Strong Ties Promote the Evolution of Cooperation in Dynamic Networks*

David Melamed
The Ohio State University

Brent Simpson
University of South Carolina

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* We greatly acknowledge support from the Army Research Office (W911NF-14-1-0398). Direct correspondence to David Melamed, Department of Sociology, The Ohio State University, Columbus, OH 43210. E-mail: melamed.9@osu.edu. Phone: (440)759-6943.

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Cooperation in nature is something of a paradox as cooperators may be exploited by defectors, or those who take advantage of others' cooperative behaviors. One emerging line of research addresses the conditions under which structured or networked populations promote cooperation (Fehl, van der Post, and Semmann 2011; Hanaki et al. 2007; Rand, Arbesman, and Christakis 2011). In particular, dynamic networks allow cooperators to shed relationships to those who do not reciprocate their benevolent acts (Santos, Pacheco, and Lenaerts 2006; Wang, Suri and Watts 2012), which enables cooperators to maintain many ties and form clusters characterized by high levels of cooperation (Bravo, Squazzoni, and Boero 2012). Mutual cooperation, in turn, increases the fitness of those cooperators, making cooperation a more viable strategy in dynamic networks than in unstructured populations.

Thus far the literature on the evolution of cooperation has assumed that relations are equally weighted (e.g., Rand, Arbesman, and Christakis 2011; Wang, Suri and Watts 2012). Here we aim to bring in sociological insights about the strength of ties to the problem of cooperation in dynamic networks. We argue that as tie value increases, so should the stability of relationships and thus their duration. Duration is a key dimension of tie strength (Granovetter 1973) and one of the best indicators of it (Marsden and Campbell 2012). In turn, these more durable, stronger ties promote cooperation. We elaborate this argument below and evaluate it using agent-based models. We then test it using data from a controlled laboratory study. The results from both studies support our argument. The agent-based model shows that tie value is positively related to cooperation. Likewise, as expected, our laboratory experiment shows that tie strength, as operationalized by relationship duration, mediates the effect of tie value on cooperation. At the same time, we find low levels of cooperation in dynamic networks in which tie value and

strength do not vary between relations. Below we review the relevant literature leading up to our argument.

When Do Networks Promote Cooperation?

A recent review (Rand and Nowak 2013) pointed to five theoretical bases of cooperation, *structured populations* being the most relevant for sociologists.¹ Structure can result from geography (e.g., Hauert and Doebeli 2004) or social networks. Here we focus on networks and describe the conditions under which they enable cooperation to persist. Specifically, our work addresses cooperation in *dynamic networks*, where ties can be altered (added or deleted) over time.

Two processes have been shown to promote cooperation in dynamic networks. First, simulation work suggests that as networks grow, preferential attachment to cooperators results in networks with scale-free degree distributions, with cooperators having a disproportionate share of connections to others (Santos and Pacheco 2005). In line with this work, Bravo, Squazzoni, and Boero (2012) found that cooperative agents establish more relations than defectors or free-riders, which increases the overall fitness of cooperators. Likewise, Eguíluz and colleagues (2005) found that “leaders” emerge within regions of large simulated networks and these leaders are cooperative agents with many ties and high payoffs. Each of these studies demonstrate that in dynamic networks, cooperators are likely to have more ties, and hence more opportunities to accumulate resources, than defectors.

The second process that facilitates cooperation in dynamic networks has been demonstrated in both simulations and experiments with human subjects across a variety of network conditions. While cooperation in static networks generally requires that clusters of

¹ The others, less relevant to our aims, include *direct-* and *indirect-reciprocity*, *multi-level selection*, and *kin selection* (Rand and Nowak 2013).

cooperators be imposed exogenously (Assenza, Gómez-Gardeñes, and Latora 2008), research on dynamic networks reveals how clusters of cooperators emerge endogenously, as cooperators maintain ties to each other while severing ties to non-cooperators (Fu et al. 2008; Poncela et al. 2008; Wang, Suri, and Watts 2012; Fehl, van der Post, and Semmann 2011; Rezaei and Kirley 2012).²

Importantly, multiple experiments with human subjects (Rand, Arbesman, and Christakis 2011; Shirado et al. 2013) have found that the rate of relation changes or tie swaps in dynamic networks affects aggregate levels of cooperation. If actors can only alter relations infrequently, it is difficult to shed ties to non-cooperators. Non-cooperators then take advantage of the fact that their partners are stuck with them. As a consequence, defection dominates cooperation. At the other extreme, research shows that, if relations are updated too frequently, non-cooperators quickly reattach to cooperators which, again, favors defection.³ Thus, as typically studied, network dynamics exhibit a “Goldilocks” effect (Shirado et al. 2013) where moderate levels of relation changes yield optimal levels of cooperation.⁴

² This result closely parallels earlier studies that, although not framed as investigations of network structure, demonstrated how the ability to enter or exit relations favors more cooperative strategies (Orbell and Dawes 1993; Yamagishi and Hayashi 1996; Boone and Macy 1999).

³ Note, however, that this result occurs only because, in these prior studies, actors seeking to form new ties are randomly connected to another actor in the *entire* pool of available actors, including those to whom they have previously shed ties. This is, of course, an unrealistic simplifying assumption. In the studies introduced below, we allow actors to form new ties only among the pool of actors to whom they have not previously been connected.

⁴ Specifically, Shirado and colleagues reported maximum levels of cooperation when 70% of the dyads were selected for tie updates. While this percentage might seem high, it is important to note that previously severed relations could be added in subsequent rounds of the experiment. Wang, Suri and Watts (2012) used a different approach, but also found that increasing the number of tie updates promotes cooperation. Importantly, when participants were asked to form new ties with others, they were provided with their decisions to cooperate or defect on the previous 5 rounds. It is therefore unclear whether increased levels of cooperation result from network dynamics or reputation effects, which also promote cooperation (Nowak and Sigmund 1998). The tie updating strategy we employ in the studies outlined below is more in line with the Wang et al. (2012) method, though we are careful to avoid conflating dynamic network effects with reputation effects.

Tie Strength and Cooperation

The research reviewed in the prior section has significantly advanced our understanding of how networks shape cooperation, but we can substantially extend and sharpen our understanding of the role of networks in the evolution of cooperation by investigating variation in the value and strength of social relations. The value of social relations derives from an array of sources, including the benefits that accrue to the actors from the relation (Molm and Cook 1995), the existence of alternative relations (Emerson 1962), the status value of association with a contact (Berger et al. 1972), or the emotional “buzz” actors attribute to the relation (Collins 2004; Lawler 2001; Molm 2008). Regardless of the “source” or type of value, more valued relations will tend to generate stronger ties, since actors will be more motivated to spend time in the relation and, most relevant to our arguments, more motivated to maintain them.

