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Social mobility and network reciprocity shape cooperation in collaborative networks

Wen-Jing Li [a,b], Zhi Chen [c], Jun Wang [a,b], Luo-Luo Jiang [d], Matjaž Perc [e,f,g,h,i,*]

[a] College of Information Engineering, Zhejiang University of Water Resources and Electric Power, Hangzhou, Zhejiang 310018, China
[b] International Science and Technology Cooperation Base for Utilization and Sustainable Development of Water Resources, Hangzhou, Zhejiang 310018, China
[c] Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China
[d] School of Information Management and Artificial Intelligence, Zhejiang University of Finance and Economics, Hangzhou, Zhejiang 310018, China
[e] Faculty of Natural Sciences and Mathematics, University of Maribor, Koroška cesta 160, 2000 Maribor, Slovenia
[f] Department of Medical Research, China Medical University Hospital, China Medical University, Taichung 404332, Taiwan
[g] Alma Mater Europaea, Slovenska ulica 17, 2000 Maribor, Slovenia
[h] Complexity Science Hub Vienna, Josefstädterstraße 39, 1080 Vienna, Austria
[i] Department of Physics, Kyung Hee University, 26 Kyungheedae-ro, Dongdaemun-gu, Seoul, Republic of Korea

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ABSTRACT

Relationships in social networks change over time due to various factors, including mobility, preferences for moral behavior, and the consequent making and breaking of social ties. We therefore study how these factors affect cooperation in actual collaborative networks, where individuals adaptively move with a certain probability. We find that individuals preferentially move towards the sites with a high degree, which yields networks with a higher average degree, but at the same time is conducive to cooperation because positions at the hubs are most beneficial in that way. On the one hand, social mobility thus enhances network reciprocity by generating much more cooperation seeds than the original network, but on the other, it also washes out the network structure and creates well-mixed like conditions if too frequent. Thus, only with limited mobility is network reciprocity optimally enhanced and can yield best conditions for robust cooperation in social networks. And we expect optimal conditions for other forms of moral behavior to require the same patterns of moderate social mobility.

1. Introduction

The remarkable progress of human beings comes down to amazing capability of extensive cooperation from every aspects [1,2]. The factors contributing to this cooperation include kin selection, direct or indirect reciprocity, group selection and partner choice, etc [2,3]. Among them, network reciprocity plays an important role in human social interaction. To date many kinds of network structures have been studied by scholars. Nowak and May in their pioneer work found that the spatial structure can enable cooperators to form clusters and thus affect the cooperation [4]. Then other researches were conducted on different network structures, e.g., regular networks [5], complex heterogeneous networks such as scale-free networks [6–9], interdependent networks [10,11], and dynamical networks [12]. These network structures could greatly influence the spreading of cooperation. For example, social networks may effectively promote disadvantaged cooperators to gather into clusters, inducing higher benefits of cooperators' group. When such cooperative clusters grow, a strong cooperation will eventually be established through the evolution [7,8]. Here social networks provide a link which connects benefits between individuals and clustering groups, and help maintain a stable level of cooperation. Therefore, although some individuals constantly try the defect strategy to obtain their greater benefits which may have advantage in short term, network reciprocity can still be spread through this link and acts of goodwill usually receive corresponding responses.

Recent studies also indicate that social mobility heavily influence the spreading of cooperation. Especially, when the population is low, the introduction of costly movement is usually harmful to defectors. Social mobility thus provides a significantly higher cooperation level [13]. However, at an intermediate population density, the situation is more complex and the presence of mobile individuals could be detrimental to the society under certain circumstances [13]. Further, from an agent-based modeling approach, there has been causal evidence supporting that higher relational mobility promotes greater network integration [14]. And empirically, the societies with higher relational

* Corresponding author at: Faculty of Natural Sciences and Mathematics, University of Maribor, Koroška cesta 160, 2000 Maribor, Slovenia.
E-mail address: matjaz.perc@gmail.com (M. Perc).

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mobility present more proactive interpersonal behaviors [15]. Lastly, positioning in the mobility is also important: a few cooperators can spread cooperation better if they are well strategically positioned than a large number of cooperators which are placed badly do [16].

Based on the discoveries presented above, A question is naturally raised: can cooperative clusters in mobile networked populations keep separated from the environment of defectors? A positive answer would imply that the collective cooperation is enhanced by these cooperative clusters. To this end, in current research we propose to investigate how combination of mobility and network reciprocity on collaborative networks affect cooperation through simulations of Prisoners' dilemma (PD) game.

So far, researches on the role of social mobility in public cooperation have mainly focused on spatial games. However, in the network game based on social relations, social mobility is more common, because individuals tend to pursue higher positions and better relationships. The scenario here is similar to that of the population mobility in social networks, which connects enterprises and individuals and is often manifested in the mobile social interaction of individuals. For example, when an employee has left and made a vacant position in the enterprise, the social relationship between the enterprise and the enterprise could still exist. The impact of such mobile social interaction on cooperation is still poorly understood. Thus far more work on this matter is calling. We further note that in previous studies on this matter individuals tend to punish defectors. Nevertheless such action inevitably brings the cost of punishment. To better assess the impact of mobile social interaction on the evolution of cooperation, in current study we switched off the punishment and individuals in the game move driven by the social mobility, where players were wrestling to distance themselves from defectors. With the similar mechanism on regular lattice, a limited mobility of minorities has been found to facilitates cooperation in social dilemmas as long as the network reciprocity is still functioning [17].

