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Connected Coordination

Network Structure and Group Coordination

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Networks can affect a group's ability to solve a coordination problem. We use laboratory experiments to study the conditions under which groups of participants can solve coordination games. We investigate a variety of different network structures, and we also investigate coordination games with symmetric and asymmetric payoffs. Our results show that network connections facilitate coordination in both symmetric and asymmetric games. Most significantly, we find that an increase in the number of connections improves coordination even when payoffs are highly asymmetric. These results shed light on the conditions that may facilitate coordination in real-world networks.

Keywords: *social networks; game theory; coordination problems; elections; policy implementation; experimental design*

Social scientists have devoted enormous attention to understanding how real-world political actors can coordinate to solve collective problems. Much of this research focuses on situations in which actors must resolve a coordination problem that occurs within a network. Two areas in which coordination within a network are common in American politics are elections and policy implementation. In the electoral arena, the ability of disaggregated individuals to coordinate on campaign strategy and fundraising affects the ability of a candidate to win elected office. Networks affect the adoption of coordinated policy solutions as well as the ability of disaggregated actors to coordinate on implementing policy solutions.

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To study how network structure affects coordination, we embed game theoretic models of coordination into various network structures. The experimental setting allows us to vary network structure without changing anything else, thereby providing a causal test of how networks affect coordination games. The empirical literature on the effects of networks is largely unable to make causal claims, because the network does not vary independently of other aspects that may affect behavior. Our experiments resolve this problem and allow us to make causal claims about how network structure affects group behavior.

We find that when participants have common, symmetric incentives to coordinate, they can successfully achieve coordination regardless of network structure. However, with asymmetric incentives, network structure significantly affects the ability of a group to coordinate—networks with more connections facilitate coordination better than networks with fewer connections.

The article proceeds as follows. In the following section, we briefly review the literature on coordination and networks. Then, we elaborate our model of coordination within a network. We then present the specifics of our experimental design. Next, we analyze the results of our experiments, and in the last section, we discuss and conclude.

Literature Review

Scholars of American politics have studied many situations in which coordination is affected by the interaction between decision makers. The underlying coordination games can be either symmetric or asymmetric. In symmetric games, payoffs are equivalent across outcomes as long as coordination occurs. In asymmetric or impure coordination games, payoffs are still contingent on successful coordination, but the payoff to each person differs as in the battle of sexes game. We now discuss two common types of coordination problems in American politics.

Coordination problems frequently occur in electoral politics and policymaking. Two examples from the electoral arena are decentralized scheduling of campaign functions and fundraising decisions. The need to coordinate campaign activity occurs because the scarcity of time creates an allocation problem. This fits the general condition Calvert (1992) identifies, “A common variety of impure coordination problem arises whenever a group must agree on how to allocate some fixed stock of value among themselves” (p. 11). For example, consider a situation in which

multiple political activists agree on the candidate they want to support, and they each desire to organize some type of campaign activity (fundraiser, voter registration/mobilization, canvassing, etc.). The candidate's supporters will want to coordinate the timing of the multiple events so that they are not all scheduled on the same day. If all the events are scheduled for the same day, then attendees can only attend one event, even if they would be willing to attend multiple events. As a result, campaign activities may not be as effective as if they were spread out among multiple days.¹ Even though these activists all want the events to take place, they may disagree on whose event will occur first, second, third, and so on. Therefore, the organizers have an incentive to coordinate timing, and the situation resembles an asymmetric coordination game. The process of communication reflects the existence of a network that determines how information spreads among the multiple actors.

Another example from electoral politics is explained in Cox (1997), who considers how campaign donors decide to allocate their financial resources. Donors to the same party will likely have different preferences about which candidate they prefer, but they will also prefer that their party's nominee win the general election. As it becomes clear who the front-runners are in a party's primary, donors will have incentives to coordinate their activity to ensure that the candidate most likely to win in the general election emerges from the primary election. Coordination is facilitated by information about candidate characteristics, the activities of other donors, and how much time remains before the primary election. The information to facilitate coordination moves between different actors based on the connections, that is, the network, between individuals.

The relationship between network structure and coordination has been studied extensively by scholars interested in policymaking (Hecklo, 1978; Laumann & Knoke 1987). Policymakers share information among themselves, which can play a role in the ability to solve coordination problems in a decentralized fashion. Scholz, Berardo, and Kile (2008) find that cooperation among estuary management organizations depends on the network in which the organizations operate. In their view, a network is formed by connections between different organizations and the connections facilitate information flow about others' actions, thereby improving collaboration. Policy actors who are highly connected to others are more likely to work together on policy implementation, suggesting that networks influence coordination. Likewise, Carpenter, Esterling, and Lazer (2004) show that network structure is both affected by and affects information flow between interest groups attempting to influence policymaking. In particular, they

conclude that when demand for information increases, lobbying firms invest more resources in creating strong ties in their network but that the resulting network actually impedes the distribution of information. Mintrom and Vergari (1998) find that network connections facilitate the spread of policy ideas between states. Policy entrepreneurs learn about policies and then propose similar policies (a form of coordination) based on information from the networks.²

This empirical literature suggests that networks will have considerable affect on attempts to coordinate policy implementation. However, it is difficult, if not impossible, to draw causal inferences about the effect of network structure on coordination from empirical research, because the networks are endogenous to the task (or behavior). In an experimental setting, we can vary the network structure, while holding constant the coordination task that participants must complete, and therefore have a direct, causal test of the effect of networks on coordination.