Our conception of tie strength also follows prior work. For instance, Granovetter’s (1973: 1361) seminal work defined tie strength as a “combination of the amount of time, the emotional intensity, the intimacy (mutual confiding), and the reciprocal services which characterize the tie.” This definition has given rise to many operationalizations of tie strength, including relationship duration (Atterton 2007; Baer 2010; Wegener 1991), frequency of contact (Holbrook and Kulik 2001; Jones et al. 2013; Louch 2000), type of relation (Wegener 1991), subjective closeness (Baer 2010), and the amount of support received from the tie (Holbrook and Kulik 2001). Marsden and Campbell (1984, 2012) noted that closeness and relationship duration, especially outside of families, are good indicators of tie strength (Most kinship ties are not dynamic, making duration a poor indicator of the strength of ties between family members.) As detailed more fully below, we use duration as an indicator of tie strength for two main reasons: (i) it is straightforward to objectively measure in our empirical studies, and (ii) it would be

impossible to implement psychological closeness in our agent-based model without introducing unnecessary additional assumptions.

Although tie strength has been used to explain employment (Bian 1997; Granovetter 1974, 1985; Lin and Dumin 1986; Montgomery 1992, 1994), information flows (Onnela et al. 2007), social support (Wellman and Wortley 1990), and a host of other outcomes, no prior work has addressed the impact of tie strength on network dynamics and cooperation. That said, a few recent findings are suggestive. Harrison, Sciberras, and James (2011) found that individuals were willing to incur greater costs to benefit more strongly tied alters. Specifically, using innovative experimental methods, they found that individuals agreed to experience greater physical discomfort for the benefit of alters to whom they were more closely tied. They argued that close ties were likened to kin by the participants, and kinship is another key mechanism that promotes cooperation and self-sacrifice (e.g., Nowak 2006). While the study by Harrison and colleagues illustrates that individuals are more likely to cooperate with strong ties, it is silent on how tie strength impacts network dynamics and the emergence and robustness of cooperation. In other work, Macy and Skvoretz (1998) used a genetic computational model to show that trust and cooperation may evolve in neighborhoods and spread through weak ties. In this context, however, tie strength was not an explicit focus, but was instead used generically to denote ties to “strangers” (i.e., nodes with whom ego had not interacted).⁵

Why specifically should tie strength matter for cooperation in dynamic networks? Relationship duration is one key dimension of tie strength (Granovetter 1973; Marsden and Campbell 2012). Relations that endure allow for the development of trust and commitment within the dyad (Kollock 1994; Yamagishi, Cook and Watabe 1998; DiMaggio and Louch

⁵In contrast to our focus, other work on tie strength and cooperation (Flache and Macy 1996; see also Horne 2001; Kitts 2006) addresses how dyadic ties between individuals in a group impact contributions to collective actions.

1998). Moreover, relations that persist over time in dynamic networks tend to be between more cooperative actors, whereas relations connecting cooperators to defectors, or defectors to one another, are more likely to be severed, because trust and commitment have been violated by at least one party.

Because of the increased fitness of cooperative agents resulting from strong ties, we expect replicator dynamics (Page and Nowak 2002) to favor cooperation over defection as the ecology evolves. Specifically, in dynamic networks where the value of ties varies, we expect that relationships between cooperators will become stronger as tie value increases. In turn, the stronger ties between cooperators will increase the fitness of cooperators, enabling cooperation to evolve and persist in the ecology.

Taken together, the forgoing yields the following hypotheses:

H1: Allowing tie value to increase promotes cooperation in dynamic networks.

H2: Tie strength, as indicated by relational duration, mediates the impact of tie value on cooperation.⁶

Recall that prior work shows that network dynamics promote cooperation only when actors can update their ties at a sufficiently high rate (Rand, Arbesman, and Christakis 2011; Shirado et al. 2013). We therefore expect that the positive impact of tie value on cooperation will be weaker or non-existent when the rate of network dynamics is slow. This is because cooperators will be less able to shed ties to defectors in order to establish strong ties with fellow cooperators. In short, we expect that the effect of tie value on cooperation will be moderated by

⁶ Note that, in contrast to our predictions, there are also reasons to expect that tie value might negatively impact cooperation. Specifically, empirical work on signaling shows how more opportunistic actors tend to act cooperatively when, by doing so, they can develop more beneficial relations that can subsequently be exploited (Barclay and Willer 2007; Simpson and Willer 2008; Gambetta and Przepiorka 2014). As Granovetter (1985, 491) notes, the “trust engendered by personal relations presents, by its very existence, enhanced opportunity for malfeasance.”

the rate of tie swaps in dynamic networks. Because we do not have an *a priori* prediction about the strength of this moderation effect (e.g., whether the impact of tie value on cooperation will be weak or non-existent when ties are updated infrequently), we state our hypotheses as main effects. We use the agent-based models described below to explore the strength of the moderation effect.

Below we investigate our predictions using an agent-based model of interactions in iterated Prisoner's Dilemma (PD) games, and then explicitly test them using an experiment with human participants. As detailed more fully below, the experiment also allows us to test how variation in tie value impacts network dynamics.

Study One

Simulation Dynamics

Following related work on the evolution of cooperation, our agent-based model employs an evolutionary game theoretic framework (e.g., Hofbauer and Sigmund 1998; Macy and Skvoretz 1998; Mark 2002). This framework models systems of agents programmed to use one of a set of strategies (e.g., either cooperate or defect) in their interactions with other agents. The outcomes of these interactions yield a feedback loop that drives the evolution of strategies within the ecology. Most studies of the evolution of cooperation assume that the structure of incentives in these interactions is equivalent to a PD (e.g., Fowler and Christakis 2010; Kollock 1993; Macy and Skvoretz 1998; Wang, Suri, and Watts 2012). In its basic form, each player in a two person PD decides whether to cooperate or defect in each interaction. These two choices yield four possible outcomes at the dyadic level, including R (reward) for mutual cooperation, P (punishment) for mutual defection, S (sucker) for cooperation when alter defects, and T (temptation) for defecting when alter cooperates (e.g., Macy and Skvoretz 1998). For a PD, $T >$

$R > P > S$, which ensures that, absent strategic incentives, rational egoists will always defect, regardless of whether alter cooperates (since $T > R$) or defects (since $P > S$). An additional defining feature of a PD is that $2R > T + S$, which ensures that mutual cooperation is more beneficial than taking turns being exploited.

