Network Architecture, Salience and Coordination*

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Abstract

This paper reports the results of an experimental investigation of dynamic games in networks. In each period, the subjects simultaneously choose whether or not to make an irreversible contribution to the provision of an indivisible public good. Subjects observe the past actions of other subjects if and only if they are connected by the network. Networks may be incomplete so subjects are asymmetrically informed about the actions of other subjects in the same network, which is typically an obstacle to the attainment of an efficient outcome. For all networks, the game has a large set of (possibly inefficient) equilibrium outcomes. Nonetheless, the network architecture makes certain strategies *salient* and this in turn facilitates coordination on efficient outcomes. In particular, asymmetries in the network architecture encourage two salient behaviors, strategic delay and strategic commitment. By contrast, we find that symmetries in the network architecture can lead to mis-coordination and inefficient outcomes.

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1 Introduction

A perennial question in economics concerns the conditions under which individuals coordinate to achieve an efficient outcome. One of the obstacles to efficiency is the presence of asymmetric information, which typically prevents the attainment of the first best. In this paper, by contrast, we find that a particular type of asymmetric information can improve efficiency by allowing subjects in an experimental setting to coordinate on a salient outcome. In the experimental design, subjects are part of a *network* and can only observe the actions of subjects to whom they are connected through the network. Our goal is to identify the impact of network architecture on the efficiency and dynamics of behavior.

We study a simple *monotone game* that is naturally interpreted as a step-level, or threshold, public good game. Players make voluntary contributions to the provision of an indivisible public good, which is provided if and only if the contributions equal or exceed the cost. The players' contributions are irreversible and, in particular, are not returned to the players even if the public good is not provided. A player's payoff equals the sum of his consumption of the public good and his consumption of the private good.[1]

More specifically, in the game we study there are three players. Each player is endowed with a single indivisible token. The game is divided into three periods. In each period, the uncommitted players simultaneously choose whether or not to contribute to the provision of the public good. The cost of the public good is assumed to be two tokens. If the public good is provided, each player receives two tokens in addition to the number of tokens retained from his endowment. Since the value of the public good is two tokens, it is always efficient for the good to be provided but each player has an incentive to be a free rider.

To complete the description of the game, we need to specify the information structure, which is represented by a network or *directed graph*. Each player is located at a node of the graph and player i can observe player j's past actions if there is an edge leading from node i to node j. The games that make up the various treatments in our experiments differ only with respect to their network architecture. The experiments reported here involve the benchmark three-person *empty* and *complete* networks, and all

[1] A monotone game is like a repeated game except that actions are irreversible: players are constrained to choose stage-game strategies that are non-decreasing over time. Gale (1995, 2001) demonstrated that this irreversibility structure allows players to make commitments. Every time a player makes a commitment, it changes the structure of the game and the incentives for other players to cooperate.

three-person networks with one or two edges.

We call the unique 1-edge network the *one-link* network. There are four 2-edge networks, called the *line*, the *star-in*, the *star-out*, and the *pair* network. The set of networks we consider is illustrated in Figure 1, where an arrow pointing from player i to player j indicates that player i can observe player j.[2]

[Figure 1 here]

The game defined by each of the networks we study has a large number of equilibria and the equilibrium outcomes associated with the one- and two-link networks as well as the complete network are virtually identical. Thus, theory does not provide us with strong predictions about how the various networks will influence the play of the games. Nonetheless, as Figure 2 illustrates, the degree to which subjects coordinate on efficient outcomes (total contribution equals the cost of the good) appear to vary across the different networks.

[Figure 2 here]

How are we to understand the impact of the network architecture on subjects' behavior and the efficiency of the outcomes? In this paper, we argue that asymmetries in the network architecture makes certain strategies *salient*. We identify two main ways in which this network architecture gives rise to salient strategies. We call these behaviors *strategic commitment* and *strategic delay*:

- **Strategic commitment:** There is a tendency for subjects in certain network positions to make contributions early in the game in order to encourage others to contribute. Clearly, commitment is of strategic value only if it is observed by others. Strategic commitment tends to be observed among *uninformed-and-observed* subjects – subjects in positions where (i) they cannot observe other positions and (ii) they are observed by another position.

[2]This set of networks has several non-trivial architectures, each of which gives rise to its own distinctive information flows. To keep the scope of our study within reasonable bounds, we exclude the large set of networks with three, four and five edges. For practical purposes, the networks with zero, one or two edges provide a sufficiently rich set of networks, reveal important features of the game, and illustrate the main features of the complete set of networks.

- **Strategic delay:** There is a tendency for subjects in certain network positions to delay their decisions until they have observed a contribution by a subject in another position. Obviously, there is an option value of delay only if the decision depends on the information. Strategic delay tends to be observed among *informed-and-unobserved* subjects – subjects in positions where (i) they can observe other positions and (ii) they are not observed by another position.

The bottom line is that, in some networks where the degree of coordination is high, the structure of observability make certain behaviors – and possibly certain equilibria – salient.[3] Conversely, some network architectures have the opposite effect, that is, the structure of observability causes problems coordinating on an efficient outcome. Mis-coordination tends to arise in networks where two players are *symmetrically* situated. In symmetric situations, it becomes problematic for two players to know who should go first or, if only one is to contribute, which of two should contribute.

The rest of the paper is organized as follows. The next section describes the properties of the set of sequential equilibria corresponding to each network treatment. Section 3 describes the experimental design and procedures. The results are gathered in Sections 4. Section 5 concludes by discussing the results and relating them to the literature. The paper also includes three data and technical online appendices for the interested reader. Sample experimental instructions are attached in Online Appendix I. Online Appendix II provides a more refined analysis and discussion of the implications of the data for equilibrium behavior. In reporting our results, we pool the data from all experimental sessions and rounds for each network. We provide a detailed discussion of the robustness of the results to subject pools and learning effects in Online Appendix III.

