NETWORK SCIENCE

The strength of dynamic ties: The ability to alter some ties promotes cooperation in those that cannot be altered

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Dynamic networks, where ties can be shed and new ties can be formed, promote the evolution of cooperation. Yet, past research has only compared networks where all ties can be severed to those where none can, confounding the benefits of fully dynamic networks with the presence of some dynamic ties within the network. Further, humans do not live in fully dynamic networks. Instead, in real-world networks, some ties are subject to change, while others are difficult to sever. Here, we consider whether and how cooperation evolves in networks containing both static and dynamic ties. We argue and find that the presence of dynamic ties in networks promotes cooperation even in static ties. Consistent with previous work demonstrating that cooperation cascades in networks, our results show that cooperation is enhanced in networks with both tie types because the higher rate of cooperation that occurs following the dynamics process "spills over" to those relations that are more difficult to alter. Thus, our findings demonstrate the critical role that dynamic ties play in promoting cooperation by altering behavioral outcomes even in non-dynamic relations.

INTRODUCTION

The existence of cooperation is a critical issue in the social and biological sciences. Although essential for the success of human societies, cooperation entails paying a cost and the risk of exploitation. Increasingly, research has considered the role of structured populations in promoting cooperative behavior among humans. This work has consistently demonstrated that dynamic networks, where ties between interaction partners can be severed and new ties can be formed, increase cooperation (*1*–*5*). Dynamics allow cooperators to insulate themselves from free riders by enabling them to shed ties to defectors and selectively interact with each other.

That dynamic networks promote cooperation is clear. However, previous work has only compared fully dynamic networks, where all network ties can potentially be severed, to fully static networks, where none can (*1*–*5*). As a result, past work has confounded the benefit of dynamic ties with fully dynamic networks.

This is an important omission because real-world networks are characterized by a mix of ties that are more or less susceptible to change. While people typically have control over with whom they interact and selectively alter their interaction partners over time (*3*, *6*), severing ties can be costly (*7*), and some ties are far more difficult or costly to shed than others (*8*). Thus, research on fully dynamic networks may tell us less than we now assume about the high levels of cooperation we observe in the real world, unless the presence of dynamic ties also promotes cooperation in more static relations. Here, we consider whether cooperation is higher in fully dynamic networks alone, in dynamic ties alone, or also in static relations in networks where dynamics are possible.

A straightforward extrapolation from previous work might suggest that, in networks with both tie types, people will tend to be more cooperative in dynamic ties and relatively uncooperative in static relations. However, we expect instead that the beneficial effects of dynamics will promote cooperation in static ties. There are several potential mechanisms through which this could occur.

First, because developing and maintaining a good reputation increases one's ability to attract new interaction partners, reputations promote cooperation in dynamic networks (*9*–*11*). In networks where at least some ties are dynamic, cooperation should be increased for the same reason, as people seek to create and maintain cooperative relations. According to this argument, in networks with both types of ties, cooperation will increase not only in dynamic ties but also in static relations. This is because, in networks where reputations are available, behavior in static relations has implications for establishing new partners. That is, actors in networks with both dynamic and static ties can strategically build a positive reputation by cooperating with both their dynamic and static ties. Thus, cooperation in networks with at least some dynamic ties may be similar to that of fully dynamic networks when reputation building is possible, but reduced, especially among static ties, when reputation building is not possible. Our experiment tests this possibility by manipulating whether reputation information is available.

Second, past work has shown that dynamic networks promote cooperation even when reputations are not available (*1*, *2*, *7*, *12*). Of particular interest is how the dynamics process, where ties are deleted and new ties are formed, might affect behavior even in non-dynamic ties. Past work has demonstrated that cooperative behavior cascades, or "spills over," in networks from person to person (*13*) and from repeated interactions to one-shot interactions (*14*). We examine whether the enhanced cooperation that occurs as a result of dynamics, even when reputations are not available, spreads to static ties. If the cooperative behavior that occurs as a result of tie deletion and addition spills over to static ties, cooperation is likely to be promoted in networks regardless of tie type. Of course, noncooperative behavior also cascades (*13*). It is therefore possible that the less cooperative behavior typical of static ties will spill over to reduce cooperation in dynamic ties. If so, cooperation in networks with both tie types might look similar to that of fully static networks, at least where reputations are not available.

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We conducted an experiment that embedded actors in fully static, fully dynamic, and combined static and dynamic ("mixed") networks, with or without reputations, to test these arguments. We expected, following the arguments outlined above, that the presence of dynamic ties in mixed networks would promote cooperation in static ties in those networks. However, we made no explicit prediction as to whether dynamic ties would promote cooperation in static ties via reputations, spillover, or both.

