Assortative mixing and resource inequality enhance collective welfare in sharing networks

Hirokazu Shirado[a,1], George Iosifidis[b], and Nicholas A. Christakis[c]

[a]School of Computer Science, Carnegie Mellon University, Pittsburgh, PA 15213; [b]School of Computer Science and Statistics, Trinity College, Dublin 2, Ireland; and [c]Yale Institute for Network Science, Yale University, New Haven, CT 06520

Edited by Mary C. Waters, Harvard University, Cambridge, MA, and approved September 27, 2019 (received for review July 10, 2019)

Resource sharing can impose an economic trade-off: One person acquiring resources may mean that another cannot. However, if individuals value the social process itself that is a feature of economic exchanges, socio-structural manipulations might improve collective welfare. Using a series of online experiments with 600 subjects arrayed into 40 groups, we explore the welfare impact of 2 network interventions. We manipulated the degree assortativity of the groups (who were engaged in resource sharing) while keeping the number of people and connections fixed. Distinctly, we also manipulated the distribution of sharable resources by basing endowments on network degree. We show that structural manipulation (implementing degree assortativity) can facilitate the reciprocity that is achievable in exchanges and consequently affect group-level satisfaction. We also show that individuals are more satisfied with exchanges when each node is unequally endowed with resources that are proportional to the number of potential recipients, which again facilitates reciprocity. Collective welfare in settings involving resource sharing can be enhanced without the need for extra resources.

collective welfare | resource sharing | reciprocity | network intervention | inequality

Resource sharing can challenge the standard notion of collective welfare. If an actor increases the resources the actor shares (from a fixed pool) with a certain partner, the actor has to reduce the resources allocated to others (1). Due to this zero-sum property of such social exchange schemes, the total utility of a group cannot improve without increasing the amount of exchangeable resources or without taxation and redistribution in certain circumstances (2).

Yet, prior work suggests that subjective satisfaction from an economic transaction may depend not only on the strictly economic outcomes, but also on the particular social processes leading to the outcomes in social exchange networks (1). People might accrue additional utility when they are involved in reciprocal exchanges that are symmetric. This reciprocity-induced utility can be implicated in the maintenance of stable social systems.

Here, we perform network-based experiments in social groups to assess the collective welfare derived from such reciprocity-induced utility, which suggests a possible Pareto improvement in social exchange without a change in economic production. In social exchange, individuals are more likely to reap a benefit if they hold a monopolistic position. One is likely to receive more resources not only when one has more partners but also when one's partners themselves have fewer partners. Because of this flip-flop impact of network degree, degree assortativity (3) can affect the ease of achieving reciprocal exchanges (4).

Hence, if reciprocity affects subjective satisfaction (1), group-wide satisfaction could vary with degree assortativity alone. This suggests that a global rearrangement of network structure could affect social welfare even without a change in individual-level network properties (that is, even while keeping the overall degree distribution constant) and even without a change in the total resources in the population.

We also examine whether this reciprocity-induced utility can be obtained under conditions of wealth disparity by manipulating the distribution of endowments. Implementing reciprocal exchanges is challenging when individuals do not have enough resources to reciprocate the amounts shared by their partners. Thus, when individuals having many neighbors are endowed with relatively more resources, the group is likely to achieve a higher level of reciprocity. Under our hypothesis of reciprocity-induced utility, groups with such unequal endowments (conditional on network degree) could paradoxically be more satisfied than those whose resources are more equally distributed.

We tested these hypotheses in experiments involving social exchanges in which human subjects embedded in a network mutually and repeatedly exchange resources with their neighbors (5). We recruited subjects (n = 600) via Amazon Mechanical Turk and randomly assigned them to 1 of 4 experimental treatments (Fig. 1). They were then randomly assigned to a location in a network, and they interacted with their connected neighbors in a resource-sharing game (4).