In our previous study [18,19], we investigated the combination of one aspect of multidimensional mobility and network reciprocity on a regular lattice. And we found that such combination facilitates cooperation remarkably, provided a limited mobility rate is in used. However, if the mobility rate is high, the synergy between mobility and network reciprocity weakened due to decreasing odds of meeting old interactive partners. As a result, collective cooperation fails.

In current study we propose to extend the study of combination of the mobility and network reciprocity on cooperation to more complex heterogeneous networks. On one hand, the heterogeneity could interact with the collective cooperation. For example, heterogeneous networks have shown the ability to strongly promote the emergence of prosocial behaviors in social goods dilemmas [20]. Specifically, compared to regular networks, heterogeneous scale-free networks may provide much more cooperators on the network of contacts (NOCs) and induce the emergence of cooperation [7]. On the other hand, despite the interaction between two individuals are opted to structure, in real world environment some nodes (positions) often have evolutionary advantage over others, e.g., certain people may have far more number of friends than others. Such advantage could induce heterogeneity in the network.

In current study, we adopt both true networks and BA scale free network and characterize quantitatively the degree of the nodes. Our simulation results indicate that a limited mobility facilitates cooperation effectively despite different types of networks. This level of mobility could alienate defectors and avoids behavior of mutual defecting while network reciprocity is functioning. Thus cooperation is enhanced. We also observe that mobile individuals move preferably towards the sites with high degree when they adaptively move. Such adaptive mobility rebuilds the network structure through the evolution. Individuals on sites with high degree would generally cooperate voluntarily. Thus mobility enhances network reciprocity by generating much more cooperation seeds than original network. As a result, cooperation is further enhanced. However, when the mobility is too high, network reciprocity is weakened due to decreasing odds of meeting old interactive partners and the collective cooperation would fail. We hope our results could help understand how mobility and network reciprocity together affect cooperation in real world.

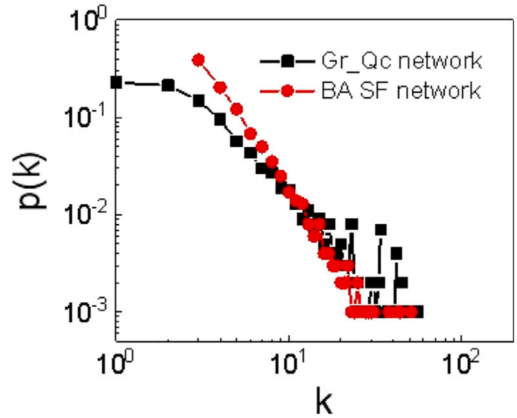

Fig. 1. The degree distribution of a collaborative network (Gr_Qc network) as well as of a BA scale free network (BA SF network), both of which have 5242 nodes, and average degree $\langle k\rangle \approx 3$.

2. Models

Networks. Various social networks are ubiquitous in reality. To characterize the relationships between population, we here considered a true collaborative network dataset General Relativity and Quantum Cosmology (Gr_Qc) [21], which covers scientific collaborations between authors who submitted papers to General Relativity and Quantum Cosmology category from January 1993 to April 2003. On this graph, if an author i co-authored a paper with the author j, then there is an undirected edge between i and j. If the paper is achieved by k authors, a completely connected graph on k nodes is generated. This dataset contains 5242 nodes and 14496 edges totally.

The edge between any two nodes on the graph represents interactive relationships between two individuals technically. Neither like regular lattice where there are four direct neighboring nodes for each node, nor like networks generated by algorithms we are acquainted with, there seem no simple rules that how this collaborative network creates. The uncertainty about how edges link is the major difference between true network and network models. In spite of it, it is found that the collaborative network follows power-law degree distribution basically, as shown in Fig. 1. For the sake of comparison, we also considered a BA scale free network [6] which has similar degree distribution as well as the number of nodes and edges with the collaborative network. It is found that the most of actual networks in reality follow power-law degree distribution on the whole, although they do not obey it completely. Specifically, the number of sites with low degree is smaller than that of BA scale free network. On one hand, the gap between both degree distribution curves turns larger as k decreases. On the other hand, the nodes with lower degree than average degree $\langle k\rangle$ (≈ 3) actually exist on true network instead of network models. In addition, the average clustering coefficient of collaborative network is about 0.5296, which is far higher than that of BA scale free network 0.01 namely.

Mobility. In reality, new chances may generate through mobility for individuals particularly for the ones trapped in dilemmas. By abandoning former negative partners, they would rather move away to rebuild new social relationships technically. Thus, mobility mechanisms affect cooperation only on structured interactions, whereas it loses impact on random interactions, such as well-mixed population. Based upon following two considerations, we thus construct our models on a collaborative network instead of network models. Firstly, as one of the representative ubiquitous social networks, Gr_Qc network exhibits some unique properties that network models do not show, which may benefit deep understanding of cooperation. Secondly, the method of combining modeling with true network dataset could narrow down the gap between theory and reality.