A total of 334 participants recruited from the general student populations at two U.S. universities were embedded in 20 networks. Participants were embedded in each type of network (static, dynamic, and mixed) in random order. Network type was therefore a within-subject manipulation. Participants played an iterated Prisoner's Dilemma game (PDG) with each of their alters, choosing to cooperate or defect independently with each of them (for more details, see Materials and Methods and the Supplementary Materials). In static networks, relations were unalterable; in dynamic networks, participants could select one tie every three rounds to replace; and in mixed networks, half of the ties were randomly selected to be static and the others were dynamic. As in the dynamic networks, after every three rounds, participants could drop one of their alters and initiate a new tie, provided that the relation was dynamic. Reputation was a between-subject manipulation: In half of the networks, the percent of time alters cooperated in that type of network was shown when participants who chose to drop a tie selected new alters during the dynamics process (*2*, *4*); in the other half of the networks, no information about past behaviors was provided during the tie selection process.

RESULTS

We begin by considering cooperation rates by experimental condition. We focus on the final three rounds of the phase, i.e., after tie dropping and adding (and reputational information, if available) had occurred three times and thus could have affected cooperation patterns. After we present these results, we examine round-level analyses to examine the unfolding of these processes over time.

Table 1 shows network-level cooperation rates in the final three rounds by our manipulated factors: the type of network (static, dynamic, or mixed) and whether reputation information was available during the tie selection process or not. Generally, cooperation rates were highest in fully dynamic networks and lowest in static networks. In addition, across network types, cooperation was higher when reputations were available.

An analysis of variance (ANOVA) with network type as a within-subjects condition revealed that network-level cooperation rates in the final three rounds differed by network type ($F_{2,46} = 41.76$, $P < 0.001$) and whether reputations were available ($F_{1,46} = 6.72$, $P = 0.01$). The interaction between network type and reputations was nonsignificant ($F_{2,46} = 0.20$, $P = 0.82$). These results control for phase (i.e., whether the condition was completed first, second, or third; $F_{2,46} = 6.96$, $P = 0.002$), the order in which the three phases were completed ($F_{5,46} = 1.54$, $P = 0.2$), and network size ($F_{1,46} = 0.2$, $P = 0.65$).

Table 1. Network-level cooperation rates in the final three rounds, by condition. $n = 20$ networks per within-subjects condition (60 total), 10 each in the No reputations and Reputations conditions. SEM reported in parentheses.

	No reputations	Reputations
Dynamic only	0.92 (0.02)	0.98 (0.01)
Mixed networks	0.86 (0.03)	0.90 (0.02)
Static only	0.70 (0.04)	0.73 (0.05)

Given the significant effect of network type, we followed up with a two-level mixed model with network types nested in networks to examine how cooperation rates differed across the three network types. This model included the same control variables as the ANOVA and revealed that cooperation rates were lower in static networks and higher in dynamic networks compared to our mixed network condition (coef = −0.18, $P < 0.001$ and coef = 0.07, $P < 0.01$, respectively).

Having confirmed that our network type and reputations manipulations affected cooperation rates at the network level, we turn to examining differences in cooperation at the lower levels of analysis that the aggregated data do not capture. We used mixed models to account for the four-level nested structure of the data, where alters were nested in rounds, rounds were nested in participants, and participants were nested in networks.

First, although our primary question is centered on cooperation at the dyadic level—i.e., cooperation within static versus dynamic ties in networks with both tie types—we also tested for broader network effects in our results. Replicating past work (*13*), we find a cascade effect, which demonstrates network dependencies beyond ego-alter relationships. The proportion of alter's alters who cooperated two rounds prior was associated with ego's cooperation in the current round (coef = 1.16, $P < 0.001$; Table 2, model 1).

Notably, even after controlling for these network effects, we find differences across conditions. As a result, in our remaining models, we turn from network-level effects to an analysis of differences in cooperation rates by condition. Figure 1 displays cooperation rates over time by network type (static, dynamic, or mixed), both overall (A) and by tie type in the mixed network condition (B). Figure 1A shows that cooperation declined in static networks across the 12 rounds of the phase. On the other hand, cooperation increased over time in dynamic networks, particularly in those rounds that immediately followed a tie-dropping opportunity (after every third round). These results are consistent with past work demonstrating that fully dynamic networks promote the evolution of cooperation (*2*–*4*).