Subjects played the game for 15 rounds, without knowing when it would end. Subjects were given a certain amount of resources which they could not use for themselves. Instead, they could share this excess resource (which was useless to them) with their neighbors (think of unused internet bandwidth or an empty bedroom in a home). In every round, subjects chose the amount of resource they wanted to give to each of their neighbors. They did not have to allocate their entire resource but the nonallocated capacity neither carried over to the next round nor counted toward their score. Each subject's final score depended only on the units received from neighbors, which were converted to real compensation at the end of the game ($1.00 = 200 units).

Subjects were asked about their satisfaction based on the game play at the end of the game. Subjects answered whether they agree or disagree, using a 7-level rating system, with the following 5 statements: "In most ways, the interactions with my neighbors were close to my ideal"; "The conditions in the game were excellent"; "I was satisfied with my interactions with my neighbors"; "I got a sufficient amount of resource from my neighbors"; and "If I could play the game again, I would change almost nothing." These questions were modified from a standard satisfaction-with-life scale (6). We transformed the 7-category answers into the values from –3 to 3, with higher values indicating higher satisfaction. With responses to the 5 items averaged, the resulting scale had high reliability (Cronbach's alpha = 0.89), and the highest

Author contributions: H.S., G.I., and N.A.C. designed research; H.S. and G.I. performed research; H.S. analyzed data; and H.S., G.I., and N.A.C. wrote the paper.

The authors declare no competing interest.

Data deposition: The data reported in this manuscript are available in the Human Nature Lab (http://humannaturelab.net/publications/assortative-mixing-and-resource-inequality-enhance-collective-welfare-in-sharing-networks).

[1]To whom correspondence may be addressed. Email: shirado@cmu.edu.

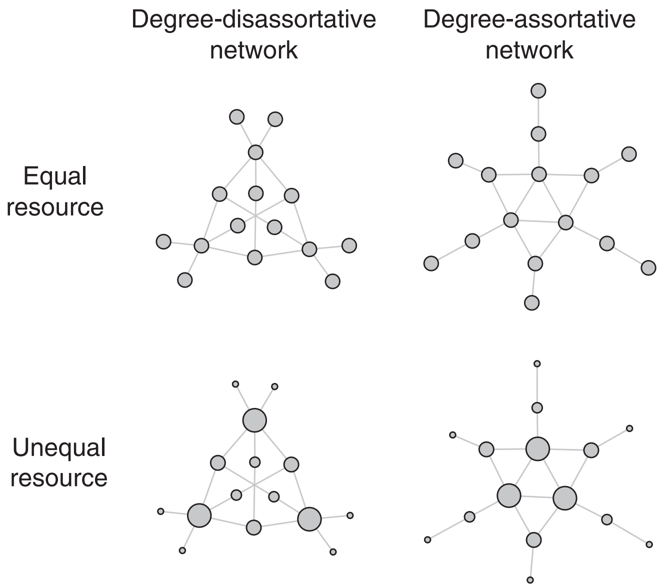

Fig. 1. Experimental treatments. Subjects were randomly assigned to 1 of the 4 treatment combinations: 2 types of network topology crossed with 2 types of resource distribution. Node size indicates the amount of endowment that the assigned subjects have (bigger nodes have more at each round). All networks have the same degree distribution, but they have opposite degree assortativity.

eigenvalue was 3.57. We therefore used the average score as a measure of subject satisfaction.

We allowed participation only by subjects who passed a series of tests assessing their understanding of the game. We prevented subjects from playing more than once. Subjects consented, and this study was approved by the Yale Human Subjects Committee.

Within this basic setup, we then manipulated degree assortativity using 2 simple networks (Fig. 1). The 2 networks both have 15 nodes and 18 edges and also the exact same degree distribution: 6 nodes with 1 edge, 3 nodes with 2 edges, 3 nodes with 3 edges, and 3 nodes with 5 edges. On the other hand, one network is degree disassortative (i.e., the nodes having many connections connect with the nodes having few connections; the coefficient of degree assortativity is −0.744), and the other is degree assortative (i.e., the nodes having a similar number of connections connect with each other; the coefficient is 0.233) (3).