From the perspective of games, all potential negative impacts for an individual could be attributed to the existence of defector partners. The behavior of mobility for individuals is triggered by avoiding exploitation by defectors [22–27]. Thus, the adaptive mobility mechanism [22] is considered here for it characterizes the friendliness of individuals' surroundings quantitatively. The odds of moving away for an individual is positively related to the number of defectors in his/her community, which conforms more to reality. Considering the fact that not all mobility could be achieved for human beings in reality, we thus introduced a parameter mobility probability p to signify the odds of mobility. For an individual provided a hospitable surroundings (being surrounded by cooperators), he/she would rather stay put than migrate away. Whereas for those in dire need of complete change, opportunity of mobility comes precious. In our models, an individual could choose one of empty sites in his/her direct neighborhood randomly before he/she moves. In case of the shortage of empty sites, individuals fails to move. In areas with high population density, the risk of mobility failure is particularly high [18]. Initially, the empty sites (population) are randomly and evenly distributed on the whole network with 30.00% (population density is about 70.00%) probability [17].

PD Game. Prisoners' dilemma (PD) is one of the most commonly adopted game models to characterize social dilemmas. In a PD, each individual has two strategies to obtain his/her payoff, either cooperate (C) or defect (D). The according payoff depends on not only his/her own strategy but also his/her partner's strategy. Both cooperators (defectors) share rewarding payoff R (punishing payoff P). The cooperator encountering defectors gets sucking payoff (S), whereas the defector obtains temptation payoff (T). In a PD, the parameters satisfy both $2R > T + S$ and $T > R > P > S$. Here, we set R=1, P=0 for simplicity. Without losing generality, we introduced a parameter δ to obtain $T = 1 + \delta$ and $S = -\delta$ to characterize dilemmas quantitatively. The payoff matrix is as follows.

$$\begin{array}{cc} & \begin{array}{cc} \mathbf{C} & \mathbf{D} \end{array} \\ \begin{array}{c} \mathbf{C} \\ \mathbf{D} \end{array} & \begin{pmatrix} 1 & -\delta \\ 1+\delta & 0 \end{pmatrix} \end{array}, \tag{1}$$

Here, δ reflects the extra profit that defectors possibly take but at cooperator's expense. The strength of dilemmas is positively related to δ. In the absence of effective mechanisms functioning, cooperation frequency falls as δ increases theoretically.

Remarkably, human beings have the ability to observe and copy successful behaviors. Limited by information spreading path etc, the most successful behavior in a community is well known and popular [28–32]. Here, the most profitable local strategy updating rule is thus adopted in our model. Initially, individual either cooperates or defects randomly. In our scenario, each individual has two approaches to raise his/her payoff, either moves with a p probability, or updates strategy with 1-p probability accordingly. To investigate the cooperation level of the system, we center on the parameter cooperation frequency f_C, which is the ratio of cooperators to whole population. After enough relaxation time, we average last ten points to obtain one data point. Considering the possible effect of initialization as well as calculating time, we run another 100–400 simulations to average out each data point finally.

3. Simulation results

We firstly investigate how mobility probability p affects cooperation frequency f_C on both collaborative network and BA scale free networks, as shown in Fig. 2 (A) and (B) respectively. In terms of $p = 0.0$, all individuals would update strategies rather than migrate. Due to network reciprocity, f_C value is far higher than 0.0 which is obtained on well-mixed population [18]. In addition, f_C is sensitive and inversely proportional to δ in both panels. On both networks, it is found that the value of f_C is quite different for same δ, which suggests network reciprocity differs. Although they have similar number of nodes and edges as well as similar degree distribution, two heterogeneous networks may have quite distinctive structures. In helping cooperators surviving, network reciprocity mainly determined by structure plays the major role in the absence of other mechanisms. In terms of large δ, between short-term high payoff as a defector and severe loss as a sucker, a reasonable individual would rather behave as a defector. Huge economic interests may generate lots of deal-breaker even between old cooperative partners. A subsequent rise in the number of defectors may get the system stuck in stagnation or crippled totally. Besides network reciprocity, there is an urgent need for other more effective mechanisms to shake off this difficult situation.

Better yet, the situation is vastly different if individuals could move. There is a wide range of p that could enhance cooperation on both networks for small δ, such as $\delta = 0.3$. To promote cooperation, it seems positive and unconditional for p in weak dilemmas (small δ). Mobility mechanism itself is the key to high cooperation. As δ grows, the increasing temptation cracks the borderline of more and more potential cooperators. Facing high temptation, they give up resistance and surrendered as defectors. Remarkably, it is observed that small p is still effective to facilitate cooperation even in dilemmas with high temptation such as $\delta = 0.5$. The similar results are also found on BA Scale free network, as shown in panel (B). Either on regular lattice [18,19] or on heterogeneous network in current simulations, interestingly to find that the changing trend of f_C curves is similar, which suggests the impact of p on cooperation does not concerned the social networks.

By further observation on f_C curves obtained on collaborative network and networks generated by algorithms, it is found that there is a big gap between f_C maximums. Be more specific, the maximum of f_C obtained on network models (such as BA scale free network or regular lattice) is as high as 1.0, which is far higher than that on collaborative network, 0.80 or so. It occurs to us that whether the network reciprocity of network models works better than that of collaborative network on promoting cooperation. This argument is not tenable for following reasons. Firstly, in terms of $\delta = 0.5$, the maximum of f_C on collaborative network is 0.75 or so, which is much higher than that on BA scale free network, 0.65 namely. In addition, the effective range of p on promoting cooperation on collaborative network is much wider than that on network models for same δ. It is thus interesting to figure out what may result in the f_C maximum gap between collaborative network and network model.