A four-level generalized linear model predicting cooperation revealed an effect of round qualified by a round × network-type interaction (Table 2, model 2). Cooperation decreased over time in the fully static networks (coef = −0.03, $P < 0.01$), but increased over time in the fully dynamic networks (coef = 0.18, $P < 0.001$).

Perhaps more importantly, Fig. 1A also shows that the pattern of cooperation in mixed networks tended to look like that of fully dynamic networks, remaining high over time. Cooperation also increased over time in mixed networks compared to static ones (coef = 0.11, $P < 0.001$; Table 2, model 2). These results control for whether reputation information was available during the tie selection process or not (which we discuss in turn). We also control for direct reciprocity (i.e., whether the alter had cooperated in the previous round; as a result, round 1 behavior was excluded from analyses), network size, number of ties, phase, and the sequence in which each phase was completed. Typically, alter's past cooperative behavior promoted cooperation along with our manipulated factors, as did whether the condition was completed later in the study (i.e., in the second or

Table 2. Four-level generalized linear mixed models predicting cooperation. For model 1, n = 30,301 network-participant-round-alters. Cooperation cascade is the proportion of alter's alters that cooperated with alter two rounds ago; as a result, rounds 1 and 2 for each phase are dropped from analyses. For models 2 to 5, N = 36,072 network-participant-round-alters. Because we control for alter's past cooperative behavior, round 1 for each phase is dropped from analyses. $^{a}P < 0.05$, $^{b}P < 0.01$, $^{c}P < 0.001$. Coefficients for sequence in which phases were completed are omitted for brevity.

	Model 1	Model 2	Model 3	Model 4	Model 5
Mixed network (M)*	0.68^{c} (0.06)	−0.01 (0.11)			
Dynamic network (D)*	0.68^{c} (0.07)	-0.39^{c} (0.11)	0.74^{c} (0.05)	-0.40^{c} (0.11)	0.81^{c} (0.07)
Round (R)	0.04^{c} (0.01)	-0.03^{b} (0.01)	0.05^{c} (0.01)	-0.03^{b} (0.01)	0.05^{c} (0.01)
Cooperation cascade	1.16^{c} (0.15)				
D × R		0.18^{c} (0.02)		0.18^{c} (0.02)	
M × R		0.11^{c} (0.01)			
Mixed network, dynamic tie (MD)*			0.91^{c} (0.07)	−0.03 (0.14)	1.00^{c} (0.09)
Mixed network, static tie (MS)*			0.57^{c} (0.06)	−0.04 (0.13)	0.67^{c} (0.08)
MD × R				0.14^{c} (0.02)	
MS × R				0.09^{c} (0.02)	
Reputation information (I)†	0.47^{a} (0.19)	0.59^{b} (0.22)	0.57^{b} (0.22)	0.59^{b} (0.22)	0.67^{b} (0.22)
D × I					−0.14 (0.11)
MD × I					−0.18 (0.14)
MS × I					−0.22 (0.12)
Second phase‡	0.48^{c} (0.06)	0.66^{c} (0.05)	0.66^{c} (0.05)	0.67^{c} (0.05)	0.69^{c} (0.05)
Third phase‡	0.68^{c} (0.07)	0.97^{c} (0.05)	0.95^{c} (0.05)	0.97^{c} (0.05)	0.98^{c} (0.06)
Alter cooperated, previous round	3.31^{c} (0.05)	3.24^{c} (0.05)	3.28^{c} (0.05)	3.22^{c} (0.05)	3.28^{c} (0.05)
Number of ties	0.02 (0.02)	0.02 (0.02)	0.01 (0.02)	0.01 (0.02)	0.01 (0.02)
Network size	−0.01 (0.03)	−0.01 (0.03)	−0.01 (0.03)	−0.01 (0.03)	−0.01 (0.03)
Constant	-2.72^{c} (0.61)	−1.57* (0.71)	-2.11^{b} (0.70)	−1.57* (0.72)	-2.20^{b} (0.71)
Round	0.45 (0.67)	0.42 (0.65)	0.42 (0.65)	0.43 (0.65)	0.42 (0.65)
Participant	1.65 (1.28)	1.70 (1.30)	1.68 (1.30)	1.69 (1.30)	1.68 (1.30)
Network	0.02 (0.13)	0.08 (0.28)	0.07 (0.26)	0.08 (0.28)	0.07 (0.27)

*Static networks are the reference category. †No reputation information is the reference category. ‡Phase refers to the order in which the condition (static, dynamic, or mixed) was completed (first phase is the reference category).