The most direct antecedent of our work is Kearns, Suri, and Montfort (2006), who study the ability of a large group of human participants to solve a symmetric coordination problem called the graph coloring problem. The basic task in the experiment we both use is to color the nodes of a network such that every node is a different color than its immediate neighbors.³ In the experiment, participants know the color choices of all their neighbors as well as the amount of time remaining in the experiment and how close the entire network is to completion. Participants can freely change colors as often as they wish. Therefore, this set up is quite similar to a coordination game with communication. The authors find that groups of 38 participants can quickly solve the coordination problem and that an increase the number of connections leads to faster solution times. This result is consistent with the idea that communication can facilitate coordination. In this article, we build on Kearns et al.'s results and study how network structure affects the ability of participants to solve both symmetric and asymmetric coordination games.

Modeling Coordination in a Network

In this article, we embed coordination game into a multiperson, networked environment. To date, there is little experimental research that combines game theory and networks.⁴ Our experiments and model build on Kearns et al.'s (2006) study of the graph coloring problem. Although the problem is conceptually simple, it contains a number of interesting nuances that make it an appealing problem to study.⁵

Figure 1
Symmetric Incentive Coordination Game

		Player 2	
		Red	Green
Player 1	Red	(0,0)	(1,1)
	Green	(1,1)	(0,0)

First, the graph coloring problem is an example of coordination in a network making it analogous to the empirical examples that motivate our interest in the article. The problem has been widely studied by computer scientists, both theoretically and via simulation (see Jensen and Toft, 1994, for a review of much of the graph coloring research). Second, for the two-colorable graphs we focus on, there are good centralized algorithms for solving the problem, but the properties of distributed algorithms are not well understood. Our experiments use distributed problem solving because each human participant controls the color of only a single node in the network, so there is no centralized decision maker. The upshot of this is that we may be able to learn about good mechanisms to solve the graph coloring problem in a distributed fashion through human experiments. Third, the graph coloring problem is a dynamic problem in which participants can change their choices as they learn about the choices of other actors in the game, which mirrors many real-world problems in which we change our actions as we observe the actions of others. We first outline the basic, static form of each game and then move to a discussion of the dynamic model.

The basic, nondynamic two-person form of the symmetric coordination game is displayed in Figure 1. The payoff for individuals is identical whether they coordinate on action Red or Green in Figure 1. There are two Nash equilibria to this game either (Red, Green) or (Green, Red).

As Kearns et al. (2006) showed, and as previous experimental results on coordination games with communication suggest (Blume & Ortmann, 2007), participants can often solve this game. In the experimental setup, participants have a tremendous amount of information available to them as they play the coordination game. This experiment involves dynamic decision making rather than one-shot decisions, which is the typical way in which coordination has been studied experimentally. The dynamic nature of the game essentially turns the game we are studying from a one-shot coordination game without information into a coordination game with information. In the actual experiment, participants can change their color

Figure 2
Asymmetric Incentive Coordination Game
With Red as Bonus Color

		Player 2	
		Red	Green
Player 1	Red	(0,0)	(1 + B, 1)
	Green	(1,1 + B)	(0,0)

repeatedly until coordination is achieved, and they get tremendous information about their neighbors and feedback about how their actions affected the networks overall level of coordination. Therefore, we expect that human participants can solve this symmetric, dynamic coordination game.

The second type of coordination game that we used in these experiments is an asymmetric coordination game (such as a battle of the sexes). Again, participants are only paid if coordination is achieved, but the payoff to a participant depends on the outcome. Figure 2 displays a general form of this game in which the bonus amount is a parameter that can be modified.

The key difference in the asymmetric coordination game is that although there are still two Nash equilibria (Red, Green) and (Green, Red) the actors now have a preference for which color they choose. In games of this type, there is conflict over how coordination will occur. We view this as a more realistic and interesting form of coordination. In particular, in this type of game, we expect network structure to have significant effects on whether or not global coordination is achieved. We turn now to a brief discussion of the dynamic nature of these games.

Dynamic Coordination

In the previous section, we outlined a one-shot version of coordination games, but the actual game and the one we test experimentally is a highly dynamic game. In the dynamic game, participants can change their chosen color repeatedly until the time limit is reached or coordination is achieved. The one-shot models in Figures 1 and 2 display the payoffs that participants receive if coordination is achieved before the time limit is reached. In the experiment, actors can move asynchronously, and they learn about the choices of the nodes to which they are connected instantly. This turns the

Table 1
Average Degree for Each Network

Network	0-Chord Cycle	Barbell	6-Chord Cycle	Cylinder	Leader
Average nodal degree	2	2.125	2.75	3	3.625

one-shot game into a dynamic game with communication. Myerson (1991) demonstrates that in a coordination game with information (an analogous setting to the one we model here) there are an infinite number of equilibria. One implication of this is that we do not analyze whether or not participants pursue equilibrium strategies because there are no bounds on what constitutes an equilibrium strategy.^{6,7} Instead, our predictions and analysis are about a group's ability to solve the coordination problem, but not about individual strategies.