Independent of degree assortativity, we also manipulated the allocation of sharable resource endowments (Fig. 1). In the "equal-resource" condition, each subject received 30 units per round for sharing. In the "unequal-resource" condition, the amount of sharable resource that subjects received was in proportion to their network degree; 1-degree subjects received 12 units, 2-degree subjects received 25 units, 3-degree subjects received 38 units, and 5-degree subjects received 63 units per round. Group-wide sharable resources were 450 units per round in all conditions.

Results

We first confirmed with individual-level analysis that not only wealth, but also reciprocity, has a positive effect on subjective satisfaction in individuals ($P < 0.01$ for each coefficient estimated with a regression model controlling for degree and incorporating random effects for sessions; $n = 576$ [24 subjects dropped out]). Hence, apart from the satisfaction arising from the strictly economic outcomes of exchanges, subjects are more likely to be satisfied when they achieve symmetric transactions with their neighbors.

Turning to the whole-group level, as expected, overall wealth production is the same among the experimental treatments (Fig. 2*A*). On the other hand, wealth inequality, reciprocity, and collective welfare vary with network structure (Fig. 2 *B*–*D*). With equal resources, the reciprocity in the degree-assortative network is significantly higher than in the degree-disassortative network (Fig. 2*C*). Degree assortativity also makes a significant difference in collective welfare ($P < 0.01$ with $n = 20$; t test; Fig. 2*D*); on average, subjects are dissatisfied with their exchanges in the degree-disassortative network and satisfied in the degree-assortative network.

This structural constraint of degree-disassortative networks was, however, eliminated when resource inequality was implemented. In the unequal-resource condition (where the endowments were distributed in proportion to degree), subjects show a high level of reciprocity from the beginning in both assortative and disassortative networks (Fig. 2*C*). Since all of the subjects could share more evenly among their neighbors with a degree-based resource distribution, they could more easily achieve mutual exchanges at the dyadic level.

Given these high levels of reciprocity in their transactions, group-wide satisfaction substantially improves in both types of networks in the unequal-endowment condition (Fig. 2*D*), even with a large wealth gap (Fig. 2*B*). Especially in the assortative network, subjects were, on average, more satisfied when given unequal allocations, even though the wealth gap increased. When it comes to utility, there is declining marginal return to money (2); hence, it is possible that degree assortativity improved collective welfare in the equal-endowment conditions, not because of the reciprocal process, but solely because of the reassignment of money away from the "rich" to the "poor" (Fig. 2*B*). However, the degree-based endowment allocation, which facilitates reciprocity, satisfies subjects without correction of the wealth disparity (Fig. 2*D*).