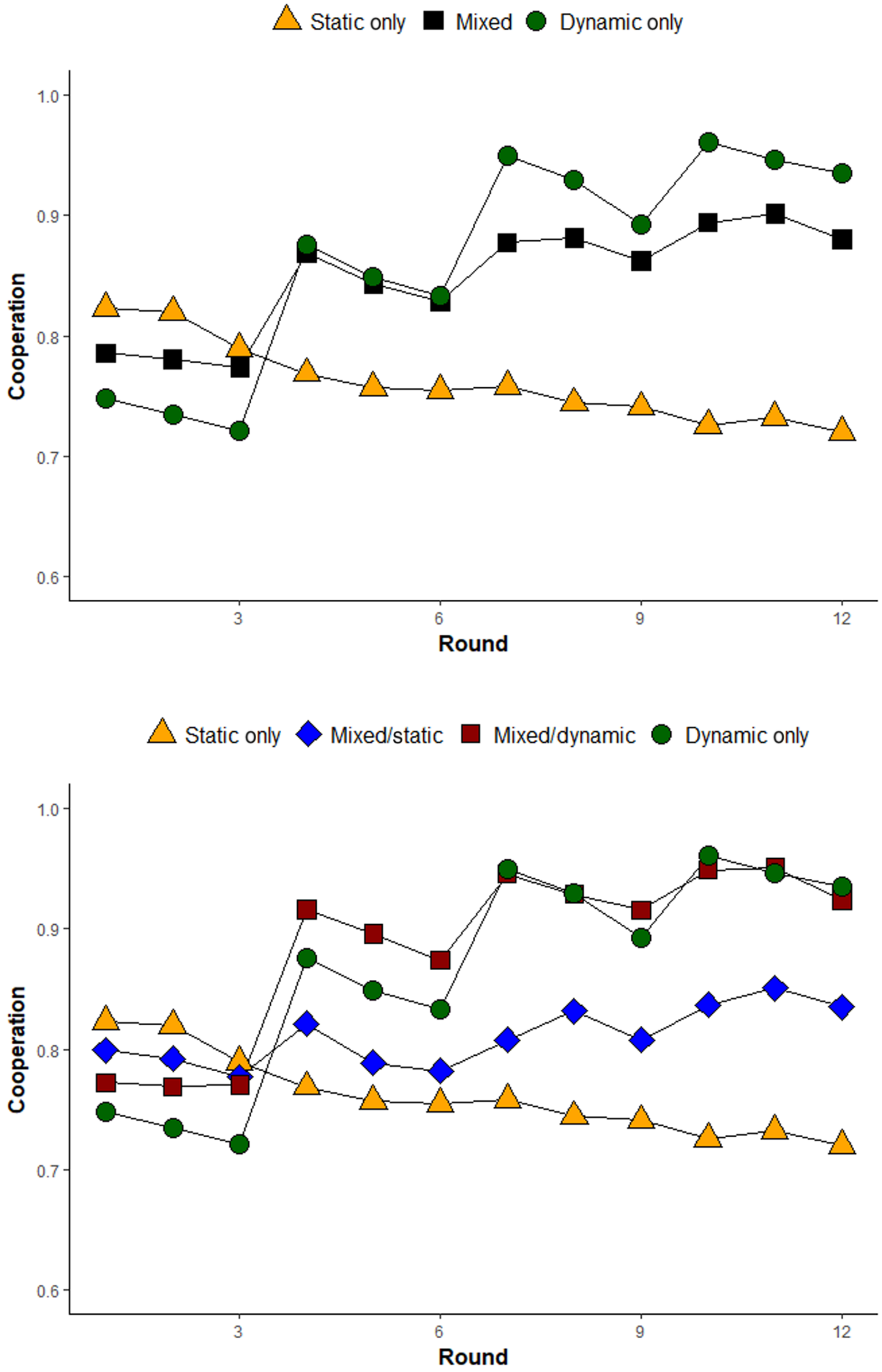

Fig. 1. Cooperation rates by condition. (**A**) Overall. (**B**) By tie type in the mixed network condition. The labeled round numbers (i.e., 3, 6…) denote that a tie-dropping opportunity occurred after that round and before the next round.

third phase, compared to the first). Network size and number of ties were not associated with cooperation. Additional controls for gender and the participant's university affiliation were also not associated with cooperation and did not substantively affect results.

Cooperation patterns by tie type

Although cooperation patterns in networks containing both static and dynamic ties were similar to those of fully dynamic networks, our key question was whether, within mixed networks, the presence of dynamics promoted cooperation even in static relations. To answer this question, we examined cooperation rates across the different tie types in the mixed network condition.