2 Properties of equilibrium

The monotone game we study can be interpreted as follows. There are three players indexed by $i = A, B, C$, and three periods indexed by $t = 1, 2, 3$. Each player has an endowment of one indivisible token that he can contribute to the production of a public good. The contribution can be made in any of the three periods, but the decision is irreversible: once a player

[3] Our concept of salience, based on structural properties of the game, is quite different from the concept of "psychological" salience introduced by Schelling (1960) as part of his theory of focal equilibria.

has committed his token, he cannot take it back. We assume that the public good is indivisible and costs two tokens to produce. The good is provided if and only if the total contribution is at least two tokens. If the public good is provided, each player receives a payoff equal to two tokens *plus* his initial endowment of one token *minus* his contribution. If the public good is not provided, each player receives a payoff equal to his initial endowment *minus* his contribution. Note that the aggregate endowment and the aggregate value of the public good are greater than its cost, so that provision of the good is always feasible and efficient.

The information available to each player is defined by a directed graph or network. The network architecture is common knowledge. A player i can observe the past actions of another player j, if and only if there is a directed edge leading from player i to player j. Note that the edges need not be symmetric: the fact that i can observe j does not necessarily imply that j can observe i. The seven networks we study are illustrated in Figure 1 above and are used as treatments in the experimental design.

In the remainder of this section, we summarize the properties of equilibrium in these games. Unfortunately, the game associated with each network has a large number of sequential equilibria and the equilibrium outcomes in the games defined by the one-and two-link networks (as well as in the game defined by the complete network) are virtually identical. In other words, theory has little to tell us about how the game will be played in practice.

2.1 Pure-strategy sequential equilibria

The sharpest result applies to the case of pure-strategy sequential equilibria. We begin with the empty network, which serves mainly as a benchmark to which the other networks can be compared. In the empty network, no player can observe any other player. Although a player can make his contribution in any of the three periods, the fact that no one receives any information in any period makes the timing of the decision irrelevant. This game is essentially the same as the one-shot game in which all players make simultaneous, binding decisions. More precisely, for each equilibrium of the one-shot game, there is a set of equilibria of the dynamic game that have the same outcome.

The one-shot game has multiple pure-strategy equilibria: There are three equilibria in which two players contribute and one does not and the good is provided with probability one. Conversely, there exists a pure-strategy equilibrium in which no player contributes and the good is not provided. Obviously, if a player thinks that no one else will contribute, it is not optimal for him to contribute.[4] Each of the pure-strategy equilibria of the one-shot game has its counterpart in the dynamic game defined by the empty network.[5]

In the empty network all players are symmetrically situated. Adding one link to the empty network creates a simple asymmetry among the three players. Now A can observe B's past contributions and condition his own decision on what B does, while B and C observe nothing. The addition of a single link eliminates one of the equilibrium outcomes present in the empty network. The pure-strategy sequential equilibrium with zero provision is not an equilibrium in the one-link network.[6]

The remaining pure-strategy equilibria of the one-shot game have their counterparts in the dynamic game defined by the one-link network. These equilibria can be implemented if players simply wait until the final period and then use the strategies from the one-shot game. In addition to these simple replications of the one-shot equilibria, there are variations in which the players choose to contribute in different periods. Similar arguments apply to any of the two-link networks.

We summarize the preceding discussion in the following simple proposition.

Proposition 1 (pure-strategy sequential equilibria) *In the game defined by each of the networks, any history of actions consisting of exactly two players contributing is consistent with a pure-strategy sequential equilibrium. In the game defined by the empty network, no player contributing is also consistent with a pure-strategy sequential equilibrium.*

[4] Provision of the good in equilibrium depends crucially on the fact that each contributing player is *pivotal* in the sense that, *at the margin*, his contribution is necessary and sufficient for provision (see, Bagnoli and Lipman, 1992 and Andreoni, 1998).

[5] For example, consider the equilibrium in which A and B contribute and C does not. In the dynamic game A and B can choose different periods in which to contribute but as long as they contribute with probability one before the end the game, their strategies constitute a sequential equilibrium of the dynamic game.

[6] To see this, suppose to the contrary that there exists an equilibrium in which no one contributes and consider what happens if B deviates from this equilibrium strategy and contributes in period 1. At the beginning of period 2, A knows that B has contributed and he knows that C does not know this. Then A knows that C will not contribute (C believes he is in the original equilibrium) and it is a dominant strategy for A to contribute. Anticipating this response, B will contribute before the final period of the game, thus upsetting the equilibrium.

2.2 Mixed-strategy sequential equilibria

To get a more robust result, we should take account of pure and mixed strategies. Mixed strategies are relevant because they expand the set of equilibrium outcomes, even if mixed strategies are only used off the equilibrium path. The experimental data will show that they are also empirically relevant. Except for the game defined by the empty network, all outcomes consistent with a pure-strategy equilibrium are efficient (the total contribution is two tokens). The use of mixed strategies can change this result.

Notice that the one-shot game possesses a symmetric mixed-strategy equilibrium where each player contributes with probability 1/2 because each player is indifferent between contributing and not contributing. Thus, the game defined by each network possesses a symmetric mixed-strategy equilibrium where all players simply wait until the third period and each player contributes with probability 1/2. Thus, the total number of contributions at the end of the game can be strictly greater or less than the cost of the public good.

Additionally, in the games defined by each of the networks, if one player contributes his token in the first or second period (using a pure strategy), the continuation game consists of two active players only one of whom needs to contribute a token in order to provide the good. This continuation game possesses a symmetric mixed-strategy equilibrium where each of the two players contributes with positive probability.[7] The use of mixed strategies can therefore support outcomes with more or less than two contributions on the equilibrium path.

Hence, whereas all pure-strategy sequential equilibria prescribe efficient provision of the public good (except in the case of the game defined by the empty network), mixed-strategy equilibria allow under-provision and over-provision. Nevertheless, even in the case where the outcome is efficient, one cannot conclude that players are necessarily using a pure strategy. There exist mixed-strategy equilibria which are efficient, including some in which mixing occurs on the equilibrium path.

Our next proposition summarizes the preceding argument and generalizes the case of pure-strategy equilibria.[8]

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[7] A necessary and sufficient condition for a symmetric mixed strategy $0 < \alpha < 1$ to be an equilibrium strategy is that each player be indifferent between contributing and not contributing. If a player contributes, the good is provided for sure and the player receives two tokens. If he does not contribute and the other player contributes, then the good is provided with probability α so his payoff is $2\alpha + 1$. Indifference requires that $2 = 2\alpha + 1$ or $\alpha = 1/2$.

