided with another theoretically hypothesized cooperation-promoting mechanism—costly punishment. The results reveal how networks promote and stabilize cooperation. This stabilizing effect is stronger in a smaller-size neighborhood, as expected from theory and experiments. Contrary to expectations, punishment diminishes the benefits of network reciprocity by lowering assortment, payoff per round, and award for cooperative behavior. This diminishing effect is stronger in a larger-size neighborhood. An immediate implication is that the psychological effects of enduring punishment override the rational response anticipated in quantitative models of cooperation in networks.

cooperation | defection | node strategy | payoff | evolutionary selection

From ancient hunters to modern civilizations, the stability of human societies has been maintained via various kinds of partnerships in which a cooperator usually incurs a cost to benefit others (i.e., altruistic phenotype) (1–3). It is unclear, however, why natural selection would favor cooperativeness amongst selfish individuals (4, 5). Aiming to resolve this puzzle, researchers from multiple disciplines have relied on evolutionary game theory to better understand how the benefit disadvantage could be overcome in the face of exploitation (6–8). A quintessential model in evolutionary games has been the prisoner's dilemma (PD), a succinct formulation of the tradeoff between cooperating for a common good and defecting for a personal interest (9, 10). In a PD game, the said tradeoff is faced by two opponents who choose between cooperation (C) and defection (D) to obtain seemingly the best possible payoff. One of the first approaches toward resolving the PD originated from the fact that cooperation in the real world often involves repeated interactions. This insight sparked a considerable interest—and ultimately progress—in understanding the evolution of cooperation from both theoretical and experimental viewpoints (11–15).

Past studies show that alleviating the decline of cooperation in repeated interactions calls for (*i*) particularly crafted strategies such as tit-for-tat (16), (*ii*) collective scoring and information-sharing schemes to establish reputation (17, 18), (*iii*) positive behavioral reinforcement with reward (19–21), or (*iv*) social-control mechanisms as exemplified by costly punishment (22–25). Here, costly punishment (P) is an independent action that lets an individual purposely incur a cost in order for the opponent to pay an even higher fine. This action has the potential to help cooperative trends (26–28), but it is not without controversy. When punishment is available, for instance, there is a valid concern of second-order free-riding. Furthermore, within the framework of indirect reciprocity, costly punishment provides only a narrow margin for the perseverance of cooperation, and the collective benefit is often reduced (29). Experiments involving social dilemma games also raise some doubts about the role of costly punishment because there are instances when punishment is simply ineffective (30, 31), and even when it is effective, the most successful individuals refuse to punish others (31, 32).

Another recognized cooperation-promoting factor is social structure (5, 8, 15). When individuals are arranged in a network of contacts, the only possible interactions are with immediate neighbors. In such circumstances, theory predicts that cooperative individuals self-organize into clusters to avoid being wiped

Significance

The evolution of cooperation has a formative role in human societies—civilized life on Earth would be impossible without cooperation. However, it is unclear why cooperation would evolve in the first place because Darwinian selection favors selfish individuals. After struggling with this problem for >150 y, recent scientific breakthroughs have uncovered multiple cooperation-promoting mechanisms. We build on these breakthroughs by examining whether two widely known cooperation-promoting mechanisms—network reciprocity and costly punishment—create synergies in a social dilemma experiment. While network reciprocity fulfilled its expected role, costly punishment proved to be surprisingly ineffective in promoting cooperation. This ineffectiveness suggests that the rational response to punishment assumed in theoretical studies is overly stylized and needs reexamining.

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out by defectors, thus giving rise to the notion of network reciprocity (33). This concept has been extensively tested with respect to network topology, for which theory suggests that heterogeneous connectivities are very effective in maintaining high levels of cooperation (34–37). Even in two interdependent networks, cooperativeness can be increased via synchronous formation of correlated clusters (38). Despite all of the attention from theorists, experimental evidence of the effectiveness of network reciprocity is fairly recent (39). A surprising result contradicting theoretical findings is that heterogeneous networks seem to be of little relevance for promoting cooperation (40). In dynamic networks, furthermore, only slow partner updating rate is capable of promoting cooperation by increasing assortativeness of the whole network (41–43).