Perhaps unsurprisingly, in mixed networks, cooperation was higher within dynamic ties (88.5% versus 81.1% in mixed network static ties; coef = 0.34, $P < 0.001$). However, as shown in Fig. 1B, cooperation in not only the dynamic but also in the static ties in mixed networks was significantly higher compared to the fully static networks (coefs = 0.91 and 0.57, respectively, Ps < 0.001; Table 2, model 3). The presence of dynamic ties in our mixed network condition promoted cooperation even among non-dynamic ties in the network.

Follow-up results examining differences in the effect of round by condition revealed that, in the fully static condition, cooperation decreased over time (coef = −0.03, $P < 0.01$; Table 2, model 4), but in the dynamic and mixed network conditions—for both dynamic and static ties—cooperation increased over time (Ps < 0.001; Table 2, model 4). Figure 2 illustrates this result, showing the marginal probabilities of cooperation by tie type over time.

Do reputation processes explain why dynamic ties promote cooperation in static ties?

The network-level cooperation rates described above demonstrate that the availability of reputational information promotes cooperation, as it has in past work (*9*–*11*), but our main objective in manipulating the availability of reputations was to assess whether mixed networks promote cooperation in static ties via a reputation process. If cooperative behavior toward static ties is a strategic response to the presence of a reputation system, we should observe pronounced differences in cooperation in static ties in mixed versus fully static networks when reputations are available, and similar rates of cooperation in static ties across network types when reputations are not available.

Although reputations promoted cooperation across network types (coef = 0.59, $P < 0.01$; Table 2, model 4), we do not find any evidence that the availability of reputation information explains the higher levels of cooperation we observed in static ties in mixed networks versus those in fully static networks. Cooperation in static ties in mixed networks remained significantly higher than in fully static networks (coef = 1.00, $P < 0.001$; Table 2, model 5), and this effect did not differ based on the presence of reputations (i.e., the reputation × mixed static tie interaction was not significant). Rather, cooperation was higher among static ties in mixed networks, compared to fully static networks, both when reputations were available and when they were not.

Do higher cooperation rates in dynamic ties spill over to static ties?

Another possible explanation for the increased cooperation in static ties in mixed networks, as noted above, is that the enhanced cooperation that occurs as a result of the dynamics process, where ties are deleted and new ties are added, spills over to static relations. Figure 1B shows that cooperation in static ties in mixed networks tended to increase across rounds, following the pattern of cooperation observed in dynamic ties: Specifically, cooperation increased in the round after a tie-dropping opportunity, even though static ties could not be altered. Accordingly, we examined how cooperation was affected by tie-changing opportunities.

Table 3 displays results from models predicting cooperation in those conditions with at least some dynamic ties (i.e., dynamic and mixed networks). Cooperation increased in the rounds following a tie-dropping opportunity toward not only dynamic (coef = 1.37, $P < 0.01$) but also static ties (coef = 0.92, $P < 0.001$; Table 3, model 1). These results held after controlling for whether the network was fully dynamic or mixed, whether reputation information was available or