[8] The result applies to a single play of the game. The hypothesis that a single mixed-

Proposition 2 (mixed-strategy sequential equilibria) *In the games defined by each of the networks, any history of actions consisting of no player, one player, or two players contributing is consistent with mixed-strategy equilibria. Additionally, a variety of histories consisting of all players contributing are also consistent with mixed-strategy equilibrium.*

2.3 Equilibrium refinements

Since there are many sequential equilibria of the game, it is natural to look for refinements that may limit the set of equilibrium behaviors and provide stronger predictions of the theory. We have investigated several different refinement approaches, including trembling-hand perfection and forward induction, and found them either unproductive or intractable. To illustrate the reasons why the usual refinements do not produce the desired results (strategic delay and strategic commitment) we consider equilibria in the one-link network. The one-link network is a natural case to look at because of the asymmetries among the three players. The salient feature of the one-link network is the fact that A observes B, while B and C observe nothing. This suggests that, although there are many sequential equilibria, some refinements might eliminate equilibria in which A does not exhibit strategic delay and/or B does not exhibit strategic commitment. We provide a couple of counter-examples to show that this hope is not well founded.

We first show that there is an equilibrium which A and C contribute in the last period and B never contributes. Obviously, this equilibrium does not involve strategic commitment by the observed and uninformed player, B. The strategies are defined as follows:

Example 1 At any information set prior to the last period, A does not contribute. In the last period, A contributes if neither A nor B has yet contributed; A does not contribute if B has contributed. B does not contribute at any information set. At any information set prior to the last period, C does not contribute. In the last period, C contributes if he has not already done so.

Beginning with Selten's (1975) introduction of the trembling hand perfect equilibrium, game theorists have tested the reasonableness of Nash equilibria by introducing small trembles or perturbations of the strategies to see whether the equilibria respond continuously to the trembles. This equilibrium survives such tests in the sense that, whatever small trembles we

strategy equilibrium is played in each repetition of a game might be falsified statistically given sufficient data.

introduce, the player's strategies remain best responses. Given that B is not expected to contribute, it is strictly optimal for A to contribute as long as B has not done so and it is strictly optimal for C to contribute. Thus, these strategies remain optimal if B contributes with a sufficiently small probability, so the strategies of A and B respond continuously to any sufficiently small trembles.

Note that in the one-link network, it is always weakly dominant for A to delay and, if there is a small chance that B will contribute, then it is strictly optimal for A to delay. This is a general property of various games we study: delay is a weakly dominant strategy for any player who is informed but not observed. There is, however, a *strict* Nash equilibrium of the one-shot game in which player A does not contribute. The strategies of a corresponding equilibrium in the extensive-form game are defined as follows:

Example 2 A never contributes. At any information set, B and C contribute immediately if they have not already done so; otherwise, they do not contribute.

If we define strategic delay as "a decision by A to delay until B contributes and then contribute," then this provides a simple example of a equilibrium with no strategic delay. Again, the strategies remain best responses in spite of the introduction of any sufficiently small tremble.

Similar arguments apply to the other networks. In summary, standard refinement theory provides little guidance in narrowing down behavior in these games so theoretical analysis alone does not tell us which outcomes are likely to be observed; for that we need experimental data.[9,10]

3 Design and procedures

The experiment was run at the Princeton Laboratory for Experimental Social Science (PLESS) and at the UC Berkeley Experimental Social Science

[9] Iterated weak dominance (Van Damme, 1989, and Ben-Porath and Dekel, 1992) is only partially successful in restricting the set of sequential equilibria in dynamic games with simultaneous moves and *perfect* information. In the game defined by each of the networks, except for the complete network, some players have only partial information about the actions taken previously.

[10] Choi et al. (2008) conduct a comprehensive theoretical and experimental study of the complete network using a number of examples that "span" the set of parameters that define the game. Choi et al. (2008) show that when all players are symmetrically situated, the set of *symmetric* Markov-perfect equilibria yields much stronger predictions than could be derived from the set of all sequential equilibria. However, the restriction imposed by symmetry (identical decision rules) has no bite in asymmetric networks.

Laboratory (Xlab). The subjects in this experiment were Princeton University and UC Berkeley students. After subjects read the instructions, the instructions were read aloud by an experimental administrator. Each experimental session lasted about one and a half hours. Payoffs were calculated in terms of tokens and then converted into dollars, where each token was worth \$0.50. A \$10 participation fee and subsequent earnings, which averaged about \$22, were paid in private at the end of the session.[11] Sample experimental instructions, including the computer program dialog windows, are available at Online Appendix I.[12]

Aside from the network structure, the experimental design and procedures described below are identical to those used by Choi et al. (2008). We studied the seven network architectures depicted in Figure 1 above. The network architecture was held constant throughout a given experimental session. In each session, the network positions were labeled A, B, or C. A third of the subjects were designated type-A participants, one third type-B participants and one third type-C participants. The subject's type, A, B, or C, remained constant throughout the session.

Each session consisted of 25 independent rounds and each round consisted of three decision turns. The following process was repeated in all 25 rounds. Each round started with the computer randomly forming three-person groups by selecting one participant of type A, one of type B and one of type C. The groups formed in each round depended solely upon chance and were independent of the networks formed in any of the other rounds (a random matching protocol). Each group played a dynamic game consisting of three decision turns.

At the beginning of the game, each participant has an endowment of one token. At the first decision turn, each participant is asked to allocate his tokens to either an x-account or a y-account. Allocating the token to the y-account is irreversible. When every participant in the group has made his decision, each subject observes the choices of the subjects to whom he is connected in his network. This completes the first of three decision turns in the round.

At the second decision turn, each subject who allocated his token to the x-account is asked to allocate the token between the two accounts. At the end of this period, each subject again observes the choices of the subjects to whom he is connected in his network. This process is repeated in the third

[11] Throughout the experiment we ensured anonymity and effective isolation of subjects in order to minimize any interpersonal influences that could stimulate cooperation.

[12] Online Appendix I: http://emlab.berkeley.edu/~kariv/CGKP_I_A1.pdf.

decision turn. At each date, the information available to subjects includes the choices they observed at the previous dates.