Following previous work (e.g., Wang, Suri and Watts 2012), the payoff matrix for our primary agent-based model is as follows: $T = 7$, $R = 4$, $P = 1$, $S = -1$. These values incentivize defection to a greater extent than many other values that satisfy the PD constraints. For instance, the K -index (Rapoport 1967) is a standard index of the extent to which a social dilemma incentivizes cooperation or defection and ranges from 0 and 1, with larger values indicating a greater incentive to cooperate. This payoff matrix has a K value of .375. Thus, this value allows us to assess whether stronger ties promote cooperation under conditions that are relatively unfavorable to cooperation, and thus offers a conservative test of our claims. But we also wanted to ensure that our results are robust across a wide range of incentive structures. We therefore conducted replications with K values of .167, .667 and 1.0.⁷ Cooperation is problematic for K values of .167 and .667, but when K is 1.0, there is no incentive to defect and cooperation is not problematic. We thus expect the value of ties to matter when $K < 1$.

Agents interact by synchronously making decisions in the PD game with other agents to whom they are connected over repeated rounds. The initial networks on which the evolutionary dynamics played out were random (i.e., Erdős–Rényi) graphs with 250 nodes and a density of .08 (i.e., ~20 edges per node). Following related work (Santos, Pacheco, and Lenaerts 2006), once the initial network was generated, we randomly defined ~2 relations per node as immutable ties. This substructure of immutable ties ensured that the network remained connected

⁷ When $K=.167$, $T = 13$, $R = 5$, $P = 1$, $S = -11$; when $K=.667$, $T = 8$, $R = 7$, $P = 1$, $S = -1$; and, when $K = 1.0$, $T = 5$, $R = 4$, $P = 2$, $S = 1$.

throughout the simulation (see also, Watts 1999). Nodes interacted for 50 strategy updates, although absorbing states were often obtained after only 20 strategy updates. Following convention (Assenza et al. 2008; Fu et al. 2008; Hanaki et al. 2007; Pacheco et al. 2006; Rand et al. 2011), the initial population is set at half unconditional cooperators and half unconditional defectors. Unconditional cooperators (defectors) cooperate (defect) with all of their alters on any given iteration. At each iteration t each agent i plays once with every agent to whom it is connected j and accumulates payoffs P_{ij} . Each agent keeps track of payoffs from each alter through time P_{ijt} . After each interaction, agents synchronously and unilaterally delete the tie to the alter from whom they have earned the least, i.e., $\min(P_{ijt})$. New ties are then formed at random from the subset of nodes with whom i has not previously interacted (see also, Fehl, van der Post and Semmann 2011). Strategy updates entailed i selecting one j at random; if $P_i > P_j$ then i retains its strategy; if $P_i < P_j$ then i adopts j 's strategy.

Manipulations and Sensitivity Analyses

We manipulated two main factors in the agent-based model. The first is the value of ties and the second is the number of tie updates before a strategy update. Following our earlier discussion and based on previous work (Granovetter 1973; Marsden and Campbell 2012), we operationalized tie value as a multiplicative factor that affects the payoff matrix for each iteration two nodes were connected. Specifically, let v denote tie value, let t_{ij} denote the number of iterations the i, j^{th} agents have interacted and let $\mathbf{P}$ denote the payoff matrix. Then our operationalization of tie value can be defined as $\mathbf{P}v^{t_{ij}}$. The strategies of the agents define the entry of the matrix that determines their payoffs. The specific values we used for tie value were 1, 1.1, 1.2, 1.3, 1.4, and 1.5. (Preliminary analyses suggested larger values were redundant.) A tie value of 1 is akin to a control condition since, mathematically, the payoff matrix does not vary

with time. This is the assumed value in all prior work on networks and cooperation. As the value of ties increases, the entries in the payoff matrix increase in magnitude as agents interact through time. Importantly, the tie value manipulation equally impacts incentives for defection, including the temptation payoff. Our operationalization of tie value thus captures the fact that more valued relations can promote cooperative incentives as well as incentives to exploit others' cooperation (Granovetter 1985).

We introduced a second manipulation, the number of tie updates or dynamic tie switches before a strategy update, to assess the robustness of the agent based model results. Agents interacted and then updated their relationships 1 to 8 times before selecting an alter for a potential strategy update. This manipulation follows Wang, Suri, and Watts (2012) with a key exception: instead of forming ties on the basis of reputations (knowledge of strangers' previous interaction histories), new ties were formed at random from the set of actors with whom the nodes had not previously interacted. This allows us to clearly separate the effects of network dynamics from reputations, which also promote cooperation (e.g., Barclay and Willer 2007). The range of tie updates corresponds to ~5% to ~40% of each node's alters, which exceeds the range used by Wang, Suri and Watts, but is less than the optimal or "Goldilocks" level reported by Shirado and colleagues (2013); however in our model, once relationships were severed they could not be reinstated, as they could be in Shirado and colleagues' design (see note 3).

In addition to manipulating the above factors, we also investigated three other factors in sensitivity analyses. As already described above, we conducted robustness checks with different K values, i.e., payoff structures. Additionally, we replicated the agent-based model on networks that were initially clustered and on networks that initially had a scale free degree distribution, as

these factors have been shown to promote the evolution of cooperation (Assenza et al. 2008; Santos, Pacheco, and Lenaerts. 2006).

Results

We focus our discussion on results of the agent-based models where $K=.375$. The results from the simulations where $K=.1667$ and $K=.667$ are substantively identical with less and more aggregate cooperation, respectively. As expected, when $K=1.0$, the tie strength manipulation had no impact on the evolution of cooperation.⁸ Our results are averaged over 100 replications of the agent-based model at each level of the manipulated factors. First, we wish to establish a general relationship between tie value and the evolution of cooperation. Figure 1 is a heat map of the proportion of cooperators at the end of the agent-based model given the tie value multiplier and the number of tie updates before a strategy update. The first thing to notice is that when tie value is one, as has been assumed in this literature, there are *effectively no cooperators remaining in the ecology, regardless of the number of tie swaps*. But, as tie value increases, so does the proportion of cooperators; likewise, as the number of tie updates between strategy updates increases, so does the proportion of cooperators. As would be expected from prior work, there is an interaction between tie value and the number of tie updates between strategy updates: the tie value manipulation only matters when agents have an opportunity to update four or more ties before a strategy update. At that point, the effects of tie value on the evolution of cooperation are clear. Prior to that point, cooperators are not able to shed relations with defectors fast enough to avoid being replaced by them during strategy updates, which is consistent with earlier findings (Wang et al. 2012; Shirado et al. 2013).