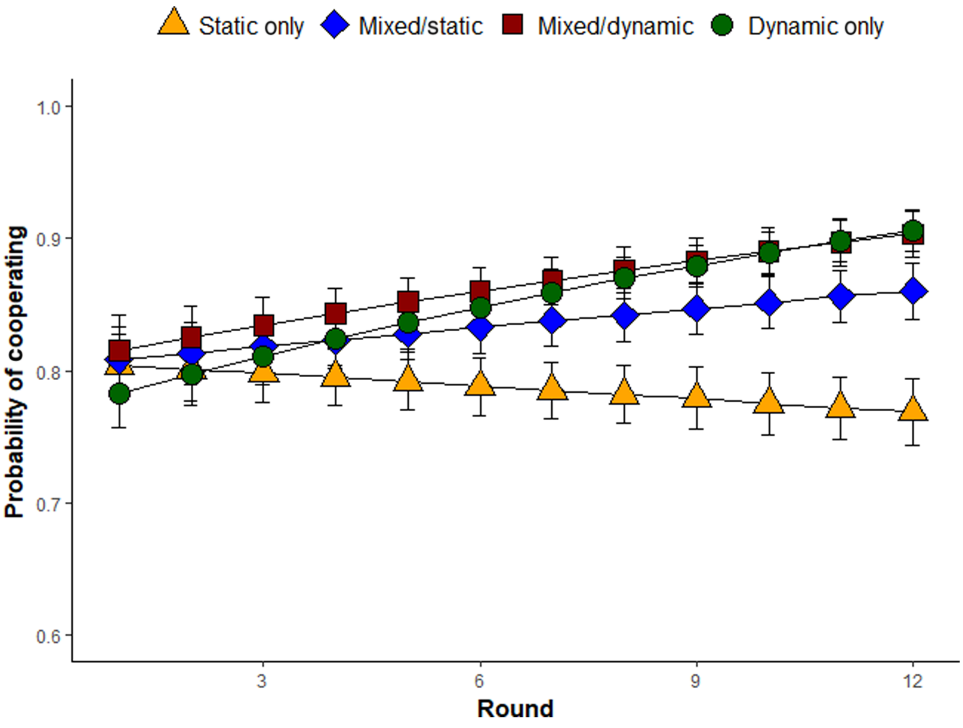

Fig. 2. Marginal probabilities of cooperation over time, by tie type. Margins come from Table 2 (model 3), with covariates set at their means.

Table 3. Four-level generalized linear mixed models predicting cooperation in networks with dynamics. Model 1 is rounds 2 to 12 in the dynamic and mixed networks (because we control for alter's past cooperative behavior, round 1 is dropped from analyses; $n = 21{,}727$ network-participant-round-alters). Model 2 is all rounds in the dynamic and mixed networks following a tie-dropping opportunity (i.e., rounds 4, 7, and 10; $n = 4117$ network-participant-round-alters). $^{a}P < 0.05$, $^{b}P < 0.01$, $^{c}P < 0.001$. Coefficients for rounds 3 to 12 (model 1) and rounds 7 and 10 (model 2) and sequence in which phases were completed are omitted for brevity.

	Model 1	Model 2
Dynamic network*	−0.21^{b} (0.08)	0.40 (0.28)
Reputation information	0.53^{a} (0.21)	0.53^{a} (0.21)
Dynamic tie (DT)	0.32^{c} (0.09)	0.70^{b} (0.24)
Tie-dropping opportunity, previous round (T)	0.92^{c} (0.19)	
DT × T	0.45^{b} (0.17)	
Was dropped by an alter, previous round (A)		1.02^{a} (0.49)
DT × A		−0.50 (0.53)
Second phase†	0.49^{c} (0.08)	0.44 (0.29)
Third phase†	0.94^{c} (0.10)	0.81^{a} (0.32)
Alter cooperated, previous round	3.34^{c} (0.08)	3.44^{c} (0.25)
Number of ties	−0.02 (0.03)	−0.02 (0.08)
Network size	0.01 (0.03)	0.01 (0.04)
Proportion of alters cooperating, previous round	0.24 (0.16)	2.60^{c} (0.52)
Constant	−1.76^{b} (0.68)	−2.77^{b} (0.99)
Variance components		
Round	0.62 (0.79)	2.34 (1.53)
Participant	2.18 (1.48)	1.08 (1.04)
Network	0.01 (0.08)	0.00 (0.00)

*Mixed networks are the reference category. †First phase is the reference category.

not, direct reciprocity (i.e., whether the alter had cooperated in the previous round), the proportion of alters cooperating in the previous round, number of ties, and network size.

In addition, being dropped by a tie in the previous round predicted increased cooperation in the subsequent round (coef = 1.02, $P = 0.04$; Table 3, model 2). Again, this was the case for cooperation in both dynamic and static ties; the interaction between whether the tie was dynamic (versus static) and being dropped previously was not significant (coef = −0.50, $P = 0.34$; Table 3, model 2). These findings are consistent with the notion that, in networks where ties vary in terms of how easily they are severed, the dynamics process has an impact on cooperation even in those ties where dynamics are not possible. Follow-up results indicated that being dropped two, three, or four rounds prior was not associated with enhanced cooperation toward either static or dynamic ties—only being dropped in the most recent tie-dropping opportunity (i.e., one round prior) predicted increased cooperation toward both tie types. These results suggest that the frequency with which dynamics occur may moderate whether dynamics will promote cooperation in both static and dynamic ties. We return to this issue in the discussion.

Earnings differences by network type

Last, as a result of enhanced cooperation in those networks with dynamics, fitness was higher in these networks as well. Even after controlling for number of ties, overall earnings were higher in dynamic and mixed networks compared to fully static networks (coefs = 22.00 and 19.18, respectively, $Ps < 0.001$; Table 4, model 1), and following the results for differences in cooperation by tie type, participants earned more in their static ties in mixed networks compared to their static ties in fully static networks (coef = 3.75, $P < 0.001$; Table 4, model 2).