Combining Coordination With Network Structure

The key aspect of our experimental design is the ability to test how different network structures affect coordination. In particular, we want to explore the relationship between the number of connections in a network and how long it takes for participants to complete the coordination game under symmetric and asymmetric incentives. The core assumption in the following predictions is that networks facilitate information flow between actors, and greater information flow (via network connections) will help to solve the coordination problem. To order the networks based on their connections, we use the average nodal degree of a network, which is defined as the sum of each node's degree divided by the total number of nodes (Knoke & Yang, 2008). The average nodal degree of each network is presented in Table 1. Our predictions are related to the interaction between network structure and incentive structure.

Prediction 1: In the symmetric coordination games, participants will be able to solve all of the games, regardless of network structure.

Prediction 2: In symmetric coordination games, more connections will lead to faster times for the participants to achieve coordination.

Prediction 3: Asymmetric coordination games will reduce the probability of a network being solved and increase the time for a solution compared with symmetric coordination games, holding the network constant.

Prediction 4: In asymmetric coordination games, a greater number of connections will increase the probability that a network is solved and decrease the time it takes to coordinate.

What Networks Do We Study?

The goal of our experiment is to understand how network structure affects group coordination, and therefore we had to determine the networks to study. We report the results of our research on five different network structures. For the sake of understanding, we called the networks 0-chord cycle, 6-chord cycle, barbell, cylinder, and leader. In Figure 3, we present a visual representation of each of the different networks.

We chose these networks because each of them is a representation of some real-world type of network that we want to study. For instance, the 0-chord cycle network is analogous to a situation in which connections are purely geographic and people do not interact with anyone other than their local neighbors. The 6-chord cycle adds a few connections across the cycle, but retains the basic cycle structure. The leader network is built from the simple cycle, but includes two nodes that are highly connected to other members of the network. To retain two colorability, one leader is connected to each odd member and the other leader to each even member. The barbell network consists of two simple cycles with eight nodes joined by a single link between the cycles. This might be similar to networks with only a few ties between groups such as political parties or racial groups. The cylinder network is similar to the barbell in that there are two cycles, but in the cylinder, every person in each of the two cycles is connected to a member of the other eight-person cycle.

Experimental Design

In all the experiments reported in this article, we used the following experimental design. The networks consisted of 16 nodes (one per participant) and were able to be successfully colored using two colors. After participants reported to the experiment, they were placed at a computer behind partitions so that they could not see the other participants. Before the experiment began, we read aloud the directions to all the participants in the room to ensure that the procedures, rules, and incentives were common knowledge. In addition, all participants took a short quiz (with payment for correct answers) to make sure they understand the experiment.⁸

given 2 of the 10 possible colors. In addition, participants in a given game chose from different colors to ensure that if they were able to see another's monitor, the participant could not learn anything about that participant's decisions. The information displayed on each computer was controlled by our central server that used a software program developed and shared by Michael Kearns and Stephen Judd and the University of Pennsylvania.

Each experimental group took part in approximately 30 attempts to solve various coordination games. The baseline payment for coordination was \$1 per participant and groups had 3 minutes to achieve coordination. Each experimental trial ends either when the time limit is reached or the group achieves coordination successfully, and this is known to all participants in the experiment. In the experiment, each participant controls the color of one node in the network so coordination is the result of distributed actions. However, participants do have more information than just the color of their own node. The screen that participants saw during the experiment contained the following information.

Local view: Participants are able to see their node and the neighboring nodes to which they are connected. Each node in their local neighborhood contains a number in its center that tells the participant how many total edges a neighboring node has. This allows them to see the color they have chosen for their node as well as the colors chosen by their neighbors.