[Figure 1 About Here]

⁸ The full results for the simulations using the alternative values of K are available from the first-listed author upon request.

Having established a basic positive relationship between tie value and the evolution of cooperation, we now turn to our predictions about *why* tie value matters for cooperation. We predicted that tie strength – operationalized as relationship duration – would mediate the effect of tie value on cooperation. To assess this, Model 1 in Table 1 presents the results of an OLS regression model predicting the average duration of relations between cooperators in the agent-based model. Since the number of tie swaps moderates the effect of tie value, we include a variable for tie swaps and its interaction with tie value in our models. The main effect of tie value is negative, but the interaction between tie value and the number of tie swaps is positive: as the number of tie swaps increases, so does the effect of tie value on relationship duration. (While this increase is statistically significant, the standard errors should be taken with a grain of salt given that the data are based on simulations [see also, Hanaki et al. 2007; Kim and Bearman 1997]). Put differently, we have argued that tie value is positively related to cooperation through duration. These simulation results suggest that tie value predicts duration between cooperators only when network dynamics unfold at a sufficiently high rate. At low levels of tie swap opportunities, cooperators get stuck with defectors and suffer as a result.

[Table 1 About Here]

To examine mediation effects, we estimated two additional regression models predicting the proportion of cooperators surviving at the end of each simulation.⁹ Model 2 (Table 1) excludes relationship duration between cooperators. Here again we see that tie value has a negative effect on the proportion of cooperators. But, as expected, the interaction with the number of tie swaps is positive: as the number of tie swaps increases, so does the effect of tie value. This is consistent with our first hypothesis. Model 3 includes relationship duration. Consistent with our second hypothesis, which predicts that relationship duration mediates the

⁹ Tobit models with censoring at zero and one replicate findings from the OLS regressions presented here.

impact of tie strength on cooperation, we find that both the main effect of tie value and its interaction with the number of tie swaps are diminished, relative to Model 2. The main effect decreases by 64% (from $-.069$ to $-.025$), and the interaction with the number of tie swaps decreases by 65% (from $.029$ to $.01$). Thus, comparing models, the effect of tie value and its interaction with the number of tie swaps decreases both substantively and significantly, though again, we emphasize that these are synthetic data. This mediation result is consistent with the logic underlying our second hypothesis.

To summarize, the results reported thus far are consistent with our argument. In dynamic networks, as tie value increases, relationships between cooperators last longer, i.e., the ties become *stronger*. At the same time, the length of relationships between cooperators and defectors decreases as tie value increases (supplemental analyses, not shown). As a result, we observe higher levels of cooperators as the potential value of ties increases, provided there are sufficient tie switching opportunities before agents update their strategies. As noted above, we checked whether these results hold under other initial conditions that have been shown to affect the evolution of cooperation. Below we report the results of simulations with initially scale-free networks and initially clustered networks.

Scale-free Networks

Scale-free (or power-law) degree distributions have been shown to promote cooperation (Assenza et al. 2008; Santos, Pacheco, and Lenaerts. 2006). As many real-world networks follow this type of degree distribution (Albert and Barabási 2002), we investigated how a scale-free degree distribution for the initial network shapes the evolution of cooperation. For the simulated degree distribution, we used an exponent of 2.5 (see, Dorogovtsev and Mendes 2003).

Figure 2 presents another heat map of the proportion of cooperators at the end of the simulation by tie strength and the number of tie updates before a strategy update. These results, at first glance, appear less straightforward than those of Figure 1. We observe a positive effect of tie value on cooperation until the agents make 6 tie updates before a strategy update. From 6 – 8 tie updates before a strategy update, the effect of tie value on the proportion of cooperators is *negative*. This is confirmed by a regression analysis: the main effects of tie value and the number of tie updates are positive, but the interaction is negative (all $p < .001$), meaning that the effect of tie value decreases as the number of tie updates increases.

[Figure 2 About Here]

On the one hand, we were encouraged by the effect of tie strength when there are relatively few tie updates. But the effect of tie value when there are relatively many tie updates was puzzling. To address why this occurred, we investigated the distribution of defectors after each strategy update when agents updated ties eight times before a strategy update. We found that the effect is driven primarily by cases when defectors were hubs, i.e., those nodes with many ties. Because hubs have so many connections, not all cooperators could drop them in a single round, and they were tied to (and therefore able to “convert”) many cooperators. This allowed well-connected defectors to continue to fare well for longer periods of time than they would have otherwise. As defectors remain in the ecology, the likelihood of converting cooperators to defectors increases.

To put this finding into perspective, note that these well-connected defectors were well-connected as a result of initial conditions. But it is highly unlikely that defectors would end up as hubs in the first place: agents that defect in all of their interactions would be unlikely to establish or maintain many ties. This highlights an important shortcoming of our model: the set of agents

is fixed at the beginning of the simulation. Other work on the evolution of cooperation shows that scale free degree distributions are an endogenous result of network dynamics, rather than an initial condition. Specifically, Poncela and colleagues (2008) find that as agents join the network, they prefer to interact with cooperative agents. This preferential attachment means that cooperative agents are more likely to end up being the stars or hubs in scale free networks, and since they have so many ties, they can sustain some ties to defectors. Thus, under more realistic conditions, the negative interaction between tie strength and tie updates we observed in our simulations of scale free networks would be unlikely.

Clustered Networks

An additional factor that promotes cooperation is clustered network structures (Assenza, Gómez-Gardeñes, and Latora 2008). It may be that the value of ties is irrelevant if the initial network structure is clustered, e.g., by kinship, clans, or some other basis. Given that networks are often clustered, this would limit the import of tie value for our understanding of the evolution of cooperation. We therefore ran another set of agent-based models to investigate whether tie value promotes cooperation even in clustered networks. This time the initial network was a small-world network with an average nodal clustering of .71. (The average nodal clustering in the Erdős–Rényi graphs was .08 – the same as the density since ties were random.) Figure 3 presents a similar heat map to Figure 1. The results are very similar to those obtained with an initially random network: tie value promotes cooperation, particularly when agents can make several tie switches before a strategy update.