When the first round ends, the computer informs subjects of their payoffs. The earnings in each round are determined as follows: if subjects contribute at least two tokens to their y-accounts, each subject receives two tokens plus the number of tokens remaining in his x-account. Otherwise, each subject receives the number of tokens in his x-account only. After subjects are informed of their earnings, the second round starts by having the computer randomly form new groups of participants in networks. This process is repeated until all the 25 rounds were completed.

There were three experimental sessions for each network, except for the complete network which is thoroughly studied by Choi et al. (2008). The experimental design table below summarizes the experimental design and the number of observations in each treatment (the entries have the form a / b where a is the number of subjects and b the number of observations per game). For each network treatment, two sessions (columns 1 and 2) comprising 12, 15, 18, or 21 subjects were run at Princeton; several larger sessions (column 3) comprising 27, 33, or 36 subjects were run at Berkeley. The three sessions for each treatment were identical except for the number of subjects and the *labeling* of the nodes of the graphs, which we changed in order to see whether the labels were salient (and as far as we could tell, they were not). Overall, the experiments provide us with a very rich dataset.

Network	Session 1	Session 2	Session 3	Total
Empty	12 / 100	15 / 125	33 / 275	60 / 500
One-link	15 / 125	12 / 100	27 / 225	54 / 450
Line	15 / 125	21 / 175	36 / 300	72 / 600
Star-out	18 / 150	15 / 125	36 / 300	69 / 575
Star-in	15 / 125	15 / 125	36 / 300	66 / 550
Pair	18 / 150	12 / 100	36 / 300	66 / 550
Complete	−−	−−	33 / 275	33 / 275

Remark 1 (matching protocol) Our experimental design uses the *random matching protocol*, in which subjects are randomly matched with replacement. Random matching is desirable to avoid the "repeated game" effects that arise if the same group of subjects play a game repeatedly. The advantage of using subjects repeatedly in different configurations is that it allows us to generate a large amount of data from a given number of subjects. Other protocols, such as the *perfect* *stranger protocol*, where subjects are never rematched, and the *no-contagion protocol*, where subjects are neither rematched nor matched with anyone who had been matched with their previous partners, require large subject pools or provide fewer observations. The disadvantage of random matching is that, since the same subjects participate in multiple games, the observations may not be independent. There is no general agreement in experimental economics about which design is better; each methods has its strengths and weaknesses (see, for example, the discussion in Fréchette, 2007).

Our choice was to conduct relatively large sessions, using a random matching protocol with multiple observations per subject. There were several reasons for this choice. First, the theoretical motivation for the experiment was based on the analysis of a one-shot game. By having a large number of subjects per session (as many as 36), we mitigate repeated game effects, and reduce dependencies in the data that can arise – even in the absence of strategic repeated game effects – from the interaction of learning and shared histories.[13] Second, running more sessions using a perfect stranger protocol with few subjects per session would allow subjects to repeat the task only a small number of times, which creates problems in controlling for heterogeneity and also eliminates the possibility of learning over time. Because of concerns about heterogeneity and learning, it was necessary for subjects to repeat the task a large number of times. This is especially important in complicated, multi-stage games of coordination, most of which are asymmetric.

4 Results

In this section, we present the experimental results. One of the main interests of our research is to see which network architecture can support high levels of cooperation. We therefore begin our analysis with a descriptive overview of some important features of the aggregate data, concerning the provision of the public good and the efficiency of the contribution level. We use the contribution rates to assess the level of cooperation within each net-

[13] The importance of designing away from repeated game effects when studying theoretical predictions about one-shot games has been widely discussed in the experimental literature. There is considerable evidence supporting the notion that random matching protocols with a sufficiently large number of subjects is an effective way to minimize repeated game effects. For a recent example, see Duffy and Ochs (2009).

work treatment (Section 4.1). We then move to a non-parametric analysis of the relationship between the strategic behavior in the form of strategic commitment and strategic delay and the data. In this section we look at the evolution of contributions over time in the different networks. The analysis is mainly focused on qualitative shifts in subjects' behavior resulting from changes in the network architecture (Section 4.2).

We also explore relationship between equilibrium and empirical behavior. It is very difficult to establish that subjects are behaving consistently with equilibrium, partly because there are so many equilibria and partly because individual behavior is heterogeneous. However, we want to see whether some outcomes might "stand out" or "suggest themselves" to human subjects and to uncover discrepancies between the modal behavior in each network and the predictions of any sequential equilibrium. To economize on space, we provide the analysis in Online Appendix II.[14]

Our analysis pools the data from all rounds of all sessions for a given treatment. We have conducted a parallel analysis of the data using only the last 15 rounds of each session. The findings are very similar to the 25-round pooled data set, with some small improvements in coordination rates over time. We have also investigated behavior at the level of the individual subject. Not surprisingly, there is some heterogeneity across subjects, but the choices made by most of our subjects reflect clearly classifiable strategies which are stable across decision-rounds. Furthermore, the data from the experiments at Princeton and the data from the experiments at Berkeley present a qualitatively similar picture, with only relatively small differences across subject pools in some networks. We provide a detailed discussion of the robustness of the results to subject pools and learning effects in Online Appendix III.[15] The tables and figures based on the last 15 rounds of observations and the tables and figures based on the data from each campus are also available in Online Appendix III.

4.1 Cooperation

Result 1 (cooperation) *All networks support a higher level of cooperation compared to the empty network. Conversely, the complete network does not promote the highest level of cooperation. There are also significant differences in the levels of cooperation across networks so the network architecture plays a key role in solving the coordination problem.*

[14] Online Appendix II: http://emlab.berkeley.edu/~kariv/CGKP_I_A2.pdf.

[15] Online Appendix III: http://emlab.berkeley.edu/~kariv/CGKP_I_A3.pdf.