Experiments show that network reciprocity promotes cooperation under a restrictive condition: The benefit of cooperation must outweigh the total cost of cooperating with all neighbors (39). Our question, therefore, is whether this condition can be relaxed by combining two cooperation-promoting mechanisms. Specifically, are there any synergies to be gained by aiding network reciprocity with costly punishment? Across a wide array of model definitions and hypotheses, quantitative approaches suggest a positive answer because costly punishment enhances cooperativeness, sometimes in abrupt manners that are reminiscent of first-order-like phase transitions in physics (44–46). Here, we attempt to validate these theoretical results by performing a social dilemma experiment and examining whether the option to punish helps improve the overall level of cooperation among individuals arranged in an unchanging (i.e., static) network of contacts.

We divided the experiment into three separate trials. In the control treatment (CD), participants played a traditional PD game in which C and D were the only available actions. Each participant interacted with two other individuals in one round, after which connections were randomly reshuffled to simulate the well-mixed interaction. The static network treatment with two neighbors (CD_2) consisted of the same game as CD but without reshuffling. The purpose was to measure the effectiveness of network reciprocity relative to CD. Finally, the static network treatment with punishment (CDP_2) consisted of the same game as CD_2, with P being available as an independent action. The purpose was to detect synergies between network reciprocity and punishment. Although it is possible to enrich the control treatment with action P, we did not consider such an enrichment because the resulting setting would have been very similar to that of refs. 30–32. In total, 225 participants were recruited to play 50 rounds of the game. The experiment was approved by the Tianjin University of Finance and Economics, as well as the Yunnan University of Finance and Economics Ethics Committees on the use of human participants in research, and carried out in accordance with all relevant guidelines. In particular, informed consent was obtained from all participants. The game was characterized by the following unilateral and bilateral payoff matrices:

$$\begin{array}{c} \\ C \\ D \\ P \end{array} \begin{array}{c} \begin{array}{cc} \text{Own}^1 & \text{Foe's}^2 \end{array} \\ \begin{pmatrix} -1 & 3 \\ 1 & -1 \\ -1 & -4 \end{pmatrix} \end{array} \Rightarrow \begin{array}{c} \\ C \\ D \\ P \end{array} \begin{array}{c} \begin{array}{ccc} C & D & P \end{array} \\ \begin{pmatrix} 2 & -2 & -5 \\ 4 & 0 & -3 \\ 2 & -2 & -5 \end{pmatrix} \end{array}. \qquad [1]$$

^{1}Own and ^{2}foe's benefit or cost

Because administering punishment requires effort, P is a costly action and a punisher pays one unit. A punishee experiences a relatively high loss of four units as a consequence. The exact ratio of 1:4 follows the recommendation from ref. 32. Further details on methodology are given in *Materials and Methods* and *SI Appendix*, *SI Materials and Methods*.

Results

Statistical data analyses revealed that network reciprocity promotes cooperation (Fig. 1). We report cooperativeness and its variation in terms of the median (M) and the interquartile range (IQR), respectively. In the control treatment (well-mixed interactions; CD), the level of cooperation was $M = 4\%$ with $\mathrm{IQR} = 8\%$. In the static network (CD_2), by contrast, the level of cooperation rose to $M = 38\%$ with $\mathrm{IQR} = 45\%$, which is significantly higher than in CD despite a large variation in the data (z-score -8.051; two-tailed Mann–Whitney U test $p < 10^{-9}$). Interestingly, in the static network with punishment (CDP_2), the level of cooperation was $M = 37\%$ with $\mathrm{IQR} = 40\%$, practically the same as in CD_2 (z-score -0.326; two-tailed Mann–Whitney U test $p = 0.741$). The same cooperativeness of participants in CD_2 and CDP_2 was surprising and shows that punishment fails to boost the cooperation-promoting effect of network reciprocity. It is furthermore notable that the lower level of defection in CDP_2 relative to CD_2 ($M = 52\%$, $\mathrm{IQR} = 36\%$ vs. $M = 62\%$, $\mathrm{IQR} = 46\%$, respectively) happened only because some participants replaced defection with punishment ($M = 7\%$, $\mathrm{IQR} = 10\%$) when this action was available.