[Figure 3 About Here]

To sum up, our results indicate that as the value of ties increases, relationships between cooperators last longer than relationships between cooperators and defectors. The durability of

relationships between cooperators promotes the overall fitness of cooperators, which in turn leads to their prevalence. These results are robust to the amount of clustering in the initial network and, when agents make few (five or fewer) tie switches before a strategy update, in networks that initially follow a scale-free degree distribution. These simulation results thus lend support to our claim that the strength of ties between actors can contribute to the evolution of cooperation in dynamic networks.

Discussion

The agent-based model has a number of particularly desirable properties. First, it allowed us to investigate a large parameter space. There were 48 “conditions” in the simulation (plus the simulation was replicated with other K values), given that we crossed tie value with the number of tie swaps before a strategy update. Second, the model provides insight beyond the mere “aggregation of individual attributes” (Macy and Willer 2002), by highlighting emergent properties that result from the relational dynamics of interacting agents. However, the model also has a number of drawbacks. First, following convention in this literature, the agents in the simulation used unconditional strategies. While this allows us to assess the overall viability of cooperation in environments where cooperation is problematic, it is an unrealistic assumption, as human actors make decisions both conditionally and relationally. For instance, I may cooperate with one of my alters with whom I am on good terms, but not cooperate with an alter who did not cooperate with me in a previous interaction. Second, while there are disagreements about the role of agent-based models in theory testing (c.f., Gilbert and Troitzsch 2005), such models are clearly not substitutes for behavioral data from humans. To this end, we designed a controlled laboratory experiment to test our key claims with human participants.

For comparability purposes, the experiment mimics the agent-based in most respects. There are, however, three key differences between the two studies. The first, as already noted, was that while the agents in the simulation used unconditional strategies, the human participants in our laboratory experiment could decide whether to cooperate or defect separately for each alter in each round. We did not allow the agents in the simulation to adopt these conditional strategies because it would have required either an arbitrary decision rule (e.g., Nowak and Sigmund 1992) or an arbitrary probability distribution. Further, the vast majority of agent-based models of the evolution of cooperation in networked populations employ unconditional strategies (e.g., Assenza et al. 2008; Fu et al. 2008; Hanaki et al. 2007; Pacheco et al. 2006; Rand et al. 2011).

Second, the agents in the simulation were programmed to delete ties to those from whom they earned the least over the duration of the simulation. But in the laboratory experiment described below, participants made their own decisions about which tie, if any, to dissolve. Again, we restricted the behaviors of the agents in the simulation to avoid imposing an arbitrary decision rule.

Finally, the agent-based model was conducted on networks with an immutable sub-structure, which ensured that the network remained connected throughout the simulation. While we did not use the same strategy with the laboratory experiment, the end result was the same: if the participant deleted a tie, they were connected to a different alter, ensuring that they remained connected to the broader network for the duration of the experiment. These three differences in design preclude any direct comparisons between the agent-based models and the laboratory experiment. But to the extent that the two methods yield similar conclusions, we would have

particularly compelling evidence of the role of tie strength in the evolution and stability of cooperation.

In addition to testing our basic argument that tie strength will mediate the effect of tie value on cooperation (H1 and H2), the experiment will also allow us to assess how tie value affects network dynamics. We expect that networks in which tie value increases over time will be more stable than networks where the value of relations is constant. Specifically, when the value of relations increases over time, deleting ties entails forgoing particularly valuable relationships. As such, we expect:

H3: When the value of ties increase over time, participants will be less likely to swap ties compared to when the value of ties remains constant over time.

H4: When participants decide to break a tie, relationship duration (tie strength) will be negatively associated with breaking the tie, and this effect will be strongest in networks where the value of ties increases over time.

Study Two

Participants were undergraduate students from a large public university, recruited based on the opportunity to earn money. Eighty-seven participants were randomly assigned to one of four experimental conditions. Following a standardized debriefing procedure, participants were interviewed to ensure that they understood the instructions and to assess suspicion. Seven participants indicated that they did not believe they were interacting with other people. The remaining 80 participants, who expressed no such suspicions, were evenly distributed across the four conditions. The experiment manipulated two factors: whether the value of ties increased with relationship duration and the tie deletion strategies of the simulated agents (see below). Across conditions, participants interacted in networks where all other network positions were

occupied by simulated actors. All network ties were exchange opportunities, with a structure of incentives equivalent to a PD. The Appendix contains screenshots with the instructions from the experimental program.

Procedures

Upon arriving at the experimental laboratory, participants were directed to isolated rooms and informed that they would be interacting with several other people over the Internet. In reality, partners were simulated actors that behaved in predetermined ways, as detailed below. Multiple participants were scheduled for each session to help convince participants that they were interacting with others in a large online experiment. After the participants completed the consent process, the remainder of the experiment was computer mediated.

Given the large networks used in the study ($n = 24$), the instructions informed participants that they were taking part in a collaborative study with two other universities, and that they would be interacting with others via the web. Interaction was described as an opportunity to contribute to a joint task, and participants were told that they would make this decision for each of their ties. We adopted the same payoff matrix as in our primary agent-based model (i.e., $T = 7$, $R = 4$, $P = 1$, $S = -1$). Participants were told that they would be paid \$0.05 for every point they accumulated during their interactions. This is consistent with other operationalizations of value in laboratory settings (e.g., Molm 2010; Smith 2003).

Participants were also told that they would occasionally have an opportunity to stop interacting with one of their ties and to form a tie with another person. Specifically, participants could choose whether they wanted to delete a tie, and if so, which one. If they decided not to swap a tie, they waited while the other ostensible participants presumably swapped ties. If they decided to swap a tie, they picked which tie to swap, and that relation was then replaced “at

random from the set of others with whom they have not yet interacted.” While participants were not told this, tie swap opportunities occurred after every three rounds of PD and there were a total of 21 rounds of PD.

The simulated others employed one of four strategies: always cooperate, always defect, tit-for-tat (Axelrod 2006), and win-stay/lose-shift (Nowak and Sigmund 1993). Tit-for-tat is a basic strategy that mimics the behavior of the interaction partner in the previous round. For example, if your partner defected in the previous round, you defect in the present round; if your partner cooperated in the previous round, you cooperate in the present round. Simulation models show that win-stay/lose-shift can outperform tit-for-tat (Nowak and Sigmund 1993). The rule is simple: if awarded either of the two highest payoffs (T or R) on the previous round, it stays with the strategy employed in the previous round; if awarded either of the two lowest payoffs (P or S), it switches strategies. The strategies of simulated alters with whom participants interacted were randomly assigned at the programming stage of the experiment, ensuring that the experiences of the actual participants were as similar as possible across conditions. That is, by simulating the partners’ behaviors, we were able to maintain control over the participants’ experiences, allowing cleaner contrasts between experimental conditions. While there are advantages of having human participants occupy all network positions, doing so would have necessarily resulted in a loss of experimental control.