Comparing with collaborative network, the structures of network models are predicable because they are generated by according algorithms. Whereas the structures of true networks are various and complicated. To expand our knowledge of the collaborative network, we show its structure as well as the strategy distribution on it directly and visually, as shown in Fig. 3. Initially, equal proportion of cooperators (green spot) and defectors (red spot) are randomly distributed on sites without distinction of site degree or group size, as shown in panel (A). One observes that there are lots of small isolated groups at the outer ring area. Among them, there are a few links in groups internally, and few or no links with other groups externally. In the center area, one observes a mass of sites as well as links. Obviously, a number of hubs occupied either by cooperators or defectors show up well against white background.

After relaxation time, the dynamic equilibrium of evolution is shown in panel (B). On the whole, the distribution of colors is more clearly distinct apart from sporadic red hubs. With almost green (cooperator) center and red (defector) outer ring, both cooperators and defectors are separated. Note that, the size of central cooperator groups is far larger than outer ring area defector groups. In addition to these, it is found that the population groups seem homogeneous ignoring empty sites, either cooperator groups or defector groups.

Note that the collaborative network is a real heterogeneous network, which is generated after a period of evolution. In this graph, there exists a large number of small groups where an author co-authored

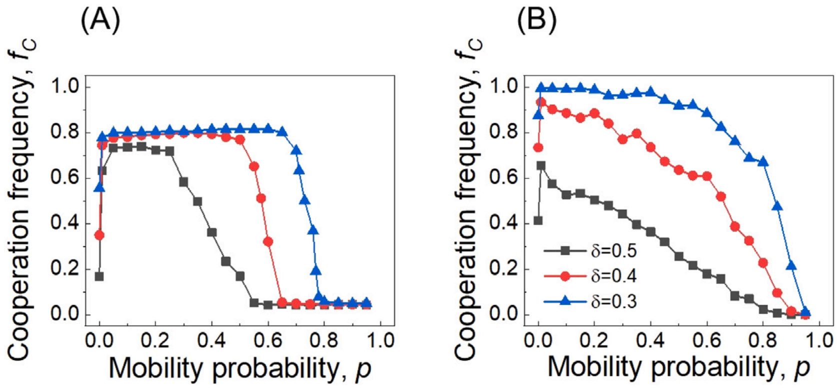

Fig. 2. Cooperation frequency (f_C) as a function of p on different networks. Both panels show the f_C curves obtained on collaborative network (A) and BA scale free networks with $\langle k \rangle \approx 3$ (B) respectively. A limited mobility yields robust cooperation, which does not concerned network.

papers with same authors, as well as big groups where a few of authors co-authored papers with different authors. In any one of groups, the first author is the hub site. Actually, no matter what type of the network is, the site where an individual locates reflects the way that he/she survives, and characterizes his/her evolutionary advantages in reality. Obviously, the cooperators take over a large percentage of sites in big groups, and leave available sites in small groups for defectors. Although the cooperators benefit from limited mobility, the individuals in small defector groups could not get rid of dilemmas either by mobility or social learning due to physical disconnection. These considerable number of crippled small defectors groups are the main reason for low maximum of f_C.

Due to unique heterogeneous structure of the collaborative network, we observed small p creates situation advantageous to mobile cooperators who occupy sites in large groups. Remarkably, there seems little interactive relationships between cooperators and defectors. Without considering empty sites, there are 3 different types of edges in total among population, C–C, C-D and D-D namely. We further calculate the proportion of three types of edges for different p in quantitative dilemmas, as shown in Fig. 4. Despite of different δ, three according curves have similar changing trends on the whole. Obviously, the proportion curve of C–C edges is consistent and similar with f_C curve over p in Fig. 2. Whereas the proportion curves of D-D edges show opposite changing trend with C–C curve accordingly. Yet, the proportion of C-D curves is almost a constant 0.0 approximately except p=0 which is higher obviously than other cases.

The cooperation frequency f_C highly depends on the proportion of C–C edge, as well as correlates with the proportion of other two types of edges. Their relationships with f_C could be simply written as

$$f_C \propto \frac{\chi_{CC} + \frac{\chi_{CD}}{2}}{\chi_{CC} + \chi_{DD} + \frac{\chi_{CD}}{2}} \tag{2}$$

where, χ_{CC} χ_{CD} and χ_{DD} is the proportion of the edges of C–C, C-D and D-D respectively. As shown in three panels in Fig. 4, the proportion curves of C-D edges are all almost zero in cases of $p \neq 0.0$. We thus obtain

$$f_C \propto \frac{\chi_{CC}}{\chi_{CC} + \chi_{DD}} \tag{3}$$

then f_D, the proportion of defectors in whole population could be calculated by

$$\begin{aligned} f_D &= 1 - f_C \\ &\propto \frac{\chi_{DD}}{\chi_{CC} + \chi_{DD}} \end{aligned} \tag{4}$$

Obviously, both proportion curves of C–C and D-D are inversely proportional with each other. According to visual observation of 2-D patterns in Fig. 3 as well as proportion of edges calculated in Fig. 4, there are barely edges between cooperators and defectors. Besides separating cooperators from defectors, mobility mechanism brings out homogeneous groups.