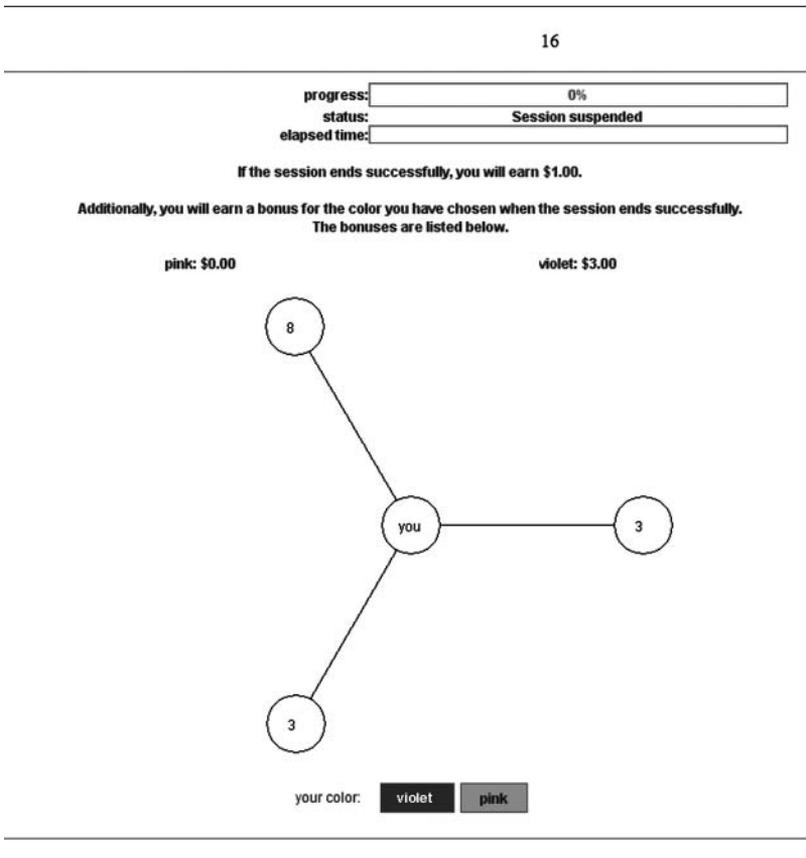
Color choices: Participants can see the two colors from which they can choose.

Elapsed time bar: This bar kept track of the amount of time since the session began and allows participants to determine how much time is remaining before the time limit.

Completion percentage bar: This bar provides information about how close the entire network is to completion. The percentage completed represents the number of edges without a coloring conflict divided by the total number of edges in the graph.

Figure 4 displays a typical screenshot that a participant sees before the experiment begins. By looking at the screen, a participant with this picture can determine that he or she is connected to three nodes and that one of those nodes has eight total connections (and the other two nodes each have three total connections). The participant can also see that he or she can choose between pink and violet during this session and will receive a normal payoff of \$1 if the network is colored successfully and he or she ends up as pink, and will receive \$4 if the network is colored successfully and he or she ends up as violet when the session ends. During the experiment, participants continue to see this screenshot, but the progress bar and elapsed time bars change to reflect the global condition of the network.

Figure 4
A Participant's Screen Shot Before the Experiment Begins



The screenshot shows that although participants have a tremendous amount of information available to them during the experiment, they do not know the structure of the entire network, nor do they know who their geographic neighbors are in the experiment. In addition, participants are assigned to their node randomly at the beginning of each session within a given experiment. This procedure ensures that participants do not always occupy the same position in a network when we repeat network structures with different bonus parameters. Because participants do not know the entire structure of the network, they are not able to learn anything about how their choices relate to the group's success or failure for a given network type.

Incentive Structures Used During Experiment

We used the two general (symmetric and asymmetric) payoff structures as described in Figures 1 and 2. In both types of payoff structure, participants were only paid if global coordination was achieved. The baseline payment was \$1 for successful coordination, which we augment with bonus amounts of \$1, \$2, \$3, and \$4 to create asymmetric incentives. Before each time that we changed the bonus amount, we read participants a brief description of the new bonus amount and how it would be implemented. Additionally, the first time the participants were exposed to the bonus rounds, they took a quiz to ensure they understood how bonuses operated.

Data Analysis and Results

Our experiment employs both within- and between-subject designs. In all our experiments, participants take part in trials that involve symmetric and asymmetric games and that involve multiple network structures. However, we cannot rely solely on within-group analysis because we cannot conduct enough trials with one group of participants to explore all the relevant combinations of networks and levels of asymmetry. Furthermore, we want different groups to attempt the same networks and bonus structures so that we can ensure that our results are not due to one group of idiosyncratic participants.

A first cut at the data is shown in Table 2, where we present the relationship between bonus ratio and successful network coordination across all the network structures that we use. These results strongly support Prediction 1 that under symmetric incentives (asymmetry level equals 0), participants will be able to solve the networks. There is only one instance out of 19 trials with symmetric incentives where participants fail to complete successfully the coordination problem. We also include in this table the average time spent on all the networks across the five different levels of asymmetry. These averages include instances in which the network is not solved, which are counted as lasting for 180 seconds, which clearly biases the average time downward for networks in which many of the graphs are not solved. Increases in the bonus ratio are associated with less coordination and longer times for successful coordination.

We combine connectivity, bonus structure, and time spent solving a network in Figure 5 that presents the average amount of time to solve a given combination of network and bonus amount.⁹ The figure allows us to explore Predictions 2, 3, and 4 by examining comparisons along the x -, y -, and z -axes in the figure. We start by focusing on the observations where the

Table 2
Overall Completion and Time Spent on Each
Graph Coloring Problem

Bonus Ratio	0	1	2	3	4
Proportion of networks solved	0.95 (18/19)	0.50 (3/6)	0.56 (14/25)	0.43 (13/30)	0.25 (6/24)
Average time spent on a trial	31 seconds	144 seconds	128 seconds	149 seconds	153 seconds