DISCUSSION

Past work has consistently demonstrated that dynamic networks, where ties can be deleted and new ties can be added, promote cooperation. But notably, this previous work has only considered networks where either all ties can be shed or none can. These fully dynamic or fully static networks have confounded the benefits of dynamic networks with the presence of dynamic ties within the network, leaving open whether dynamics enhance cooperation among even static ties so long as some relations in the network can be altered.

This is a particularly critical gap in the literature because humans are embedded in networks composed of ties that vary in their susceptibility to change. Although existing research on networks and cooperation has assumed that dynamics work because uncooperative alters are dropped, in real-world networks, people are often constrained from dropping ties to even their most "difficult" alters (*8*). Our work accounts for the richness of real-world networks by examining whether and how dynamics promote cooperation even when some ties in the network cannot be severed.

To consider whether the presence of dynamic ties in networks promotes cooperation even among static ties, we randomly assigned whether ties in our mixed network condition were static or dynamic. The result was that, in mixed networks, 50.6% of ties could be altered; the remainder were static. Future work might examine what percentage of network ties must be dynamic to promote cooperation in static ties. In our study, the vast majority of participants began the mixed network phase with at least one dynamic tie (85%; likewise, 85% began with at least one static tie). It seems likely that when dynamic ties are relatively common (rare) in the network, they will be more (less) likely to promote cooperation across that network. Likewise, while our study manipulated whether ties could be broken or not, future research may instead alter how costly it is

Table 4. Three-level (model 1) and four-level (model 2) linear mixed models predicting earnings. n = 11,540 network-participant-rounds (model 1) and 36,072 network-participant-round-alters (model 2). [a]$P < 0.001$. Coefficients for sequence in which phases were completed are omitted for brevity.

	Model 1: Total earnings across all alters	Model 2: Earnings by alter
Mixed network*	19.09[a] (1.65)	
Dynamic network*	21.88[a] (1.69)	6.16[a] (0.48)
Mixed network, dynamic tie*		6.70[a] (0.55)
Mixed network, static tie*		3.75[a] (0.55)
Reputation information	6.95 (4.51)	2.16 (1.18)
Round	1.26[a] (0.19)	0.30[a] (0.06)
Number of ties	41.51[a] (0.45)	−0.09 (0.12)
Network size	−0.15 (0.68)	0.04 (0.18)
Second phase†	23.43[a] (1.68)	5.22[a] (0.47)
Third phase†	28.85[a] (1.67)	6.73[a] (0.47)
Alter cooperated, previous round		9.40[a] (0.52)
Constant	−49.56[a] (14.89)	20.37[a] (3.89)
Variance components		
Round	—	18.14 (4.26)
Participant	75.78 (8.71)	2.42 (1.56)
Network	70.39 (8.39)	4.68 (2.16)

*Static networks are the reference category. †First phase is the reference category.

to break each individual tie. Whether the cost of tie-breaking and forming new relations affects cooperation rates in networks with multiple tie types could be tested in a straightforward extension of the experiment presented here.

In summary, we find that cooperation and fitness are enhanced not only in fully dynamic networks but also in networks consisting of both dynamic and static ties. Cooperation evolves in networks even when some ties cannot be shed, so long as other ties can be altered. Consistent with previous work demonstrating that cooperation cascades in networks, our results show that cooperation toward even static ties is influenced by the dynamics process: When dynamics are possible, cooperation with both dynamic and static alters increased following a tie-altering opportunity, and being dropped by an interaction partner further promoted cooperation even among static ties. More generally, in networks with dynamics, cooperation toward static ties is improved because the higher rate of cooperation in dynamic ties "spills over" to those relations that are more difficult to alter. The presence of alterable relations in our networks promotes productive and harmonious interactions, even among those ties that are more resistant to change. Thus, by documenting the beneficial spillover effects of alterable relations to ties that cannot be changed, we demonstrate the power of dynamics for cooperation under more general, and realistic, conditions.

MATERIALS AND METHODS

Experimental design

Students responded to the opportunity to take part in a study for course credit plus a monetary bonus. Study sessions were scheduled in groups of at least 12 and up to 24. In total, we ran 20 networks with 334 unique participants. Network sizes ranged from 12 to 24 (M = 16.7), depending on the number of participants that attended the study session. This minimum, range, average, and variation are standard in past work on cooperation in networks (*12*, *15*–*17*).

As participants arrived at the laboratory, they were seated at an isolated computer station. Before beginning the study, participants completed a consent form detailing the study procedures and their expected payment for participating. Thereafter, a custom Web application displayed instructions for an iterated PDG. Participants began with an endowment of 1000 monetary units (MUs). Following past work (*2*, *12*, *15*, *18*), cooperation entailed paying 50 MUs and resulted in the alter gaining 100 MUs. Defection entailed paying nothing and generating no benefits. Several comprehension check questions, with feedback, were included in the study instructions (see the Supplementary Materials for additional details, including screenshots of the study instructions).