The top panel of Table 1 reports the total contribution rates across networks. From these data we can immediately infer the provision rates and the efficiency of contributions. Efficiency depends on the total number of contributions, not just the provision rate. More precisely, inefficiency can arise from under-contribution (total contribution is less than two tokens) and from over-contribution (total contribution is more than two tokens). In order to highlight the differences in efficiency across networks, we tabulate the rates of under-contribution, efficient contribution, and over-contribution. In the bottom panel of Table 1, the average total contributions from each pair of networks are compared using the Wilcoxon (Mann-Whitney) rank-sum test. In the last column, the provision rate in each network is compared to the empty network.

[Table 1 here]

In Table 1, significant differences in subjects' behavior can be identified across the different networks. The highest provision rate (0.762) is observed in the star-out network and the smallest (0.518) is observed in the empty network. The empty network is isomorphic to the one-shot game in which players choose their strategies simultaneously. The provision rate in the symmetric, mixed-strategy equilibrium of the one-shot game is 1/2, which is similar to the empirical provision rate in the empty network.

There are also considerable variations in efficiency across networks (provision is efficient total contribution is two tokens). The star-out network is the most efficient (0.683), whereas the empty (0.404) and pair (0.444) networks are the least efficient. In all networks, the public-good provision rate is significantly higher than in the empty network. This suggests that there is something about the structure of some networks that allows subjects to coordinate efficiently. We return to this question later.

The highest rate of under-contribution is observed in the empty network (0.482). Again, the predicted under-contribution rate in the symmetric mixed strategy equilibrium of the one-shot game is 1/2, which is similar to the empirical under-contribution rate in the empty network. The highest over-contribution rate (0.202) is found in the one-link network, which also has a high under-contribution rate (0.336). We also observe high under-contribution and over-contribution rates in the pair network (0.415 and 0.142), which appears to indicate a mis-coordination problem, discussed further later in the paper. The complete network in which each subject can observe the other two subjects also has high under-contribution and over-contribution rates (0.302 and 0.193). Thus, subjects' behavior is *not* more efficient in the complete network, which highlights the central role of the network architecture in solving the coordination problem.

Remark 2 (statistical dependence) Our experiment employs a random matching design that generates a rich set of data. In analyzing these data, we followed the usual practice of regarding each game as an independent trial, controlling for individual heterogeneity where possible. There is no simple adjustment to the standard tests that will take care of the possible dependence among games, so we have used the null of independence, while recognizing that it may not be satisfied in this case. Independence would be satisfied, for example, if the subjects in a given session use identical mixed strategies. If there is heterogeneity among subjects, however, the outcomes of games in which the same subjects appear will not be independent. This biases the standard errors downwards, increasing the likelihood of finding a significant treatment effect. The robustness of our results to subject pools, individual behavior, and learning effects (Online Appendix III) mitigate the concerns about statistical dependence.

An alternative and much more conservative approach would be to treat each *session average* as a single observation. We have performed the analysis in Table 1 under this alternative assumption. The results are displayed in Table 1-Alt below. As one might expect, with only three "independent" observations for each network treatment, fewer differences in network means are statistically significant, although some significant differences remain. We reject this approach because it ignores a large amount of useful information. More precisely, the variation within a session is informative and reflects additional information that is lost when one considers only the session average. It may be that our approach biases standard errors downwards, but the conservative alternative, by attributing all within-session variation to session-specific factors, grossly overstates the standard errors. Given the budget constraints under which most experimentalists work, it is infeasible to generate the quantities of data required to obtain significant results under the conservative approach.[16]

[Table 1-Alt here]

[16]We used a total of 420 subjects in our experiments. To have enough sessions to guarantee significant results, under the alternative assumption, would probably require several times this number. Even a large university may not provide a sufficient pool of subjects for such a large experiment and the costs in terms of time and subject payments would be prohibitive.

4.2 Strategic commitment and strategic delay

Next, we focus on the evolution of contributions over time in the different network treatments. This allows us to identify further qualitative shifts in subjects' behavior resulting from changes in the network architecture. Table 2 presents the timing of contributions across network positions. Recall that a subject in a position where he can observe other positions is called *informed*; otherwise, he is called *uninformed*. Also, a subject is called *observed* if he is in a position where he is observed by another position; otherwise, he is called *unobserved*. The contribution rates are defined as the ratio of the number of contributions to the number of uncommitted subjects, i.e., the number of subjects who still have a token to contribute. We sometimes refer to these as *conditional* contribution rates. The number in parentheses in each cell represents the number of uncommitted subjects (subjects who have an endowment left for contribution). The last column of Table 2 reports total contribution rates.

[Table 2 here]

For uninformed-and-observed subjects (top panel), most contributions were made in the first period. The tendency of uninformed subjects to make early contributions is found in all networks, but the contribution rates in the first period and the total contribution rates vary considerably across networks and positions. For informed subjects (middle panels), by contrast, there is a general tendency to delay, especially if they are unobserved. For example, the modal behavior of subjects in position B of the line network is to contribute in the second period. Given the early contribution behavior of position-C subjects in this network, this indicates that position-B subjects delay their contribution until they observe that C has contributed. Finally, the uninformed-and-unobserved subjects (bottom panel) in the one-link and pair networks maintained low contribution rates across the three periods of the game, but they are much more likely to contribute in the Berkeley data than in the Princeton data (see Online Appendix III).

4.2.1 Strategic commitment

Result 2 (strategic commitment) *There is a strong tendency for subjects who are uninformed and observed by others to contribute early. Specifically, subjects in positions B (one-link), C (line), and A (star-in) exhibit strategic commitment. This effect is strongest for position*

C (line) and is associated with a high level of efficiency in that network.

We have already suggested that an uninformed-and-observed subject has an incentive to make an early contribution in order to encourage others to contribute. In particular, subjects occupying positions B (one-link), C (line), and A (star-in) should contribute in the first period according to this reasoning. In contrast, the uninformed-and-observed subjects occupying positions B (star-out) and C (star-out) face a coordination problem that complicates the analysis of incentives for strategic commitment. We return to them later.

The support for Result 2 comes from Figure 3 (below), which shows the frequencies of contributions across time by *uncommitted* subjects occupying position B (one-link), C (line), and A (star-in). We also include subjects in position B (line). This position is different from the others included in Figure 2, because it is both observed by position A and observes position C. Thus, in the line network, subjects in position B may be torn between the incentive to contribute early and the incentive to delay.