By either attracting cooperators or alienating defectors, mobile cooperators prevail among population in case of a small p. It is interesting to figure out what gives mobile cooperators evolutionary advantages in the process of evolution. In order to get a clear image, we further investigate how the average degree $\langle k \rangle$ of both cooperator and defector groups changes with p for different δ. Besides this, the average degree of both original network and the evolutionary stable network removing empty sites (marked as ESR) for different mobility probability p is also calculated respectively for comparison. As shown in Fig. 5, there exists an intersection point $p*$. The value of $p*$ depends on δ, $p*$ increases as δ decreases in detail. Cooperators take the sites with higher average degree than defectors when $p < p*$, and the reverse applies when $p > p*$. It seems that $p*$ is the threshold of transition from the situation where cooperators dominate to dilemmas where cooperators disappear. Furthermore, it is shown that the average degree of original network is about 2.76 (black dash line). Interestingly to find the average degree (red dash line) of all ESRs for different p is more or less higher than that of original network (black line). As p grows over $p*$, the difference between both black and red dash lines narrows sharply, but the latter is still slightly higher than the former. Actually, there should be no difference if individuals have no mobility preference. Obviously, the sites with low degree are abandoned by mobile individuals. They move towards the sites with high degree.

The potential payoff is positively proportional to the number of interactive cooperative neighbors. Having as many direct neighbors as possible to interact is a requisite for obtaining higher payoff. Thus, individuals on the sites with high degree have more evolutionary advantages than the ones on the sites with lower degree. Technically, the individual on the hub site could earn the most in case of high f_C. On the contrast, cooperators on hub sites may suffer more loss than the ones on the sites with low degree in case of low f_C. Although individuals would rather defect than cooperate to avoid severe loss, which really deviates from the original intention of acquiring competitive advantages by occupying hub sites. In terms of small p, high cooperation frequency makes lots of individuals on hub sites interact with cooperators one by one to accrue payoff. As p grows, f_C falls, and the advantages of hub sites also eliminates. The mobility preference for high cooperation level is therefore more remarkable than the case of low cooperation level. As expected, the finding that individuals have mobility preference does not surprise us. In fact, we are more interested in the structure improvement of the network caused by mobility as well as its effects on cooperation.

In general, the sites where individuals locate to some extent determine the strategy they may choose. Individuals who occupies sites with high degree (hub sites) are inclined to cooperate due to accumulative

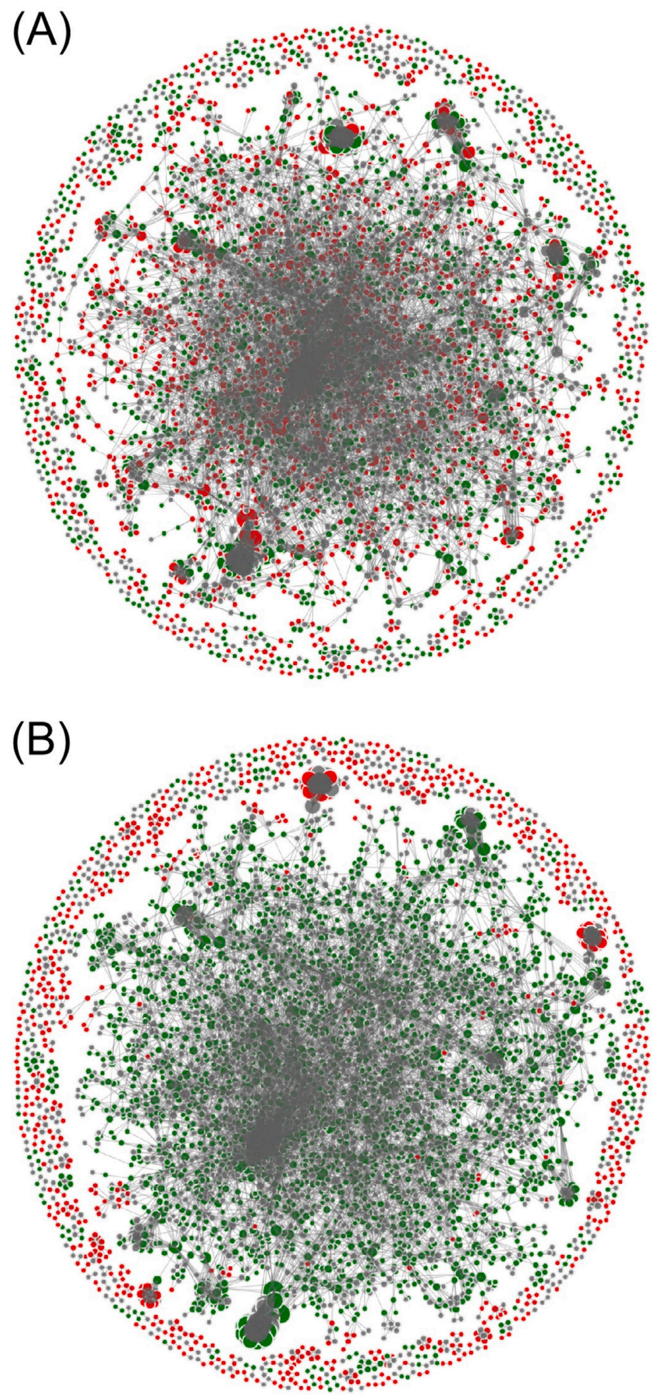

Fig. 3. The 2-D graph of cooperators distribution on collaborative network. The initial state and evolutionary stable state are shown respectively in panel (A) and (B). The color coding is as follows: green is for cooperators, red represents defectors, grey spot for empty sites. The size of the spots characterizes the degree of the site. The higher degree of the site is, the larger the site is. We set the parameters: $\delta = 0.5$, $p = 0.1$. Cooperators survive in big groups, whereas leave sites in small groups for defectors.