Manipulations

Our primary manipulation is the *value of ties*. Consistent with the agent-based model, the value of ties did not vary with relationship duration in the control condition. In the treatment condition, for each round the participant was connected to a given alter, the entries in the payoff matrix for interactions with that alter were multiplied by 1.1. That is, depending on condition, for

each round the entries in the payoff matrix were multiplied by either 1 (control) or 1.1 (treatment) raised to the power of the number of rounds the tie had persisted. We chose 1.1, the smallest value from the agent-based model, as a conservative test of our argument.

The second manipulation is the *tie deletion strategies* of the simulated actors. The participants were able to make changes to their networks, so presumably the other agents in the experiment could as well. We operationalized these strategies in two ways. In the first, the alter with whom the participant defected in the most interactions dropped the participant. If the participant defected the same number of times with all alters, one of them was selected at random to drop the participant. On the one hand, this strategy is consistent with behavioral data showing that ties to defectors are more likely to be deleted than are ties to cooperators (Fehl, van der Post, and Senmann 2011; Rand, Arbesman, and Christakis 2011; Wang, Suri, and Watts 2012). On the other hand, we reasoned that participants might eventually learn that their ties would be deleted if they defected too much. This operationalization might therefore “load the dice” in favor of cooperation.

As an alternative, our other approach was to have simulated actors drop the participant at random. Because tie deletion is independent of the behaviors of participants, it should not favor cooperation. If anything, when ties to the participant are being deleted at random, participants may be more inclined to defect. Given the potential divergent effects of these two tie deletion strategies for the evolution of cooperation, we randomly assigned participants to one of the two strategies. This allows us to determine whether any observed effects of tie value are contingent upon the tie deletion strategies of the simulated others, and to assess the robustness of our

findings across very different tie deletion strategies.¹⁰ In addition to descriptive statistics, Table 2 shows the overall design of the experiment.

Measures

The main outcome is whether the participant cooperated (=1) in each of his or her interactions. Our operationalization of tie strength is similar to the one we used in the agent-based models. However, instead of the duration of relations between cooperators, here we use relationship duration in general, since agents could employ conditional strategies (i.e., they made decisions to cooperate or defect for each individual relation, rather than making a decision to cooperate or defect that applied to all their relations). In terms of network dynamics, we model whether the participant swaps a tie (=1) and, if so, we model which alter the participant chooses to delete (=1). Additionally, where relevant, we control for the lagged behaviors of the simulated others to account for effects of direct reciprocity (Axelrod and Hamilton 1981) on cooperation. Specifically, we control for lag effects for up to three rounds.

Results

Table 2 presents the proportion of cooperative acts based on the two manipulations. It is clear that both factors have main effects on cooperative behaviors. As expected, cooperation is higher in the tie value condition than the control condition. Likewise, cooperation is higher in the condition in which simulated alters delete ties based on defection versus when alters delete the participant at random. Indeed, an ANOVA model at the level of the participant demonstrates that both main effects significantly predict cooperation (both $p < .001$). Importantly, however, the

¹⁰ Of the 7 participants who expressed suspicion that others were not real, three were in the random deletion conditions and four were in the condition where simulated others deleted ties based on level of defection. This difference is not significant ($\chi^2_1 = .14$, n.s.) suggesting that neither approach yielded more or less suspicion of alters and their strategies.

interaction between them was not significant ($p = .647$), so the effect of tie strength does not vary by the strategies of the simulated agents.

[Table 2 About Here]

Before formally evaluating our argument that tie strength mediates the effect of tie value on cooperative behaviors, we show that the tie value manipulation has the intended positive effect on tie strength, as operationalized by duration. To this end, we estimated a three-level linear mixed model with the duration of each relationship nested in rounds, and rounds nested in participants.¹¹ As expected, the results suggest that relationships in the tie value condition lasted .406 rounds longer than relationships in the control condition ($p < .05$).

Turning now to the mediation argument, we estimated two three-level logistic regression models with multiple decisions (cooperate or not) nested in rounds and multiple rounds nested in participants.¹² The results of these regressions, including the variance components, are given in Table 3.

Model 1 reveals that, net of the lagged cooperative behaviors of alters and the alters' tie swap strategies, tie value has a significant positive effect on cooperation. Specifically, participants in the tie value condition were 192% more likely to cooperate than were participants in the control condition (i.e., $\exp(1.072) = 2.92$). This, again, supports Hypothesis 1: tie value indeed promotes cooperation. Hypothesis 2 states that tie strength, operationalized as relationship duration, would mediate this effect. To this end, Model 2 in Table 3 includes relationship duration. Here we see that the effect of tie value decreases by 93% and becomes

¹¹ The model has a random intercept at the first two levels and the tie value manipulation is treated as a third-level predictor. Tests of nested models (i.e., likelihood ratio chi-squared tests) were used to determine model specification.

¹² The first model, without relationship duration, has a random intercept at the first two levels, and the second model, with relationship duration, has a random intercept at the first two levels and a random slope for the effect of duration.

indistinguishable from zero. That is, relationship duration fully explains the effect of tie value on cooperative behaviors.¹³ Substantively, for each round that a participant was connected to a given alter, she was 18% more likely to cooperate with that alter. Thus across both the agent-based model and the experiment with human subjects, we find that tie strength has a powerful impact on the evolution of cooperation in dynamic networks.

[Table 3 About Here]

Our third hypothesis states that tie value will stabilize networks, such that participants in the tie value condition will be less likely to delete ties than participants in the control condition. To evaluate this prediction, we estimated a two-level logistic regression (i.e., random intercept model) with the seven tie-swap choices nested in participants. We used the two experimental manipulations as predictors. Table 4 presents the results of this model. The tie swap strategy of the simulated others was not significant, but the tie value manipulation was negative and significant. Specifically participants in the tie value condition, as opposed to the control condition, were 56% less likely to swap a tie (i.e., $\exp(-.831) = .44$). Thus, as ties become more valuable, participants were less likely to shed them, supporting Hypothesis 3.