The number above each bar in the histogram represents the number of observations. The histograms in Figure 3 show that subjects in positions B (one-link), C (line), and A (star-in) all exhibit a tendency toward early contributions, but the actual contribution rates vary. Most noticeably, C (line) has a higher contribution rate than the other two positions – the contribution rate in the first period is 0.657 for C (line), whereas the corresponding rates for B (one-link) and A (star-in) are 0.578 and 0.571, respectively – but the differences are not statistically significant.[17]

[Figure 3 here]

The high contribution rate for C (line) is another reflection of the greater efficiency of the line network. Given the strategic commitment of C (line), we note that subjects in position B (line) have more in common with informed subjects than with subjects who are uninformed and observed: most subjects in position B (line) contribute in the second and third periods, although there are a few subjects contributing in the first period. Another interesting feature of the data is the similarity of the contribution rates at positions B (one-link) and A (star-in). Unlike B (one-link), A (star-in) may have an

[17] Where appropriate, we test for the difference of means by estimating probit and logit models that account for the statistical dependence of observations caused by the repeated appearance of the same subjects in our sample.

incentive to delay if he thinks that he can signal to B (star-in) and C (star-in) that he is determined to be a free rider and force the other two to contribute. Thus, coordination in the star-in network would appear to be more difficult than in the one-link network. The fact that efficiency is higher in the star-in network than in the one-link network (0.500 versus 0.452) supports this conclusion. Nonetheless, we observe very similar contribution rates at the two positions and similar provision rates in the two networks.

4.2.2 Strategic delay

Result 3 (strategic delay) *There is strong evidence of strategic delay by informed subjects. In particular, subjects at position A (one-link), B (line), and A (star-out), tend to delay their decisions until another subject has contributed.*

As we have already argued, informed subjects have an incentive to delay making a decision to contribute until they observe that another subject has contributed. According to this argument, subjects in positions A (one-link), A and B (line), and A (star-out) should exhibit strategic delay. Informed subjects in positions A, B and C (complete), B and C (star-in), and A and B (pair) also have an incentive to delay but, because of the symmetry of these positions in their respective network structures, the incentive to delay is confounded with the coordination problem. For this reason, we deal with these positions separately in the following subsection.

The support for Result 3 comes from Figure 4 below. For the network positions of interest here, we present the subjects' contribution rates, conditional on their information states. The information state is 1 if a contribution has been observed and is 0 otherwise. The number above each bar of the histogram represents the number of observations. There is a strong incidence of strategic delay for subjects in positions A (one-link), B (line) and A (star-out) where observing a contribution significantly increases the subject's contribution rate. By contrast, the contribution rates for position A (line) are low in both states. This suggests that the behavior of subjects in position A (line) can be best described as free riding. But note that given the tendency of subjects in positions B and C (line) to contribute, the behavior of position-A subjects is optimal and efficient.

[Figure 4 here]

4.2.3 Mis-coordination

Result 4 (mis-coordination) *There is evidence of coordination failure in networks where two subjects, such as B and C (star-out, star-in) and A and B (pair), are symmetrically situated. Coordination failure explains the majority of inefficient outcomes in the star-out, star-in and pair networks.*

We have delayed the discussion of positions B and C (star-out, star-in) and A and B (pair), because they involve a coordination problem that complicates the analysis of incentives for strategic delay and strategic commitment. The common feature of these pairs of positions is that they are symmetrically situated in their respective networks. In the star-out network, B and C have an incentive to encourage A but, at the same time, they have an incentive to be free riders and let the other encourage A. In the star-in network, B and C have an incentive to delay in order to see whether A contributes but, once A has contributed, they have an incentive to be free riders and let the other provide the public good. In the pair network, A and B have both an incentive to encourage the other and an incentive to delay. This conflict may lead to inefficient outcomes. From the same reason, the symmetry of the complete network architecture makes it difficult for subjects to coordinate their contributions to the provision of the public good. In fact, there is no salient solution to the coordination problem in the complete network. We next investigate the coordination problem in the star-out, star-in and pair networks. We begin with the star-out network.

The star-out network We first investigate the coordination problem by revisiting the efficiency results presented in Table 1 above. The star-out network has the lowest rate of over-contribution (0.078) among all networks. This result is not surprising. Subjects in position A play the role of a central coordinator in the star-out network. The position-A subject waits to see whether the peripheral positions, B and C, contribute and only contributes himself, if necessary, in the last period. It is less obvious how much of the under-contribution rate (0.238) is attributable to mis-coordination between B and C. To answer this question, Figure 5 depicts the total contributions made by subjects in positions B and C in each period. The numbers $\frac{a}{b}$ above each bar of the histogram represent the rates of (a) under-contribution and (b) over-contribution after this state the game.

[Figure 5 here]

It is interesting that the frequency of no contribution by subjects in positions B and C during the first two periods (0.205) is quite close to the rate of under-contribution (0.238). This suggests that the under-contribution outcomes in the star-out network are mainly caused by a coordination failure between position-B and position-C subjects. We can check this by focusing on the 118 (out of 575) games in which neither B nor C contributed by the end of the second period. The public good was provided in only four of those games. This implies that 83.2% (= 0.198/0.238) of the total under-contribution rate is attributable to a failure by subjects in positions B and C to coordinate their contributions.

The star-in network In the star-in network, we distinguish two types of coordination failures, one that occurs when position-A subjects contribute first and one that occurs when they try to free ride. We divide the sample according to the timing of contributions of position-A subjects, and re-calculate the efficiency results. The new results are presented in Figure 6 below. The numbers represent the total number of observations. One interesting feature of the data presented in Figure 6 is that, even when the subjects in position A contribute in the first two periods, the under- and over-contribution rates are relatively high (0.188 and 0.241, respectively) purely because of a coordination failure between the subjects in positions B and C. On the other hand, when position-A subjects do not contribute, the under-contribution rate is very high (0.822), which strongly suggests that the coordination between B and C becomes more difficult when A does not contribute. Of course, the failure to coordinate depends on A's refusal to commit, so this could be interpreted as a failure of A to coordinate with B and C. In any case, the under-contribution rate when position-A subjects do not contribute is much higher than the under-contribution rate in the benchmark empty network (0.482).