To confirm that network reciprocity truly promotes cooperation, aside from a higher overall cooperativeness in the static network (CD_2) compared with the well-mixed interactions (CD), it was necessary to determine whether or not the level of cooperation in CD_2 decreased over time. We found that the well-mixed interactions were detrimental for cooperativeness, even though the level of cooperation could be quite high initially (Fig. 2*A*). During the first 10 rounds of CD, the nonlinear transient

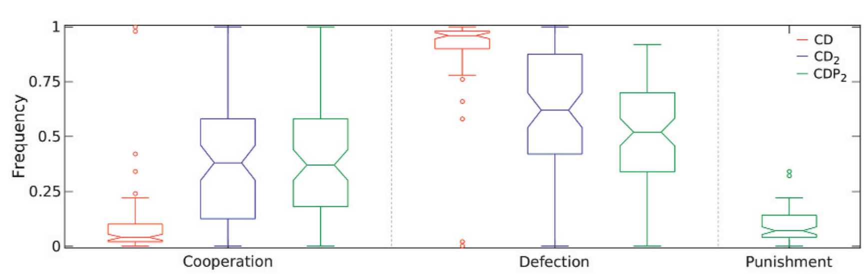


Fig. 1. Punishment fails to boost the cooperation-promoting effect of network reciprocity. Pairwise comparisons indicate that network reciprocity (CD_2) effectively increases the frequency of cooperation and decreases the frequency of defection relative to the well-mixed interactions (CD). Introducing punishment (CDP_2) has no effect on the frequency of cooperation beyond the level established by network reciprocity. Punishment is used seldomly, most often as a substitute for defection. Box-and-whisker plots with notches characterize the empirical distribution of action frequencies. Box height determines the IQR, while the horizontal lines in between represent the median. Notches make visual pairwise comparisons possible by indicating the 95% confidence intervals for the median. Whisker height is such that 99.3% of normally distributed data would be within the whisker-defined range. Points outside of this range are drawn as outliers.

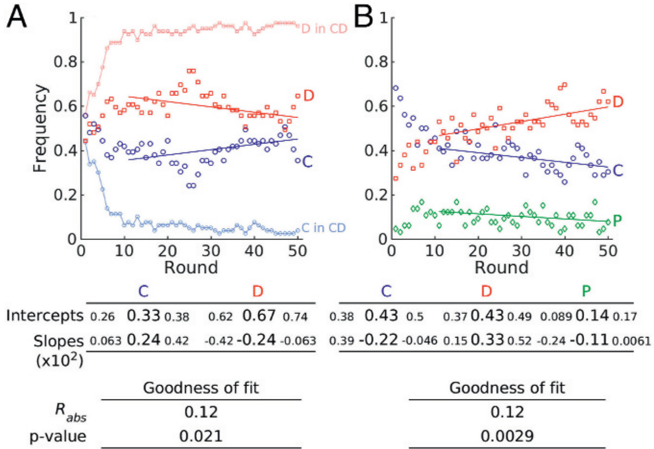


Fig. 2. Punishment interferes with the cooperation-stabilizing effect of network reciprocity. (*A*) Network reciprocity maintains a much higher frequency of cooperation than the well-mixed interactions. As indicated by the regression analysis, this frequency keeps slowly increasing over time at the expense of the frequency of defection. (*B*) When punishment is introduced, the frequency of cooperation is still relatively high, but the overall trend is now decreasing, thus hinting at a destabilizing impact of punishment on cooperation. The first 10 rounds are discarded in the regression analysis due to the strong nontransient dynamics at the beginning of experimental sessions. Smaller fonts indicate 95% confidence intervals.

dynamics was evidently strong, after which cooperativeness plunged to very low levels and stayed there for the remainder of a typical experimental session. Network reciprocity, however, was capable of maintaining a high level of cooperation throughout the experiment, despite some variability in the data (Fig. 2*A*). The regression analysis, after discarding the first 10 rounds, indicated that network reciprocity prevented cooperativeness from decreasing because the corresponding line slope was positive and statistically significant. This result was in sharp contrast with the experimental outcome when punishment was available (CDP_2). In CDP_2 (Fig. 2*B*), although the overall level of cooperation was similar as in CD_2, the regression analysis revealed that a line with negative, statistically significant slope fits the data, thus suggesting that, even after 50 rounds, cooperativeness was still decreasing. The described results are, therefore, consistent with the interpretation that punishment interferes with the cooperation-promoting effect of network reciprocity.