effect of payoff [7]. Since individuals drift towards sites with high degree from sites with low degree, adaptive mobility actually reconstructs the network structure as the one with higher average degree. The improved network structure therefore facilitates cooperation further than original network structure. In absence of other mechanisms, network reciprocity of ESR works technically better than original network on promoting cooperation. In spite of this, it is found that the improvement of network structure caused by mobility sometimes fails to rescue the situation from dilemmas, like the range of $p > p*$. Besides positive impacts of network structure improvement, there exists another powerful mechanism where cooperators are given evolutionary advantages to defeat defectors in fierce competition between cooperators and defectors.

Actually, mobility affects cooperation evolution in both ways. Besides improving network structure enhancing network reciprocity, mobility also plays a subtle roles in affecting cooperation evolution. On one hand, individuals could alienate defectors by mobility, which avoids behavior of mutual defecting. Mobility thus benefits cooperation. On the other hand, inevitably high mobility makes old partners as strangers, which decreases the odds of interacting old partners and weakens network reciprocity. Mobility undermines cooperation. In fact, the combination of mobility and improved network reciprocity plays the key role in evolution of cooperation, as shown in Fig. 6.

We refocus the condition of small p where cooperators dominate. Firstly, the average degree of the ESRs is far higher than that of original network for small p. Limited mobility constructs a better network structure than high mobility. Secondly, the potential cooperators could alienate defectors by limited mobility, yet friendship would never be damaged like big p. The frequent repeated interaction (the odds of interaction are about 1-p) nurtures old friendships to share rewarding payoff together. Last but not least, maintaining cooperation at a high level is one of effective ways to obtain higher payoff for individuals on hubs, they would prefer to cooperate voluntarily then anticipate more followers. As the positive feedback, the individuals around successful people most likely copy their behaviors in the process of social learning. Under the combination of limited mobility and enhanced network reciprocity, the strategy of cooperation could thus spread widely.

4. Discussion

Interestingly to find the conclusion that limited mobility facilitates cooperation effectively no matter what the network is. It is a big step towards understanding how the mobility mechanism works in cooperation evolution. The individuals on different sites may have different payoffs. Compared with regular lattice, there are higher odds of obtaining profound original and challenging results on heterogeneous networks, particularly true collaborative network. Due to the unique structure of the collaborative network, one observes individuals evolves as homogeneous groups, where mobile cooperator survive in big groups by alienating defectors or attracting cooperators. Remarkably, we observed there exist lots of crippled isolated groups trapped in dilemmas. Due to physical disconnection, they could not find a way out only through social learning or mobility. To be more specific, even mobility loses its impact on promoting cooperation among them. To get rid of dilemmas for individuals in small groups, a new mechanism should be considered in reality, such as a dynamic connection from big groups to them [33–35].

In reality, individuals are likely to move towards sites with more interactive connections with others because having a considerable number of interactive partners is one of the necessary conditions to obtain a higher payoff. It is analyzed that the individuals on hubs have competitive advantages only provided that the cooperation is maintained at a high level. In the situation of low cooperation level, they may lose more than others. Therefore, they generally voluntarily cooperate first on one hand, then anticipate more cooperator followers on the other hand. By limited mobility, it is found that competitive advantages are given to cooperators to defeat defectors in fierce competition. Firstly, individuals have mobility preferences. They are likely to migrate to a site with a higher degree. The mobility preference rebuilds the network structure as the new one conducive to cooperation. Particularly, the average degree of the ESR network is far higher than that of the original network for small p. To be more specific, the network structure caused by limited p is far better than that caused by big p.

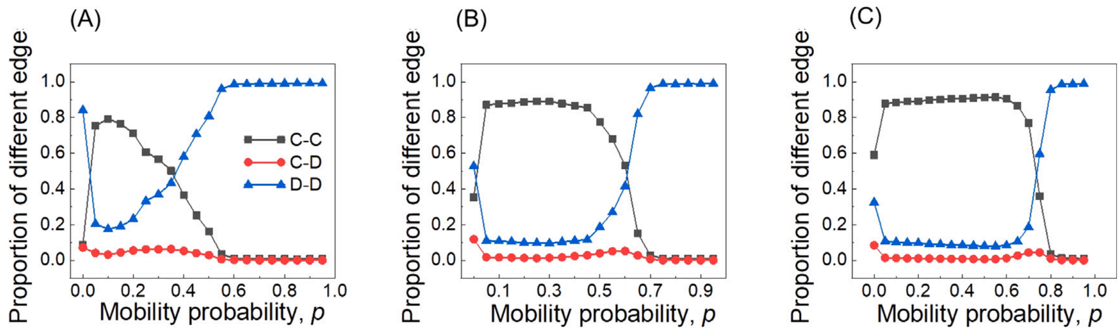

Fig. 4. The proportion of different types of edges (C-C, C-D and D-D) as a function of p for different δ. Namely, δ = 0.5 (A), δ = 0.4 (B) and δ = 0.3 (C). Few C-D edges signifies that cooperators and defectors are almost separated completely.