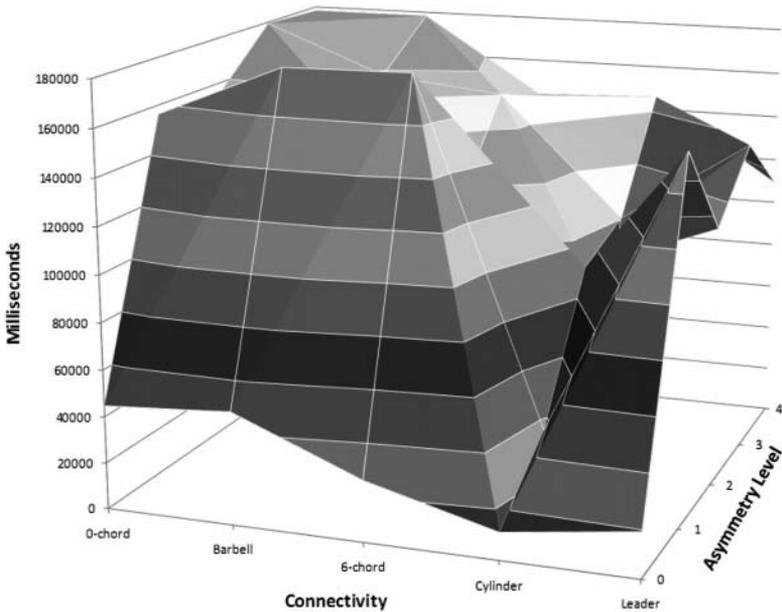
bonus ratio is zero, which allows us to examine Prediction 2. As we predicted, networks with fewer connections (on the left of the x -axis) take longer to solve than networks with more connections under the symmetric incentive condition.

To examine Prediction 3 about the effect of asymmetric coordination games on time to achieve coordination we can move along the z -axis from an asymmetry level of zero to an asymmetry level of \$4, within a given network in the figure. Doing so reveals that there is a general increase in the average time to coordinate as we move from symmetric to asymmetric games. Prediction 4 is that networks with higher connectivity will take less time than networks with lower connectivity, when compared at similar bonus structures. We can see this result by comparing the amount of time it takes for coordination within a given bonus ratio but across network structures. For example, if we focus on the networks with a bonus ratio of 4, we see that the amount of time it takes for a group to coordinate increases as we progress from the highest connected leader network to the least connected 0-chord network. The same general pattern is true across the different bonus structures.

We build on the simple descriptive results presented in the previous tables and figure by using a logit model and a Cox proportional hazard model to test the effect of the bonus and network structure on successful coordination and time until coordination.

We focus first on the logit model. To test the effect of network structure on coordination, we include a counter for the session number within each experimental group, a dummy variable for each network, a dummy variable for whether the given session was an asymmetric game, a variable for the level of asymmetry, and a variable for the interaction between the level of asymmetry and the network structure. This is analogous to a dosage-response study in which we want to understand both the effect of the treatment (asymmetry) and the dosage of the treatment (the magnitude of the asymmetry). In addition to the treatment variables, we include a fixed

Figure 5
Average Time for Coordination Based on
Asymmetry Level and Connectivity



effect for each group that participated in the experiment to account for any group-level characteristics that affect successful coordination. Our Prediction 4 is that networks with higher connectivity will be solved more often in the asymmetric condition than networks with lower connectivity. We also estimate a parameter to account for learning effects by counting the first trial in an experiment as 0 and counting upward until we reach the end of that day's trials.¹⁰

We expect to find that the interaction between bonus ratio and network structure depends on the number of connections in the network. Referring back to Table 1 where we listed the average degree of network, we would generally classify the 0-chord and barbell network as low connectivity and the other three networks as relatively high connectivity.

In Table 3, we present the results of our logit analysis. The excluded network in the analysis is the leader network, and therefore the dummy variables for each network and the interaction between the dummy variables

Table 3
Logit Analysis of Successful Coordination

	Coefficient (<i>SE</i>)
Session count	0.003 (0.08)
0-chord cycle	5.50 (3.15)*
Barbell	2.19 (1.95)
6-chord cycle	3.06 (2.17)
Cylinder	7.93 (3.66)**
Asymmetric incentives	-0.28 (0.61)
Level of asymmetry	0.38 (0.79)
Asymmetry level	
0-chord cycle	-2.51 (1.24)**
Barbell	-1.38 (0.78)*
6-chord cycle	-0.62 (0.73)
Cylinder	-2.19 (1.11)**
Total number of sessions	104
Number of groups	4

Note: Excluded category for the analysis is the leader network. Regression includes group-level fixed effects.

* $p < .10$, two-tailed. ** $p < .05$, two-tailed.

and the asymmetry level should be interpreted relative to the leader network. The level of asymmetry variable that is not interacted with a network variable is the effect of changes in asymmetry in the leader network. We turn now to the result of the analysis. There is not a main effect of asymmetry on the probability of coordination as indicated by the insignificance of the asymmetry variable. The 0-chord and barbell networks are both solved less often as asymmetry increases relative to the leader network. The 6-chord network is statistically indistinguishable from the leader network, but the cylinder network is solved successfully less often than the leader network as asymmetry increases. These results demonstrate that networks with more connections facilitate the ability of groups to solve asymmetric coordination games.