[Figure 6 here]

The pair network In the pair network, the salient solution to the coordination problem is for A and B to contribute. According to this hypothesis, under-contribution should be attributed to coordination failure between the subjects in positions A and B, whereas over-contribution is attributable to contributions from subjects isolated in position C. In order to investigate the coordination failure between subjects in positions A and B, we simply compute the relative frequency that subjects in positions A and B fail to contribute two tokens. This turns out to be surprisingly high (0.418). The uncoordinated contributions of position-C subjects sometimes lead to over-contribution and sometimes compensate for under-contribution by subjects in positions A and B. On average, as one would expect, these contributions have no effect on efficiency. In fact, the under-contribution rate (0.415) is almost identical to the frequency of under-contribution by subjects in positions A and B. So we can argue that under-contribution in the pair network is driven by the coordination failure between subjects in positions A and B. Over-contribution, on the other hand, is clearly the result of uncoordinated contributions by position-C subjects.

5 Concluding remarks

Our main conclusion is that different network architectures lead to different outcomes in coordination games. Moreover, asymmetry in the network architecture is an important factor in creating the salience of certain strategies that lead to these different outcomes. Asymmetric networks give different roles to different subjects, making their behavior more predictable and aiding the coordination of their actions. We identify several ways in which this predictability occurs in our data from monotone games. Two persistent types of behavior are strategic commitment in some network positions and strategic delay in other positions. We observe passivity in some positions, particularly isolated subjects, who can neither observe others' actions nor have their choices observed by anyone else: such subjects are less likely to contribute. As a result, the structure of observability in the network architecture gives rise to salience which, in turn, is an aid to predictability and coordination.

Our paper contributes to the literature on monotone games. Admati and Perry (1991) introduced the basic concepts and their work was extended by Marx and Matthews (2000). Gale (1995, 2001) developed the theory applied in this paper in two different environments. Choi et al. (2008) conduct a theoretical and experimental study of monotone games with perfect information: every player knows the history of the game. In the present paper, we focus instead on the case where information is imperfect. Duffy et al. (2007) investigate the model of Marx and Matthews (2000) experimentally and show that positive provision can be supported in a dynamic laboratory setting.

Our paper also contributes to the large and growing literature on the economics of networks (see Jackson, 2008). Although network experiments in economics are recent, there is now a growing experimental literature on the economics of networks (see Kosfeld, 2004, Goyal, 2005, and Jackson, 2005, for excellent, if now already somewhat dated, surveys). To the best of our knowledge, all of the previous experimental work on networks has quite different focuses than ours. Of particular interest are several articles that examine coordination is social networks. The most recent such paper of which we are aware is Cassar (2007). These studies are different from ours in several respects. Our paper is also related to the large literature on coordination games in experimental economics (see Crawford, 1997, Camerer, 2003, and Devetag and Ortmann, 2007 for comprehensive discussions).

There is clearly a lot more to be done and the uses of our dataset are far from exhausted. We varied the informational network for one specific three-person, three-period voluntary contribution game. The game was chosen because of the richness of the equilibrium set and because observability seemed intuitively to be an important factor in selecting among equilibria. To determine more precisely which factors are important in explaining strategic behavior in dynamic coordination games, it will also be useful to investigate a larger class of games in the laboratory. The methodology and approach we use could be applied to other versions of dynamic coordination games where theory makes weak (or no) predictions about equilibrium selection, and observability could plausibly be a critical selection factor.

While the present paper does not propose a specific theoretically-grounded structural model that might be applied to the data, we view that as the key next step to understanding the effect of observational networks in multiplayer coordination games. We attempted to explore the application of Quantal Response Equilibrium (QRE) analysis (McKelvey and Palfrey 1995, 1998) of these games, but there were problems of tractability because of the multiplicity of equilibria and bifurcations in the logit equilibrium correspondence. In fact, in the presence of imperfect information and simultaneous moves, even in the case of three-person networks, characterizing the set of QRE is computationally intensive. Another possible approach is to consider models with cognitive hierarchies, such as level-k theory, but the application of these approaches to complex multistage games with repeated play is bedeviled by the problem of specifying the behavior of the 0-level type. We hope the results reported here open up future theoretical and experimental research on these questions. We believe that our approach can be used to study the role of network architecture in other kinds of games.

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Table 1. The total number of contributions and provision rate by network

Network	Total contributions 0	1	2	3	Under contribution	Provision
Empty	0.092	0.390	0.404	0.114	0.482	0.518
One-link	0.071	0.264	0.462	0.202	0.336	0.664
Line	0.087	0.215	0.570	0.128	0.302	0.698
Star-out	0.146	0.092	0.683	0.078	0.238	0.762
Star-in	0.087	0.276	0.462	0.175	0.364	0.636
Pair	0.098	0.316	0.444	0.142	0.415	0.585
Complete	0.076	0.225	0.505	0.193	0.302	0.698

Wilcoxon (Mann-Whitney) rank-sum test - under (white) / over (gray)

	Empty	One-link	Line	Star-out	Star-in	Pair	Complete	Provision
Empty	--	0.000	0.469	0.046	0.006	0.179	0.003	--
One-link	0.000	--	0.001	0.000	0.264	0.011	0.756	0.000
Line	0.000	0.243	--	0.005	0.029	0.504	0.013	0.000
Star-out	0.000	0.001	0.015	--	0.000	0.001	0.000	0.000
Star-in	0.000	0.355	0.026	0.000	--	0.137	0.523	0.000
Pair	0.028	0.011	0.000	0.000	0.084	--	0.059	0.028
Complete	0.000	0.346	0.996	0.048	0.078	0.002	--	0.000