We identified clustering as a fundamental, cooperation-promoting mechanism in static networks (*SI Appendix*, *SI Results* and Fig. S4). Clustering is closely related to the concept of assortment—a measure of the extent to which cooperators recognize and group with other cooperators. To better understand how network reciprocity stabilizes cooperation, we defined assortment as a cooperator's average fraction of cooperative neighbors minus a defector's and, when available, a punisher's average fraction of cooperative neighbors. The time evolution of this quantity (Fig. 3*A*) showed that the level of assortment in the static network (CD_2) was consistently higher than in the well-mixed interactions (CD). Moreover, the regression analysis indicated that the static network stabilized assortment because the corresponding line slope was statistically indistinguishable from zero. A similar result was obtained in the presence of punishment (CDP_2; Fig. 3*B*), but the level of assortment was consistently lower than in CD_2 (z score 4.429; two-tailed Mann–Whitney U test $p < 10^{-5}$). In accordance with these results, punishment lowered the ability of cooperators to associate with other like-minded individuals.

In analyzing the anticipated synergies of network reciprocity and punishment, besides the overall level of cooperation, it is important to look at success as measured by payoff. An intuitive representation of payoff distributions by using the probability density (Fig. 4*A*) showed that network reciprocity (CD_2) led to considerably higher payoffs per round than the well-mixed interactions (CD). The payoff in CD was $M = 0.62$ with $\mathrm{IQR} = 0.68$ as opposed to $M = 1.52$ with $\mathrm{IQR} = 1.68$ in CD_2 (z score -5.830; two-tailed Mann–Whitney U test $p < 10^{-8}$; Fig. 4*B*). When punishment was introduced (CDP_2), the distribution of payoffs was still wider than in CD, but narrower than in CD_2 (Fig. 4*A*; see also Fig. 4*B* for pairwise comparisons). This narrowing was sufficient to push the payoff per round in CDP_2 back to $M = 0.58$ with $\mathrm{IQR} = 1.70$, which was indistinguishable from the level recorded in CD (z score -0.171; two-tailed Mann–Whitney U test $p = 0.864$; Fig. 4*B*). An inescapable conclusion here is that punishment harms the payoff per round, especially at the high end of the attainable range.

Generally, an action that leads to a higher payoff under the given circumstances is said to be better adjusted to these circumstances. We could therefore gain an insight into which actions were well-adjusted or maladjusted by analyzing the correlation between payoffs per round and action frequencies. We found that when the interactions were well-mixed (CD), cooperation was a maladjusted action because the regression analysis indicated that more cooperative individuals ended up with a lower payoff per round (Fig. 5*A*). This situation was reversed in the static network (CD_2), wherein more cooperative individuals were rewarded with a higher payoff per round. The same result was valid when punishment became available (CDP_2), yet the slope of the corresponding regression line was notably lower than in CD_2 (2.6 vs. 1.9; Fig. 5*A*). A lower slope in CDP_2 relative to CD_2 hinted at a potentially negative influence of punishment. This issue is addressed thoroughly below.

Defection in CD and CD_2 exhibited exactly the opposite characteristics to cooperation due to the constraint that frequencies of cooperation and defection must sum to unity (Fig. 5*B*). Defection is thus a well-adjusted action in CD, but maladjusted in CD_2. Furthermore, defection in CDP_2 has similar characteristics as in