Table 4
Duration Analysis of Time Until Successful Coordination

	Hazard Ratio (z Statistic)
Session count	0.96 (0.78)
0-chord cycle	0.83 (0.46)
Barbell	0.86 (0.33)
6-chord cycle	1.15 (0.32)
Cylinder	5.01 (2.21)*
Asymmetric incentives	0.14 (3.78)**
Level of asymmetry	1.15 (0.38)
Asymmetry level	
0-chord cycle	0.60 (3.52)**
Barbell	0.58 (3.29)**
6-chord cycle	0.96 (0.27)
Cylinder	0.67 (2.18)*
Number of observations	104

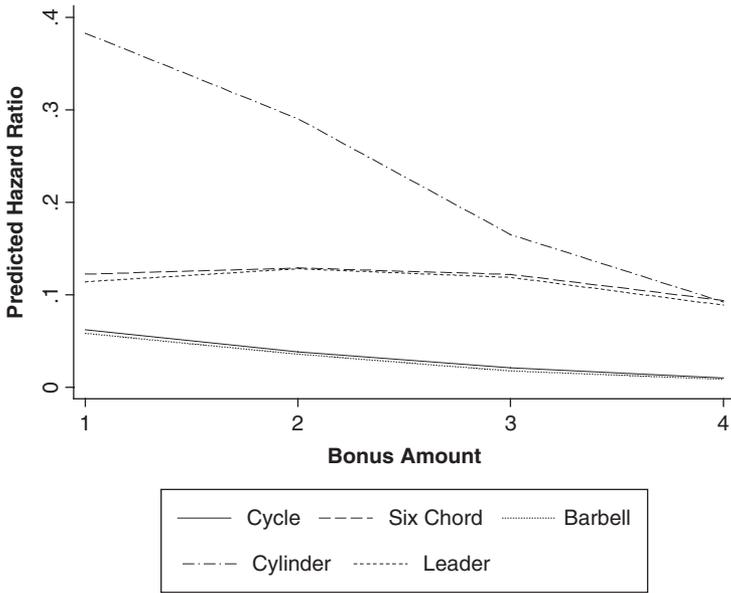
Note: Excluded category is the leader network. Analysis is stratified by day to account for any day-to-day variance in ability to solve coordination problem. Standard errors are clustered based on the network.

* $p < .05$, two-tailed. ** $p < .01$, two-tailed.

Another way to study successful network completion is to use a Cox proportional hazard model, which allows us to study the time until the network is solved. (Box-Steffensmeier & Jones, 2004). We use the same variables as in the logit analysis. We again exclude the leader network as this has the highest level of connectivity of the networks.

Table 4 presents the estimated hazard ratios from the Cox regression. A hazard ratio less than 1 implies that a given variable makes coordination less likely to happen given that it has not already occurred, whereas a hazard ratio greater than 1 means the variable makes coordination more likely to happen. We see that there is a large, significant main effect of the imposition of asymmetric coordination. Based on Predictions 3 and 4, we expect

Figure 6
Network Connections Reduce the Impact
of Asymmetric Coordination



to see that the effect of asymmetry depends on network structure. To improve interpretation, we generate predicted hazard ratios for each combination of network and asymmetry.

In Figure 6, we present each network's predicted hazard ratio along the y -axis and the level of asymmetry on the x -axis. We do not present the hazard ratio for the symmetric coordination games because there is such a significant difference between the hazard ratios for symmetric and asymmetric games that they do not make sense to place on the same figure. This means that there is a main effect of asymmetry on the time to solve the coordination game. Under asymmetric incentives, the two networks with the lowest nodal degree (0-chord cycle and barbell) have a much lower hazard ratio, indicating longer times to achieve coordination, than networks with more connections. Among the other three networks (6-chord cycle, cylinder, and leader), increases in asymmetry do cause a decline in the hazard ratio; however, the hazard ratio remains higher than it is among

the 0-chord cycle and barbell networks. The cylinder network maintains a much higher hazard ratio (more likely coordination) until the bonus reaches \$4. These results are consistent with our predictions that links between nodes can attenuate the effect of asymmetric coordination.

Discussion and Conclusion

In this article, we present experimental results from embedding standard game theoretic models of coordination into a network environment. Our results in this study shed light on the conditions under which network structure affects coordination. Prior empirical suggests that there will be a connection between network structure and coordination, but the empirical literature cannot determine the causal effect of network structure on coordination. In this study, we take the first steps toward understanding how networks affect coordination.

Our results demonstrate that with symmetric incentives, many different types of networks are quickly and easily solved by participants. These results mirror those of Kearns et al. (2006), despite the fact that we used even shorter amounts of time and different networks. In particular, our results under the symmetric incentive condition suggest that an increase in the connectivity of the network leads to faster solutions. One possible way to extend these results is to study how human participants can solve coordination problems when the task becomes more complex. Second, our results demonstrate that when we move to asymmetric coordination games that better mirror many real-world situations, there is a considerable difference between network structure and the ability of groups to solve coordination problems. Our experiments reveal that connections in a network help overcome asymmetry in a coordination game. This is an important result because many real-world coordination situations involve asymmetric payoffs, and these results may help us better design networks that can lead to successful coordination.