[Table 4 About Here]

Our fourth hypothesis states that in the tie value condition, the longer the participant is tied to an alter, the less likely she will be to delete that tie. Here, provided that participants wanted to swap a tie, they could choose to delete one alter from the set of alters with whom they interacted for at least the previous three rounds. So participants had a series of conditional choices: if they choose alter ‘a,’ they cannot choose the other alters, and so on. Further, because

¹³ Given our experimental setup, the value of social relations could potentially be operationalized as lagged earnings: agents value alters to the extent that they earned a lot from them on the previous round. Substituting lagged earnings for the tie value condition dummy variable yields substantively similar results: relationship duration mediates the effect of tie value on cooperative behaviors.

there were multiple tie swap opportunities, several of these conditional choices were nested in participants. As such, we estimated a conditional logistic regression with participant-clustered standard errors. Table 5 presents the results of the conditional logistic regression.

Because we expect that participants will be unlikely to drop cooperative alters, we control for whether the partner cooperated in the previous three rounds. As expected, the results show that participants are less likely to delete an alter if that alter cooperated on the previous two rounds of the PD (lagged cooperation becomes insignificant after two rounds). Consistent with Hypothesis 4, the effect of relationship duration is indistinguishable from zero in the control condition, but it is negative and significant in the tie value condition. Thus, participants were less likely to delete an alter the longer they had interacted with them, but only when tie values increased over time. To understand the magnitude of this effect, consider a hypothetical situation in which there are three alters, Alter 1, Alter 2 and Alter 3. Assume that a connection to Alter 1 has lasted for 3 rounds, a connection to Alter 2 has lasted for 6 rounds, and that a connection to Alter 3 has lasted for 12 rounds. According to the conditional logistic regression, after controlling for lagged cooperation, there is an 84% chance that Alter 1 would be dropped, a 15% chance that Alter 2 would be dropped, and only a 1% chance that Alter 3 would be dropped. Thus, in networks where the value of social relations increases, ties are less likely to be severed the longer they endure. The contrast with the control condition, where duration had a null effect, is striking. This contrast provides clear support for our arguments linking variation in tie value to stronger ties and the evolution of cooperation.

[Table 5 About Here]

To summarize, tie value affects all of the mechanics of the evolution of cooperation in dynamic networks. To begin, it strongly impacts participants' decisions to cooperate or defect.

This impact, as anticipated by our argument, is fully mediated by tie strength, as operationalized by relationship duration. Increasing tie value also stabilizes networks, making it less likely that participants delete ties. And when they do delete ties, they are unlikely to delete those that have persisted over longer periods of time. Critically, these effects are unique to the treatment condition; we do not observe an effect for duration in the control condition, providing strong support for our arguments linking variation in tie value to cooperation and the stability of network relations.

Discussion and Conclusion

Since Granovetter's (1973) classic treatment, we know that ties vary in their strength, with important implications for a wide range of outcomes. Here we sought to bring these insights to bear on the problem of the evolution of cooperation in dynamic networks. Results from an agent-based model and a laboratory experiment with human participants demonstrated clearly that variation in tie value and corresponding tie strength can have powerful effects on network dynamics and the emergence of cooperation. Importantly, increases in tie value led to increased cooperation even though the incentive for participants to defect *also* increased in the tie value conditions. That is, no matter how long any dyad had been connected, the objective payoffs for defecting relative to cooperating remained constant. We think these findings are important and point to the value of bringing classic sociological insights about tie strength to bear on the study of dynamic networks and the evolution of cooperation. Thus far, research has assumed that all network ties are equally valued, and similar in strength.

Our results show that, in dynamic networks in which the value that can be derived from a given relation increases the longer it persists, cooperation can be sustained even under conditions in which dynamic networks composed of binary ties fail to sustain cooperation. In both random

and clustered networks, defectors dominated in agent-based models where tie value did not increase with relationship duration. Under those conditions, our results correspond closely to those of prior work. That cooperation was so much more prevalent when ties varied in value and strength, particularly when network dynamics unfolded quickly, underscores the importance of relational dynamics and social factors for the evolution and stability of cooperation.

We expect that tie strength will play an equally important role in networks that evolve based on actors' reputations. Reputations contribute to the evolution of cooperation via processes such as image scoring (Nowak and Sigmund 1998) whereby actors who cooperate come to have better reputations than those who do not. The question of how reputations diffuse is important but we thus far have limited insights into how network structure influences the diffusion of reputations. To the extent that networks constrain the diffusion of reputations, as has been suggested (e.g., Emler 1990), we might expect that reputational information transmitted via strong ties will be more valued and more apt to be acted on than reputational information received through weak ties. On the other hand, strong ties tend to be clustered (Granovetter 1973), leading to redundant information (Burt 1992). As a consequence, we might find that, while strong ties promote the clustering necessary for cooperation to thrive, the presence of some weak ties facilitates cooperation by providing channels for the diffusion of reputational information between otherwise disparate clusters. Understanding the structural conditions that favor both cooperative clustering and the diffusion of reputational information to promote cooperation is an important next step for future work.

Appendix: Screen shots from the experimental program

Introductory screen:

Thank you for participating in this study today!

As we are sure you are aware, you will be paid for participating in today's study.

You will be paid \$4.00 for completing the study, and
you will be paid \$0.04 for each point you earn in today's experiment.

On average, participants earn about \$15.00 total.

When the "Continue" button appears below, please click on it to
learn more about today's study.

Basic information about the study:

Today's experiment is part of a collaborative project with two other universities.

You will initially be connected to 3 other participants and asked to interact with them over the internet.
As the study progresses, you and your partners will have opportunities to stop interacting with each other
and start interacting with new people.

In total, there are 24 people, including yourself, that are involved in this session.
However, you may actually only interact with a small number of them.

PD instructions:

Over several rounds, you will be asked whether
you want to contribute to a joint task with each of the other participants with whom you may interact. How much
you earn from your interactions depends on the choices that you and the other participants make.

PD instructions:

For each other participant with whom you may interact, you will be asked whether you want to contribute to a joint fund.

If you **both choose to contribute**, you both **earn 4 points**.

If **you contribute** to the fund, but **the other participant does not**, you **lose 1 point** and **the other participant gains 7 points**.

If **you do not contribute** to the fund, but **the other participant does**, you **gain 7 points** and **the other participants loses 1 point**.

If you **both do not contribute** to the fund, **both you and the other participant gain 1 point**.

Instructions for conditions with the *Tie Value manipulation*:

This is important: for each round that you interact with each of your partners, how much you earn
from interacting with them will be multiplied by 1.1.