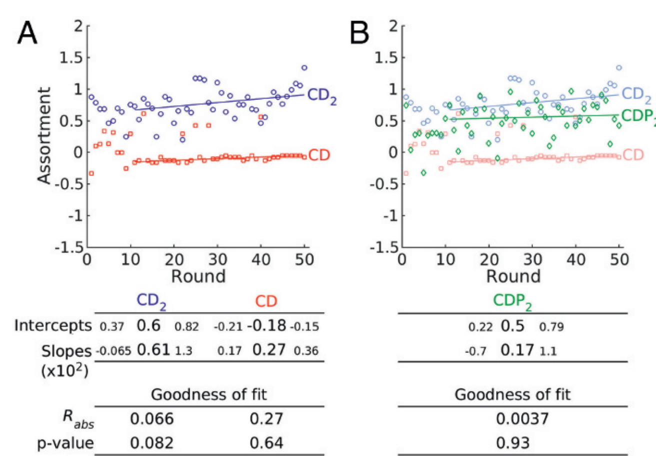


Fig. 3. Punishment lowers the ability of cooperators to associate with one another. (*A*) Network reciprocity (CD_2) stabilizes assortment—interpreted here as a measure of how well cooperators associate with other cooperators—at a much higher level than in the well-mixed interactions (CD). This stability is implied by the regression analysis because the line slope in CD_2 is statistically indistinguishable from zero. (*B*) Although assortment is not destabilized by punishment (CDP_2), as indicated by the corresponding line slope which is also statistically indistinguishable from zero, the achieved level of assortment in CDP_2 is consistently lower than in CD_2. The first 10 rounds are discarded in the regression analysis due to the strong nontransient dynamics at the beginning of experimental sessions. Smaller fonts indicate 95% confidence intervals.

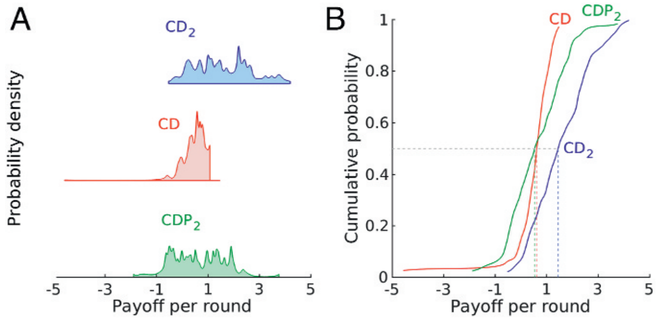


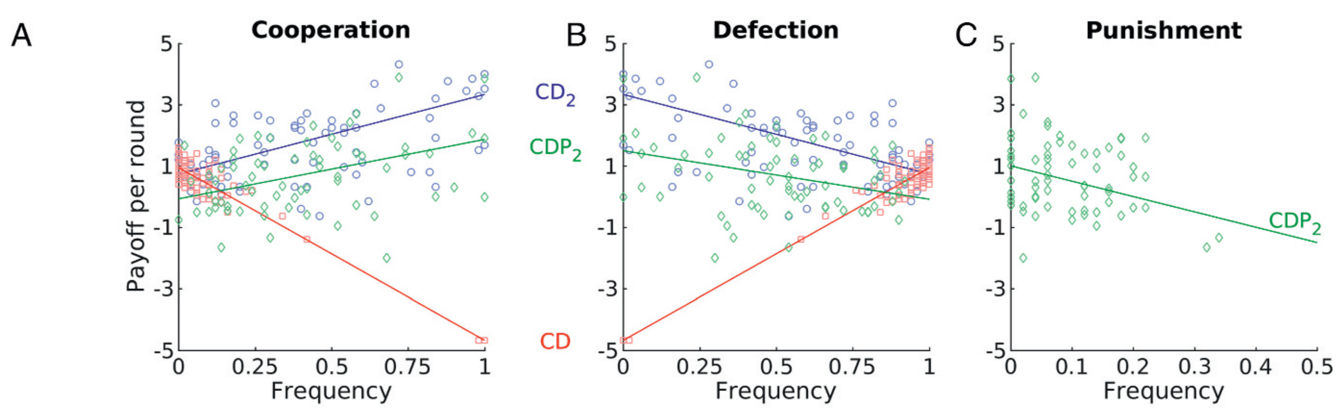
Fig. 4. Punishment reduces the obtainable payoff. (*A*) Probability densities intuitively show that network reciprocity (CD_2) has a positive effect on the payoff per round, allowing much higher values to be attained than the well-mixed interactions (CD). Punishment (CDP_2) partly counters this positive effect. (*B*) Cumulative probability distributions of the payoff per round reveal a much higher median in CD_2 than CD. When punishment is introduced, despite similar levels of cooperativeness in CD_2 and CDP_2, the median payoff is brought down to the value reached in the well-mixed interactions. Pairwise comparisons indicate that all three distributions are significantly different from one another (two-sided Kolmogorov–Smirnov test; $p < 10^{-5}$ for CD vs. CD_2; $p = 7.8 \times 10^{-4}$ for CD_2 vs. CDP_2; $p = 0.019$ for CD vs. CDP_2).