Returning to the examples of coordination discussed earlier—electoral politics and policy implementation—our results suggest that increasing the density of the network, *ceteris paribus*, can improve coordination. In particular, when coordination is difficult because of asymmetric incentives, these results suggest that building connections between actors can facilitate coordination. For instance, if settings where policy coordination is desirable, the results indicate that it may be useful to develop institutions that create more connections between various actors. As long as these connections do not

cause other changes, they may improve the possibility of successful coordination. In addition, our results provide a true causal test of many of the claims in the empirical literature about the effect of network connections.

These results can help us build better theory about the effect of networks on a wide variety of tasks. For example, our results show that the number of connections matter for coordination, but there is also some evidence that the pattern of connections might matter. The cylinder network has slightly fewer connections than the leader network, but in the cylinder network each node has the exact number of connections. Therefore, coordination may depend not just on the number but the distribution of connections. These experiments do not provide a full test of this possibility, but the results are interesting and suggestive. We will pursue this topic in future experiments.

The results in this article provide support for the empirical claims that network structure affects group coordination. We have only started to understand the conditions when, how, and why network structure influences group and individual actions. Ultimately, we must improve our understanding of dynamic games and networks to help us understand the complex interaction between information, networks, and individuals' decisions in experimental and empirical settings.

Notes

1. This is clearly a simplified example that includes a great many assumptions about the effectiveness of campaign activities, the behavior of activists and the absence of a central planning agent who can successfully solve the problem. Regardless, the example demonstrates a common form of coordination involving time constraints.

2. Coordination problems occur across a broad range of social phenomena ranging from solving common pool resource problem (Ahn, Ostrom, & Walker, 2003; Keohane & Ostrom, 1994; Ostrom, 1990) to electoral coordination (Cox, 1997), to evolution of behavioral strategies (Axelrod, 1984, 1997), to economic development and rule of law (Greif, Milgrom, & Weingast, 1994), to the development of social leadership (Calvert, 1992), to political participation (McClurg, 2003), to which side of the road we should drive on (Lewis, 1969), to ending foot binding (Mackie, 1996). At least as common as coordination problems in social settings are the presence of network effects in which the decisions of one actor affect the behavior or environment of other actors (Christakis & Fowler, 2008; Coleman, 1988; Fowler, 2006; Grannovetter, 1973, 1974; Hecllo, 1978; Huckfeldt & Sprague, 1987; Ostrom, 1990; Putnam, 2000; Scholz, Berardo, & Kile, 2008; Wasserman & Faust, 1994; Watts, 2003; see the various chapters in Kahler, 2009). Again, we simply provide a snippet of the literature that uses networks to understand behavior across a wide range of topics.

3. The general problem they are studying is the graph coloring problem, which is a form of coordination problem. In this problem, there is a minimum number of colors needed to color successfully any given network referred to as that graph's chromatic number. For instance, some graphs can be colored successfully with two colors, others with three colors, and so on. The reported experiments used the minimum chromatic color for a given graph.

4. A good theoretical discussion about networks and game theory appears in Jackson (in press). For recent papers that study experimentally game theory and networks, see Charness and Jackson (2007) and Callander and Plott (2005). Most of these studies involve only a few number of actors (fewer than 6) and still involve one-shot decision making rather than the dynamic games we study in this experiment. In addition, much of the research in experimental economics has focused on network formation rather than on the effect of different network structures, which is our focus.

5. The simplicity of the problem makes it ideal for human participant experiments because we can be confident that the participants actually understand the task facing them during the experiment.

6. We do not discuss the equilibrium properties of the dynamic game, because as Callander and Plott (2005) note, "Strategic incentives within dynamic networks are little understood and a characterization of equilibrium is not available" (p. 1474).

7. Jackson and Watts (2008) demonstrate that here are equilibrium strategies in bipartite games where participants both pick a partner and one action. However, our set up is fundamentally different because (a) participants do not pick their partners and (b) participants can change their actions after the experiment begins.

8. We use common instructions and quizzes in our experiment to ensure adherence or compliance with the protocol. This allows us to be confident that changes in our treatment (network structure and/or bonus amount) are understood by the participants who receive the treatment.

9. We include networks that were not successfully solved, which receive a value of 180,000 milliseconds although in fact it would have taken longer than 180,000 milliseconds for these networks to be solved. Therefore, some combinations of networks and bonus structures that were often unsolved will have artificially low average solution times.

10. We typically ran about 30 sessions with a given group of participants. This is an admittedly crude way to account for learning within the experiment, but it will account for general learning. To further test for learning, we looked for serial correlation within each experimental group by regressing the time it took for each session against a counter variable for the session, and then tested for first-, second-, and third-order serial correlation using Durbin-Watson's alternative test. We could never reject the null hypothesis of no serial correlation.