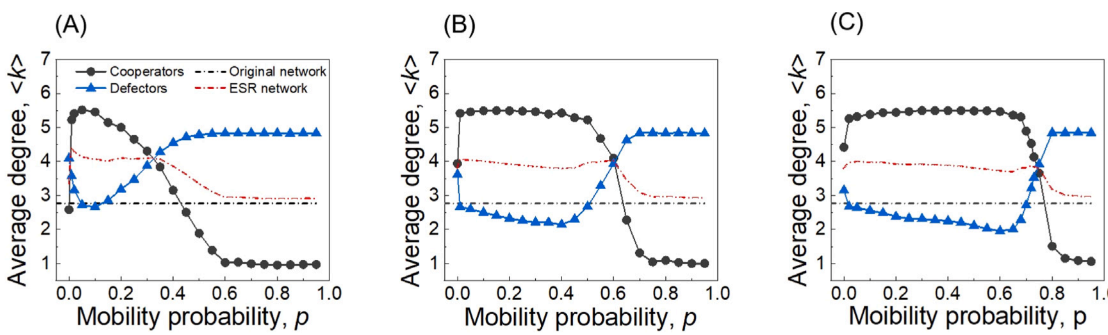

Fig. 5. Average degree $\langle k \rangle$ of cooperators and defectors as functions of p for different δ. Namely δ = 0.5 (A), δ = 0.4 (B) and δ = 0.3 (C). Here, ESR is evolutionary stable network removing empty sites. The average degree on ESR is higher than that on original network. Mobile individuals have mobility preference and drift towards sites with high degree.

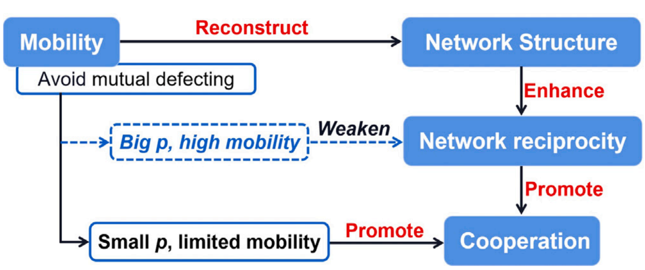

Fig. 6. Mobility facilitates cooperation in both ways. Besides enhancing network reciprocity by increasing average degree of networks, individuals could move away to avoid mutual defecting. In this case, the combination of limited mobility and enhanced network reciprocity remarkably gives cooperators competitive advantage in cooperation evolution.

Social mobility plays a subtle role in promoting cooperation. Although the network structure could be improved by mobility, it could not compensate for the loss that high mobility induces on the network structure. Actually, the combination of both mobility and network reciprocity determines the cooperation level. The cooperation could maintain at a high level only by limited p. On one hand, the potential cooperators could alienate defectors by limited mobility. On the other hand, friendship could never be damaged by high mobility. The repeated interaction helps old friends to share rewarding payoff. Actually, both the odds of meeting old friends as well as network structure determine network reciprocity. Furthermore, considering the fact that maintaining cooperation at a high level is one of the effective ways to obtain higher payoffs for individuals on hubs, they would prefer to cooperate voluntarily than anticipate more followers. The individuals around successful people most likely copy their behaviors in the process of social learning [36–41]. Under the combination of mobility and network reciprocity, the strategy of cooperation could thus spread all over the whole network except the alienated population.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

No data was used for the research described in the article.

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References

[1] Perc M, Jordan JJ, Rand DG, Wang Z, Boccaletti S, Szolnoki A. Statistical physics of human cooperation. Phys Rep 2017;687:1–51.
[2] Apicella CL, Silk JB. The evolution of human cooperation. Curr Biol 2019;29:R447–50.
[3] Nowak MA. Five rules for the evolution of cooperation. Science 2006;314:1560–3.
[4] Nowak MA, May RM. Evolutionary games and spatial chaos. Nature 1992;359:826–9.
[5] Szolnoki A, Perc M, Szabo G. Phase diagrams for three-strategy evolutionary prisoner's dilemma games on regular graphs. Phys Rev E 2009;80:056104.
[6] Barabási AL. Scale-free networks: A decade and beyond. Science 2009;325:412–3.
[7] Santos FC, Pacheco JM. Scale-free networks provide a unifying framework for the emergence of cooperation. Phys Rev Lett 2005;95:098104.