CD_2. This was reflected in the negative, statistically significant slope of regression lines between the payoff per round and the frequency of defection in both CD_2 and CDP_2, although the latter slope was notably lower in absolute value (-2.6 vs. -1.6; Fig. 5*B*). In fact, the goodness of fit for the regression line in CDP_2 was statistically indistinguishable from zero, giving us another hint that punishment poorly interacts with network reciprocity. The full extent of the problem became apparent in the static network in which neighborhood size equaled four (*SI Appendix*, SI Results).

Neighborhood size was an important factor affecting network reciprocity. Specifically, if neighborhood size increased, the level of cooperation decreased (cf $M = 38\%$, $\mathrm{IQR} = 45\%$ in CD_2 vs. $M = 9.0\%$, $\mathrm{IQR} = 26\%$ in CD_4; z score 4.670; two-tailed Mann–Whitney U test $p < 10^{-5}$; *SI Appendix*, Fig. S6). As before, aiding network reciprocity with punishment failed to increase cooperativeness (cf $M = 9.0\%$, $\mathrm{IQR} = 26\%$ in CD_4 vs. $M = 9.4\%$, $\mathrm{IQR} = 15\%$ in CDP_4; z score -0.280; two-tailed Mann–Whitney U test $p = 0.779$). Furthermore, almost the same levels of cooperation in CD_4 and CDP_4, and only a slightly lower level of defection ($M = 88\%$, $\mathrm{IQR} = 37\%$) in the latter treatment, implied that punishment ($M = 4.7\%$, $\mathrm{IQR} = 13\%$) was used as an occasional replacement for defection, but to no avail—network reciprocity weakened with neighborhood size. This notion was confirmed when success in terms of the payoff per round was related to action use (*SI Appendix*, Fig. S7). As expected, cooperation was a maladjusted action in the control treatment (CD). Although network reciprocity (CD_2) improved the prospects of cooperators, it was insufficient to establish a positive correlation between success and cooperativeness. The most defeating result, however, was that punishment (CDP_4) counteracted the positive effect of network reciprocity by making cooperation a maladjusted action once again. This result corroborated what was only a hint in CDP_2; namely, punishment acted to erase the reward that network reciprocity brought to cooperators.

Discussion

Social dilemma experiments described here yielded two main results. First, network reciprocity has proven effective in promoting



A — Cooperation

	CD_2			CD			CDP_2		
Intercepts	0.19	0.73	1.1	0.81	0.94	1	-0.74	-0.074	0.5
Slopes	1.7	2.6	3.4	-6.2	-5.6	-4.9	0.69	1.9	3.2

Goodness of fit	CD_2	CD	CDP_2
R_{abs}	0.17	0.43	0.086
p-value	0	0	0.0044

B — Defection

	CD_2			CD			CDP_2		
Intercepts	2.6	3.3	3.8	-5.2	-4.7	-4	0.67	1.5	2.2
Slopes	-3.4	-2.6	-1.6	4.9	5.6	6.2	-3	-1.6	-0.12

Goodness of fit	CD_2	CD	CDP_2
R_{abs}	0.17	0.43	0.056
p-value	0	0	0.061

C — Punishment

	CDP_2		
Intercepts	0.46	1	1.7
Slopes	-10	-5	0.086

Goodness of fit	CDP_2
R_{abs}	0.024
p-value	0.35

Fig. 5. Network reciprocity awards cooperativeness with less success when punishment is available. (*A*) Cooperation is a maladjusted action when the interactions are well-mixed (CD) because the corresponding payoff per round correlates negatively with the frequency of cooperation. Network reciprocity (CD_2), by contrast, makes cooperation a preferable action as indicated by the positive correlation between the payoff and cooperation. After introducing punishment (CDP_2), cooperation is still a preferable action, but the corresponding line slope is notably (although not statistically) lower. (*B*) Opposite to cooperation, defection is a preferable action in CD, but maladjusted in CD_2. Whether defection is still maladjusted in CDP_2 is questionable. While the estimate of the corresponding line slope is negative and statistically different from zero, the overall goodness of fit is indistinguishable from zero—the apparent correlation between the payoff per round and the frequency of defection may well be a fluke. (*C*) Punishment appears to be a maladjusted action, but seldom use of this action and considerable scatter preclude any statistical significance. Smaller fonts indicate 95% confidence intervals.

cooperation (Figs. 1 and 2). This result confirmed the recent findings in ref. 39, with the addition of identifying clustering as the key mechanism by which network reciprocity promotes cooperativeness (*SI Appendix*, Fig. S4). Clustering is interesting from an ecological perspective because closely related animals often protect themselves or gain food more efficiently by gathering in groups such as herds. Human ability to communicate may have helped to extend these grouping tendencies beyond just the closest relatives.