References

- Ahn, T. K., Ostrom, E., & Walker, J. (2003). Heterogeneous preferences and collective action. *Public Choice*, 117, 295-314.
- Axelrod, Robert. (1984). *The evolution of cooperation*. New York: Basic Books.
- Axelrod, Robert. (1997). "The dissemination of culture: A model with local convergence and global polarization." *The Journal of Conflict Resolution*, 41(2), 203-226.
- Blume, A., & Ortmann, A. (2007). The effects of costless pre-play communication: Experimental evidence from games with Pareto-ranked equilibria. *Journal of Economic Theory*, 127, 274-290.
- Box-Steffensmeier, J. M., & Jones, B. S. (2004). *Event history modeling: A guide for social scientists*. Analytical Methods for Social Research Series. Cambridge, UK: Cambridge University Press.
- Callander, S., & Plott, C. R. (2005). Principles of network development and evolution: An experimental study. *Journal of Public Economics*, 89(8), 1469-1495.

- Calvert, R. (1992). Leadership and its basis in problems of social coordination. *International Political Science Review*, 13, 7-24.
- Carpenter, D., Esterling, K., & Lazer, D. (2004). The strength of strong ties: A model of contact making in policy networks with evidence from U.S. health politics. *Rationality and Society*, 15, 411-440.
- Charness, G., & Jackson, M. O. (2007). Group play in games and the role of consent in network formation. *Journal of Economic Theory*, 136, 417-445.
- Christakis, N. A., & Fowler, J. H. (2008). The collective dynamics of smoking in a large social network. *New England Journal of Medicine*, 358, 2249-2258.
- Coleman, J. S. (1988). Social capital in the creation of human capital. *American Journal of Sociology*, 94, S95-S120.
- Cox, G. W. (1997). *Making votes count*. Cambridge, UK: Cambridge University Press.
- Fowler, J. H. (2006). Connecting the Congress: A study of cosponsorship networks. *Political Analysis*, 14, 456-487.
- Grannovetter, M. (1973). The strength of weak ties. *American Journal of Sociology*, 78, 1360-1380.
- Grannovetter, M. (1974). *Getting a job: A study of contacts and careers*. Cambridge, MA: Harvard University Press.
- Greif, A., Milgrom, P., & Weingast, R. (1994). Coordination, commitment and enforcement: The case of the Merchant Guild. *Journal of Political Economy*, 102, 745-776.
- Heclo, H. (1978). Issue networks and the Executive Establishment. In A. King (Ed.), *The new American political system*. Washington, DC: American Enterprise Institute.
- Huckfeldt, R., & Sprague, J. (1987). Networks in context: The social flow of political information. *American Political Science Review*, 81, 1197-1216.
- Jackson, M. O. (in press). Networks and economic behavior. *Annual Review of Economics*.
- Jackson, M. O., & Watts, A. (2008). Equilibrium existence in bipartite social games: A generalization of stable matchings. *Economics Bulletin*, 3(12), 1-8.
- Jensen, T. R., & Toft, B. (1994). *Graph coloring problems*. New York: Wiley-Interscience.
- Kahler, M. (Ed.). (2009). *Networked politics: Agency, power, and governance*. Ithaca, NY: Cornell University Press.
- Kearns, M., Suri, S., & Montfort, N. (2006). An experimental study of the coloring problem on human subject networks. *Science*, 313, 824-827.
- Keohane, R., & Ostrom, E. (1994). Introduction. *Journal of Theoretical Politics*, 6, 403.
- Knoke, D., & Yang, S. (2008). *Social network analysis* (2nd ed.). Thousand Oaks, CA: Sage.
- Laumann, E. O., & Knoke, D. (1987). *The organizational state: Social choice in national policy domains*. Madison: University of Wisconsin Press.
- Lewis, D. (1969). *Convention: A philosophical study*. Cambridge, MA: Harvard University Press.
- Mackie, G. (1996). Ending footbinding and infibulation: A convention account. *American Sociological Review*, 61, 999-1017.
- McClurg, S. D. (2003). Social networks and political participation: The role of social interaction in explaining political participation. *Political Research Quarterly*, 56, 448-464.
- Mintrom, M., & Vergari, S. (1998). Policy networks and innovation diffusion: The case of education reform. *Journal of Politics*, 60, 126-148.
- Myerson, R. (1991). *Game theory: Analysis of conflict*. Cambridge, MA: Harvard University Press.
- Ostrom, E. (1990). *Governing the commons: The evolution of Institutions for Collective Action*. New York: Cambridge University Press.

- Putnam, R. (2000). *Bowling alone*. New York: Simon & Schuster.
- Scholz, J., Berardo, R., & Kile, B. (2008). Do networks enhance cooperation? Credibility, search, and collaboration in joint environmental projects. *Journal of Politics, 70*, 393-406.
- Wasserman, S., & Faust, F. (1994). *Social network analysis: Methods and applications*. Cambridge, UK: Cambridge University Press.
- Watts, D. J. (2003). *Six degrees: The science of a connected age*. New York: W. W. Norton.

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