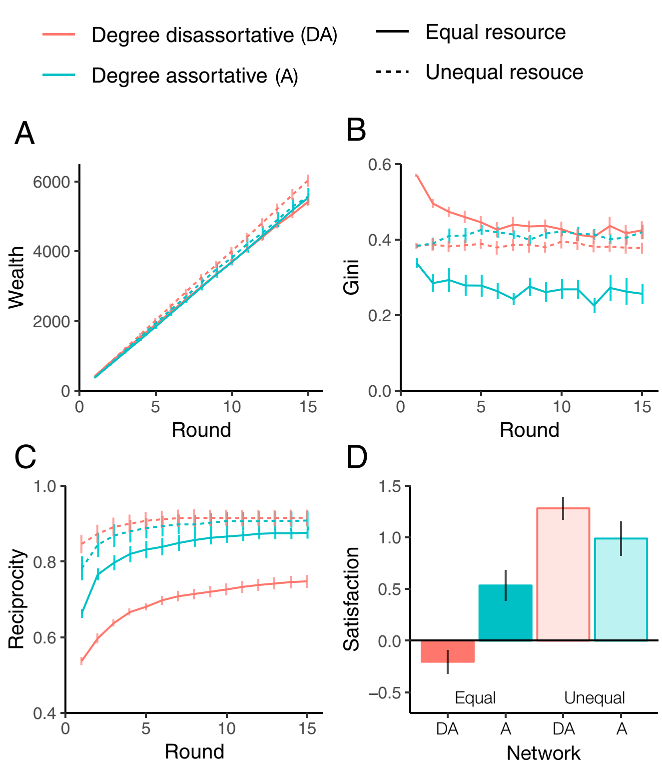

Fig. 2. Group-level results. (*A*–*D*) Group-wide wealth (total units received per group) (*A*), Gini coefficient (*B*), reciprocity over rounds (*C*), and satisfaction with overall interaction (average per group) (*D*). Error bars indicate SE ($n = 10$ for each treatment). In the unequal-resource condition, resources were given to subjects at each round roughly proportional to their degree (which facilitated reciprocal exchanges across the dyadic ties; see Fig. 1).

Discussion

Although the results of laboratory experiments do not translate directly to the real world and can be limited in clarifying behavioral mechanisms, the evidence presented here suggests that collective welfare might be improved by arranging networks to form ties between people with similar degree or by allocating resources according to degree. Conversely, network structures or resource allocations that hinder reciprocity—e.g., endowing nodes with resources inversely proportional to their degree—could even decrease satisfaction in social exchange. Other factors, such as wealth visibility, could also play a role (7). Given that many human networks are exceptionally degree assortative (3), it is possible that humans may even have evolved homophilic networks (with respect to network degree) in parallel with developing norms of reciprocity.

It is worth stressing that the tested interventions do not require additional resources to be injected into the system. In contrast to the economic value of endowments or earnings, the fact that an actor gets utility from relationships does not exclude other actors from also deriving such utility. The value of relationships can indeed be nonexclusive and noncompetitive if the interactions are properly arranged. Taking into account the impact of exchange processes on collective welfare can break the curse of resource allocation where helping one person might come at another's expense. Designing social processes in particular ways might improve collective welfare, even without any wealth redistribution.

Data Availability. The data and codes are stored in the Human Nature Lab Data Archive (5).

ACKNOWLEDGMENTS. This work is supported by Tata Sons Private Ltd., Tata Consultancy Services Ltd., Tata Chemicals Ltd., the National Institute of Social Science, and Science Foundation Ireland (Grants 17/CDA/4760 and 16/IA/4610).

1. L. D. Molm, Affect and social exchange: Satisfaction in power-dependence relations. *Am. Sociol. Rev.* **56**, 475–493 (1991).
2. A. P. Lerner, *The Economics of Control* (Macmillan Co., 1944).
3. M. Newman, M. Girvan, "Mixing patterns and community structure in networks" in *Statistical Mechanics of Complex Networks*, R. Pastor-Satorras, J. Rubi, A. Diaz-Guilera, Eds. (Springer, 2003), pp. 66–87.
4. H. Shirado, G. Iosifidis, L. Tassiulas, N. A. Christakis, Resource sharing in technologically defined social networks. *Nat. Commun.* **10**, 1079 (2019).
5. H. Shirado, G. Iosfidis, N. A. Christakis, Data from "Assortative mixing and resource inequality enhance collective welfare in sharing networks." http://humannaturelab.net/publications/assortative-mixing-and-resource-inequality-enhance-collective-welfare-in-sharing-networks. Deposited 28 September 2019.
6. W. Pavot, E. Diener, Review of the satisfaction with life scale. *Psychol. Assess.* **5**, 164–172 (1993).
7. A. Nishi, H. Shirado, D. G. Rand, N. A. Christakis, Inequality and visibility of wealth in experimental social networks. *Nature* **526**, 426–429 (2015).