Nevertheless, the levels of cooperation in the static network remained significantly below 50%, thus suggesting room for improvement. This naturally led to a question of whether aiding network reciprocity with another hypothesized cooperation-promoting mechanism—such as punishment—would boost the level of cooperation observed in static networks. Much to our surprise, punishment not only failed to boost cooperativeness, but also countered some positive aspects of network reciprocity. Why? Our data suggest an interplay between three different factors.

Decreased assortment in the static network with punishment (Fig. 3) is an indication that cooperators have a harder time identifying one another when punishing is possible. A likely reason is that punishment sends a mixed signal to neighbors. While the implied message when punishing someone is "I want you to be cooperative," the immediate effect is more consistent with the message "I want to hurt you." Evidence that punishing in social dilemma experiments can be interpreted in the latter way is seen in occasional retaliatory use of punishment whereby participants punish one another consecutively for several rounds without becoming any more cooperative than they were to begin with (31, 32). This furthermore suggests that a response to punishment may be driven by impulse as much as reason, if not more.

The fact that punishment reduces the payoff per round (Fig. 4) reveals an overall demoralizing effect of this action. Namely, individuals who get punished on multiple occasions may see a good chunk of their total payoff vanish in a short period. Breaking off from the rest of the pack thus becomes more difficult, which in turn may cause doubts about one's performance. With grim prospects for achieving a satisfactory success, players may lose interest in the game and play the remaining rounds in a less coherent manner.

Even if players remain interested in the game to the last round, punishment seems to reduce—if not eliminate—the incentive to eventually choose cooperation over defection. Namely, from the perspective of evolutionary game theory, completely rational players should cling only to actions that lead to an above-average payoff, whereas other actions should die out. This type of "selection" process should persist until only the best action(s) remain. Although the behavior of human participants in a social dilemma experiment may deviate from complete rationality, it is in line with our expectations that success, expressed in terms of the payoff per round, correlates positively with the frequency of cooperation in static networks (Fig. 5). Otherwise there would be little rationale to select cooperation over defection. However, even the results in a smaller-size neighborhood already hint that punishment blurs the positive correlation between success and cooperativeness. This hint is confirmed in a larger-size neighborhood in which network reciprocity is weaker and thereby unable to prevent punishment from completely reversing the correlation between success and cooperativeness (*SI Appendix*, Fig. S7). Players, therefore, have no way of learning to associate cooperation with success, which makes a wider adoption of this action unlikely.

Punishment has proven ineffective in our experiment, which begs the question why punishing is so ubiquitous in the real world. A partial answer would be that human brain seems to be hardwired to derive pleasure from punishing defectors (47). From a fundamental perspective, however, a more satisfying answer would be that there are alternative situations in which punishment's role as a cooperation promoter is substantial. We speculate that such situations may include asymmetries whereby one dominant side has the ability to punish without provoking retaliation. Perhaps even a variant of the present experiment would end up differently if punishment brought "more bang for the buck," i.e., if the fine associated with punishment in Eq. **1** were higher. This brings us to an important limitation of our and similar approaches.

In analyzing our experimental results, general conclusions about human behavior were drawn based on the use of a single or, at best, a few payoff matrices such as the one in Eq. **1**. Instead of basing conclusions on limited information, a preferred course of action would be to specify and systematically vary six parameters in the unilateral payoff matrix. However, executing the necessary number of treatments and replicates may cause considerable logistic strain on experimenters. Examples of such strain include the need for an excessive number of recruits, the financial burden of repeatedly paying participation fees, and an increase in the time required to execute all aspects of an experimental study. In the face of the described limitation, therefore, we have little choice but to extract valuable insights from the available data while keeping in mind that it would be unwise to extrapolate the implications of social dilemma experiments on human behavior far beyond the setting in which these experiments were conducted in the first place.