[8] Santos FC, Santos MD, Pacheco JM. Social diversity promotes the emergence of cooperation in public goods games. Nature 2008;454:213–6.
[9] Moreno Y, Nekovee M, Pacheco AF. Dynamics of rumor spreading in complex networks. Phys Rev E 2004;69:066130.
[10] Jiang LL, Li WJ, Wang Z. Multiple effect of social influence on cooperation in interdependent network games. Sci Rep 2015;5:14657.
[11] Zhang XY, Ruan ZY, Zheng MH, Zhou J, Boccaletti S, Barzel B. Epidemic spreading under mutually independent intra- and inter-host pathogen evolution. Nat Commun 2022;13:6218.
[12] Yang H, Wu Z, Zhou C, Zhou T, Wang B. Effects of social diversity on the emergence of global consensus in opinion dynamics. Phys Rev E 2009;80:046108.
[13] Lee HW, Clevel C, Szolnoki A. When costly migration helps to improve cooperation. Chaos 2022;32:093103.
[14] Li LMW, Wang S, Lin Y. The casual effect of relational mobility on integration of social networks: An agent-based modeling approach. Curr Psycho 2022. http://dx.doi.org/10.1007/s12144-022-03130-x.
[15] Thomson R, Yuki M, Talhelm T, et al. Relational mobility predicts social behaviors in 39 countries and is tied to historical farming and threat. Proc Natl Acad Sci USA 2018;115:7521–6.
[16] Yang G, Cavaliere M, Zhu C, Perc M. Strategically positioning cooperators can facilitate the contagion of cooperation. Sci Rep 2021;11:1127.
[17] Li WJ, Jiang LL, Perc M. A limited mobility of minorities facilitates cooperation in social dilemmas. Appl Math Comput 2021;391:125705.
[18] Li WJ, Chen Z, Jin KZ, Wang J, Yuan L, Gu CG, et al. Options for mobility and network reciprocity to jointly yield robust cooperation in social dilemmas. Appl Math Comput 2022;435:127456.
[19] Li WJ, Chen Z, Jin KZ, Li L, Yuan L, Jiang LL, et al. Eliminating poverty through social mobility promotes cooperation in social dilemmas. Chaos Solitons Fractals 2022;156:111845.
[20] McAvoy A, Allen B, Nowak MA. Social goods dilemmas in heterogeneous societies. Nat Hum Behav 2020;4:819–31.
[21] Leskovec J, Krevl A. SNAP Datasets: Stanford large network dataset collection. 2014, http://snap.stanford.edu/data.
[22] Jiang LL, Wang WX, Lai YC, Wang BH. Role of adaptive migration in promoting cooperation in spatial games. Phys Rev E 2010;81:036108.
[23] Cardillo A, Meloni S, Gómez-Gardeñes J, Moreno Y. Velocity-enhanced co-operation of moving agents playing public goods games. Phys Rev E 2012;85:067101.
[24] Szolnoki A, Chen XJ. Environmental feedback drives cooperation in spatial social dilemmas. EPL 2017;120:58001.
[25] Cardinot M, O'Riordan C, Griffith J, Szolnoki A. Mobility restores the mechanism which supports cooperation in the voluntary Prisoner's dilemma game. New J Phys 2019;21:073038.
[26] Zhang L, Huang CW, Li HH, Dai QL, Yang JZ. Effects of directional migration for pursuit of profitable circumstances in evolutionary games. Chaos Solitons Fractals 2021;144:110709.
[27] Lee HW, Clevel C, Szolnoki A. When costly migration helps to improve cooperation. Chaos 2022;32:093103.
[28] Li XP, Sun SW, Xia CY. Reputation-based adaptive adjustment of link weight among individuals promotes the cooperation in spatial social dilemmas. Appl Math Comput 2019;361:810–20.
[29] Zhang L, Zhang LM, Huang CW. Defectors in bad circumstances possessing higher reputation can promote cooperation. Chaos 2022;32:043114.
[30] Ichinose G, Satotani Y, Nagatani T. Network flow of mobile agents enhances the evolution of cooperation. EPL 2018;121:28001.
[31] Zhang LM, Li HH, Dai QL, Yang JZ. Adaptive persistence based on environment comparison enhances cooperation in evolutionary games. Appl Math Comput 2022;421:126912.
[32] Gao LY, Pan QH, He MF. Advanced defensive cooperators promote cooperation in the Prisoner's dilemma game. Chaos Solitons Fractals 2022;155:111663.
[33] Pacheco JM, Traulsen A, Nowak MA. Coevolution of strategy and structure in complex networks with dynamical linking. Phys Rev Lett 2006;97:258103.
[34] Wang J, Suri S, Watts DJ. Cooperation and assortativity with dynamic partner updating. Proc Natl Acad Sci USA 2012;109:14363–8.
[35] Claessens S, Kyritsis T. Partner choice does not predict prosociality across countries. Evol Hum Sci 2022;4:1–40.
[36] Amaral MA, de Oliveira MM, Javarone MA. An epidemiological model with voluntary quarantine strategies governed by evolutionary game dynamics. Chaos Solitons Fractals 2021;143:110616.
[37] Han X, Zhao XW, Xia HX. Hybrid learning promotes cooperation in the spatial prisoner's dilemma game. Chaos Solitons Fractals 2022;159:112125.
[38] Zhang FP, Wang XF, Wu T, Wang L. Evolutionary dynamics under partner preferences. J Theor Biol 2022;557:111340.
[39] Han TA. Emergent behaviours in multi-agent systems with evolutionary game theory. AI Commun 2022;35:327–37.
[40] Wang J, Cai SM, Wang W, Zhou T. Link cooperation effect of cooperative epidemics on complex networks. Appl Math Comput 2023;437:127537.
[41] Jusup M, Holme P, Kanazawa K, et al. Social physics. Phys Rep 2022;948:1–148.