The study consisted of three phases (described in more detail below). At the beginning of each phase, participants were randomly assigned to a position within a network and given a unique letter ID that was displayed throughout the phase. Initial networks were random (Erdös-Rényi) graphs with a density of 0.21, meaning that participants had 4.36 ties, on average, at the beginning of the study. In each round of the phase, participants made decisions to cooperate or defect independently for each alter to whom they were tied. Once the phase was complete, participants were randomly assigned to a position in a new random network, received a new identifier, and were given a new 1000-MU endowment before the next phase began.

We manipulated the type of network within-subjects such that each of the three conditions (or phases) was presented in random order. Following past work in studies of networks and cooperation (*1*–*3*, *15*), in the static network condition, participants were tied to the same alters through the entire phase. In the dynamic network condition, participants could sever a tie to one alter and initiate a new tie after every three rounds of the phase. Prospective new alters included any alter not currently tied to the participant, including those the participant had dropped in previous rounds. When initiating a tie to a new alter, the alter could either approve or decline the request; only if the alter accepted did the new tie form. Ties were not replaced for participants who were dropped (*2*, *3*, *18*, *19*). Any participant who lost all of their ties became an isolate and was excluded from the network for the remainder of the phase.

In our mixed network condition, we randomly assigned whether each of the participants' individual ties was static or dynamic.

Participants were aware which of their ties were static and which were dynamic when making PDG decisions. As in the dynamic network condition, after every three rounds, participants could drop one of their alters and initiate a new tie, provided the relation was dynamic. Static ties were maintained throughout the duration of the phase. New ties formed during the tie selection process were always dynamic.

In addition to manipulating the type of network, we also manipulated the presence of reputation information by either displaying reputations [i.e., the percentage of times participants had cooperated in previous rounds of the current phase (*2*, *4*)] or not when participants selected new alters in the dynamic and mixed network conditions. As a result, participants did not see reputations in the static network condition, where participants were unable to select new ties, nor did they see reputations if they chose not to drop a tie. This manipulation was between-subjects, with 10 networks in each condition. This number of networks is typical in the literature on cooperation and networks, especially when the network size is large (*2*, *3*, *17*).

Each phase lasted 12 rounds; thus, participants completed 36 rounds in total. To avoid end-game effects, participants were not told how many rounds to expect, nor were participants in the dynamic and mixed network conditions told exactly when tie-dropping opportunities would occur, only that they would happen "periodically." Each session lasted approximately 75 min. The Institutional Review Boards at both universities reviewed and approved the procedures.

There was no deception in the study, and we included extensive comprehension check items with feedback to ensure that participants understood the instructions. As a result, we did not expect to exclude any observations from analyses unless a computer error occurred. All analyses were conducted using the full dataset. See the Supplementary Materials for additional details.

Statistical analysis

Because participant-alter interactions were interdependent within the networks to which they belonged, we conducted initial tests for differences across conditions (network type and reputation information), with cooperation aggregated at the network level. Then, to analyze round- and alter-level cooperative behaviors, we modeled the data using linear (for earnings) or generalized linear (for cooperation) mixed models. These models account for the four-level nested structure of the data, with alters nested in rounds, rounds nested in participants, and participants nested in networks. All statistical tests were two-tailed.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/12/eaau9109/DC1

Experimental details

Statistical analyses

Reference (*20*)

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Acknowledgments: We thank M. McKnight for granting us access to Breadboard and J. Abernathy and C. Munn for research assistance. **Funding:** The research reported here was funded in whole under Award W911-NF-15-1-0131 from the U.S. Army Research Office/Army Research Laboratory. The views expressed are those of the authors and should not be attributed to the Army Research Office/Army Research Laboratory. **Author contributions:** A.H., D.M., and B.S. designed the research; A.H. supervised data collection; A.H. and D.M. analyzed the data; and A.H., D.M., and B.S. wrote the paper. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper or the Supplementary Materials. Data and codebook for replicating the analyses are available at the Open Science Framework (https://osf.io/u3hdr/). Additional data related to this paper may be requested from the authors.

Submitted 26 July 2018
Accepted 7 November 2018
Published 5 December 2018
10.1126/sciadv.aau9109

Citation: A. Harrell, D. Melamed, B. Simpson, The strength of dynamic ties: The ability to alter some ties promotes cooperation in those that cannot be altered. *Sci. Adv.* **4**, eaau9109 (2018).