For example, if you and a partner both decide to contribute to each other on the first round that you interact,
you will each make 4.4. If you and that same partner decide to contribute to each other on the fifth round that you interact,
you will each make 6.44 (e.g., 4×1.1^5). This is true whether each of you decides to contribute to each other or not.

Information about payment:

The computer system will keep track of your points. At the end of the experiment, you will be paid \$0.04
for each point that you earned by interacting with the other participants.

Information about the Alters:

For today's experiment, you have been designated to be **Participant K**. The other participants have also been designated letters between **A** and **X**.

Interacting with those other participants with whom you may interact simply entails deciding whether or not you want to contribute with them. To do so, you simply click "yes" or "no" for each person with whom you may interact.

You will see the designations for everyone in the experiment, but you will only be able to interact or decide to whom to contribute with those to whom you are connected. For those participants with whom you cannot interact, you will not be able to select "yes" or "no."

PD instructions:

When the time comes to interact with the other participants, it is important to take your time and make sure you interact with each participant that you may interact with. If you do not make a decision, you earn no points.

Also, before you submit your decisions you may select "yes" or "no" as many times as you want. What is important is which button you select last. So if you want to contribute to Participant X, for example, make sure "yes" is selected and that it was clicked on more recently than "no."

PD instructions:

The results of the interaction will include three things:

- 1) Your decision towards each participant with whom you may interact.
- 2) Your earnings from that interaction. So if you contributed to Participant X, for example, and you earned -1 points, then X did not contribute. Or if you earned 4 points, then you know that X contributed to you.
- 3) Finally, the results will tell you the total you earned on that round.

On the next screen, we will walk you through an example.

Then there is an interactive example.

Dynamic network instructions:

Occasionally, you will have an opportunity to stop interacting with one of the other participants and start interacting with a new participant. You will be asked whether you want to stop interacting with one of the other participants that you had been interacting with. If you do, you will choose which participant to stop interacting with, and then the computer system will link you up at random with another participant. Likewise, when you are deciding whether and with whom to stop interacting, the other participants will also be deciding whether to switch interaction partners.

Dynamic network instructions:

This is important: once you stop interacting with one of the other participants you cannot interact with them again. That is, if you choose to stop interacting with them, or they choose to stop interacting with you, you cannot interact with them again.

Overview of the experiment:

OK, here is what we will have you do in the main part of the experiment:

You will initially interact with three other participants.

Interaction entails independently deciding whether to contribute to a joint task with each other participant with whom you may interact.

If you both contribute, you both earn 4 points. If one of you contributes and the other does not, the one who does not contribute earns 7 points and the other loses 1 point. If neither contributes, you both earn 1 point.

Occasionally you will have an opportunity to change interacting with one other participant.

If you choose to eliminate an interaction partner, the computer will match you up with someone new at random.

Finally, the computer system will keep track of your points and you will be paid \$0.04 for each point you accumulate during the experiment.

Then they completed the iterated PD games with their (simulated) alters.

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Table 1: Summary of OLS regression models predicting relationship duration and the proportion of cooperators.

	<i>Outcomes</i>		
	<i>Relationship Duration Between Cooperators</i>	<i>Proportion of Cooperators</i>	
Tie Value ¹ (V)	-.998*** (.075)	-.069*** (.004)	-.025*** (.002)
Duration Between Cooperators			.040*** (.001)
Number of Tie Swaps (S)	.300*** (.058)	-.013*** (.003)	-.025 (.002)
V × S	.487*** (.015)	.029*** (.001)	.010*** (.001)
Constant	3.073*** (.292)	.016 (.015)	-.108*** (.010)

Note: * $p < .05$, ** $p < .01$, *** $p < .001$. N = 4,800. ¹Coded as 1, 2, 3, 4, 5, and 6.

Table 2: Proportion of Cooperative Acts

	Alter Strategy		
	<i>Delete Ties at Random</i>	<i>Delete Based on Defection</i>	
<i>No Tie Value</i>	.44	.59	.51
<i>Tie Value</i>	.52	.70	.61
	.48	.65	

Table 3: Generalized Linear Mixed Models Predicting Cooperative Behaviors (=1)

<i>Factor</i>	Model 1	Model 2
Alter Coop Lag 1 (=1)	.949*** (.122)	1.258*** (.133)
Alter Coop Lag 2 (=1)	.757*** (.112)	1.101*** (.123)
Alter Coop Lag 3 (=1)	.484*** (.119)	.677*** (.129)
Tie Value (=1)	1.072*** (.459)	.076 (.294)
Duration		.168*** (.030)
Alter Strategy	1.237 (.460)	.404 (.306)
Constant	-1.866*** (.407)	-3.027*** (.311)
$\hat{S}_{Round}$	.534*** (.127)	.655*** (.130)
$\hat{S}_{Participant}$	1.951*** (.196)	.728*** (.232)
$\hat{S}_{Duration}$		.209*** (.029)

Note: *** $p < .001$. N = 3,475 decisions nested in rounds, nested in participants.
Log odds ratios reported.

Table 4: Generalized Linear Mixed Model Predicting Deleting a Tie (=1)

<i>Factor</i>	Model 1
Tie Value (=1)	-.831** (.326)
Alter Strategy	.027 (.323)
Constant	-.305 (.278)
$\hat{S}_{Participant}$	1.094 (.179)

Note: ** $p < .01$. N = 546 decisions nested in participants.
Log odds ratios reported.

Table 5: Conditional Logistic Regression Predicting Which Alter to Delete (=1)

<i>Factor</i>	Model 1
Duration (Tie Value = 0)	.087 (.082)
Duration (Tie Value = 1)	-.556** (.185)
Alter Coop Lag 1 (=1) ¹	-1.064*** (.219)
Alter Coop Lag 2 (=1) ²	-.626** (.212)
Alter Coop Lag 3 (=1) ³	-.183 (.250)

Note: ** $p < .01$, *** $p < .001$. N = 674 decisions nested in participants.

Standard errors are adjusted for multiple decisions nested in participants.

Log odds ratios reported. ¹Whether the alter cooperated on the previous round. ²Whether the alter cooperated two rounds ago. ³Whether the alter cooperated three rounds ago.

Figure 1: Heat map of the proportion of cooperators at the end of the agent-based model.

Figure 2: Heat map of the proportion of cooperators at the end of the agent-based model. The degree distribution of the network at the beginning of the simulation was scale-free.

Figure 3: Heat map of the proportion of cooperators at the end of the agent-based model. The initial network structure at the beginning of the simulation was highly clustered.