Materials and Methods

Experimental Methods. For the purpose of conducting the experimental treatments described herein (CD, CD_2, and CDP_2), we recruited 225 undergraduate volunteers—mean age 20.2 y; female-to-male ratio approximately 1:1; multiple majors—from two universities in China: Tianjin University of Finance and Economics in Tianjin and Yunnan University of Finance and Economics in Kunming (for more details, see *SI Appendix, SI Materials and Methods* and Table S1). All participants engaged in a repeated PD game played in the professionally designed computer laboratories of both universities. Upon arrival, participants were randomly assigned to isolated computer cubicles, where a computer screen would display the instructions on experimental procedures. Subsequently, all participants were required to complete a short questionnaire (*SI Appendix*, Fig. S1) to verify their basic understanding of the game rules. Before beginning an experimental session, several practice rounds were played against two random opponents to let participants familiarize themselves with the experimental interface (*SI Appendix*, Fig. S2*A*). Opponents were kept anonymous apart from displaying an "opponent number" to allow examining the result of each action more easily (*SI Appendix*, Fig. S2*B*). Treatments were implemented in z-Tree, a specialized software package for socioeconomic experiments (48).

The three experimental treatments differed in (*i*) how participants connected with one another and (*ii*) what actions were at their disposal. In the control treatment (CD), each participant played a traditional PD game—in which cooperation (*C*) and defection (*D*) were the only available actions—against two opponents at a time. These opponents were randomly chosen in each round (42). In the static network (CD_2), opponents were no longer randomly chosen, but instead participants formed a ring in which the first two neighbors acted as the game opponents (*SI Appendix*, Fig. S3). This arrangement was unchanged during the game. Finally, the static network with punishment (CDP_2) differed from CD_2 only in that punishment (*P*) was available as an independent action. According to these definitions, the role of treatments CD_2 and CDP_2 was to establish the cooperation-promoting effect of network reciprocity relative to CD and the cooperation-boosting effect of punishment relative to CD_2, respectively.

All treatments consisted of two replicates (i.e., sessions or games) played between December 2015 and September 2016 by participants who had no prior experience with this kind of social dilemma experiments. No participant was allowed to play more than once. A game consisted of 50 rounds, which took ∼1 h to complete. Participants remained unaware of the exact number of rounds to avoid possible finite-game opportunism (49). One round was completed only after all participants chose their preferred actions and examined the consequences thereof. The time allotted for each of these tasks was 30 s.

Players' success was measured in terms of their total payoff, updated after every round as prescribed by Eq. **1**. This payoff was added to an initial endowment of 50 points. To provide participants with an incentive, the final endowment accumulated throughout a game was translated into the Chinese renminbi at a rate of ¥0.5 per point. If the accumulated endowment was negative, participants would still get a show-up fee of ¥15. Eearnings ranged from ¥15 to ¥148, with an average of ¥65. Before being paid out, participants were asked to confirm their final endowment and sign a cash receipt form.

Statistical Methods. Probability distributions behind socioeconomic data are rarely known. To avoid assuming any underlying distribution, we used nonparametric descriptors (e.g., median and IQR) and statistical tests (e.g., Mann–Whitney U test). Furthermore, linear regression analyses were used to determine trends and correlations in the data. Because socioeconomic data often exhibit high variation by which a few data points can disproportionately affect the results of the ordinary least squares regression, we replaced squared with absolute distances and thus reduced the effect of the potential outliers on the estimated regression parameters. This was qualitatively similar to using the quantile regression, except that minimizing the sum of absolute distances allowed for a more intuitive interpretation. The goodness of fit was assessed by using a measure analogous to the square root of the coefficient of determination, defined as $R_{\mathrm{abs}} = 1 - SA_{\mathrm{res}}/SA_{\mathrm{tot}}$, where SA_{res} is the sum of absolute residuals and SA_{tot} is the sum of absolute distances from the data mean. By definition, $0 \leq R_{\mathrm{abs}} \leq 1$, where the lower (upper) bound signifies the presence (absence) of random scatter. All 95% confidence intervals were obtained by means of bootstrapping.

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