Table 1-Alt. The total number of contributions and provision rate by session

Network	Session	Total contributions				Under contribution	Provision
		0	1	2	3		
Empty	1	0.080	0.510	0.360	0.050	0.590	0.410
	2	0.040	0.296	0.528	0.136	0.336	0.664
	3	0.120	0.389	0.364	0.127	0.509	0.491
On-link	1	0.064	0.224	0.480	0.232	0.288	0.712
	2	0.160	0.320	0.390	0.130	0.480	0.520
	3	0.036	0.262	0.484	0.218	0.298	0.702
Line	1	0.120	0.160	0.592	0.128	0.280	0.720
	2	0.040	0.166	0.697	0.097	0.206	0.794
	3	0.100	0.267	0.487	0.147	0.367	0.633
Star-out	1	0.220	0.153	0.547	0.080	0.373	0.627
	2	0.184	0.064	0.704	0.048	0.248	0.752
	3	0.093	0.073	0.743	0.090	0.167	0.833
Star-in	1	0.016	0.136	0.744	0.104	0.152	0.848
	2	0.136	0.344	0.376	0.144	0.480	0.520
	3	0.097	0.307	0.380	0.217	0.403	0.597
Pair	1	0.133	0.273	0.413	0.180	0.407	0.593
	2	0.100	0.280	0.510	0.110	0.380	0.620
	3	0.080	0.350	0.437	0.133	0.430	0.570

Wilcoxon (Mann-Whitney) rank-sum test - under (white) / over (gray)

	Empty	One-link	Line	Star-out	Star-in	Pair	Provision
Empty	--	0.127	0.513	0.275	0.275	0.513	--
One-link	0.127	--	0.127	0.050	0.275	0.275	0.127
Line	0.127	0.275	--	0.050	0.513	0.513	0.127
Star-out	0.127	0.275	0.827	--	0.050	0.050	0.127
Star-in	0.275	1.000	0.513	0.513	--	0.827	0.275
Pair	0.513	0.513	0.050	0.050	0.827	--	0.513

Table 2. The evolution of contributions over time by uninformed and informed types

A. Uninformed and observed

Network	Position	Period 1	Period 2	Period 3	Contribution rate
One-link	*B*	0.578 (450)	0.432 (190)	0.213 (108)	0.811
Line	*C*	0.657 (600)	0.121 (206)	0.160 (181)	0.747
Star-out	*B* , *C*	0.395 (1150)	0.191 (696)	0.066 (563)	0.543
Star-in	*A*	0.571 (550)	0.250 (236)	0.175 (177)	0.735
Average		0.517 (2750)	0.225 (1328)	0.117 (1029)	0.669

B. Informed and unobserved

Network	Position	Period 1	Period 2	Period 3	Contribution rate
One-link	*A*	0.140 (450)	0.248 (387)	0.409 (291)	0.618
Line	*A*	0.100 (600)	0.046 (540)	0.146 (515)	0.267
Star-out	*A*	0.096 (575)	0.123 (520)	0.507 (456)	0.609
Star-in	*B* , *C*	0.165 (1100)	0.176 (919)	0.266 (757)	0.495
Average		0.132 (2725)	0.147 (2365)	0.310 (2019)	0.489

C. Informed and observed

Network	Position	Period 1	Period 2	Period 3	Contribution rate
Line	*B*	0.187 (600)	0.406 (488)	0.434 (290)	0.727
Pair	*A* , *B*	0.255 (1100)	0.306 (819)	0.283 (568)	0.630
Complete	*A*, *B*, *C*	0.179 (825)	0.260 (677)	0.349 (501)	0.605
Average		0.214 (2525)	0.315 (1984)	0.340 (1359)	0.645

D. Uninformed and unobserved

Network	Position	Period 1	Period 2	Period 3	Contribution rate
Empty	*A* , *B* , *C*	0.351 (1500)	0.084 (973)	0.181 (891)	0.513
One-link	*C*	0.244 (450)	0.065 (340)	0.104 (318)	0.367
Pair	*C*	0.265 (550)	0.064 (404)	0.082 (378)	0.369
Average		0.313 (2500)	0.076 (1717)	0.142 (1587)	0.455

( ) - # of obs.

Figure 1: The networks

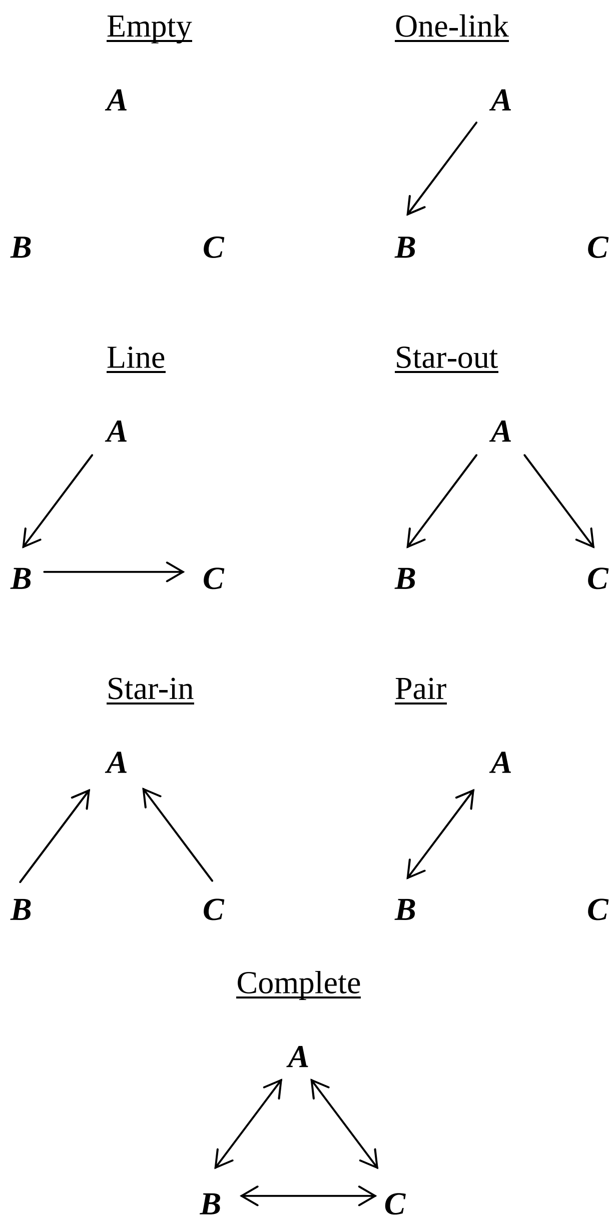

Figure 2. Efficiency rates across networks
(sample means and 95 percent confidence intervals)

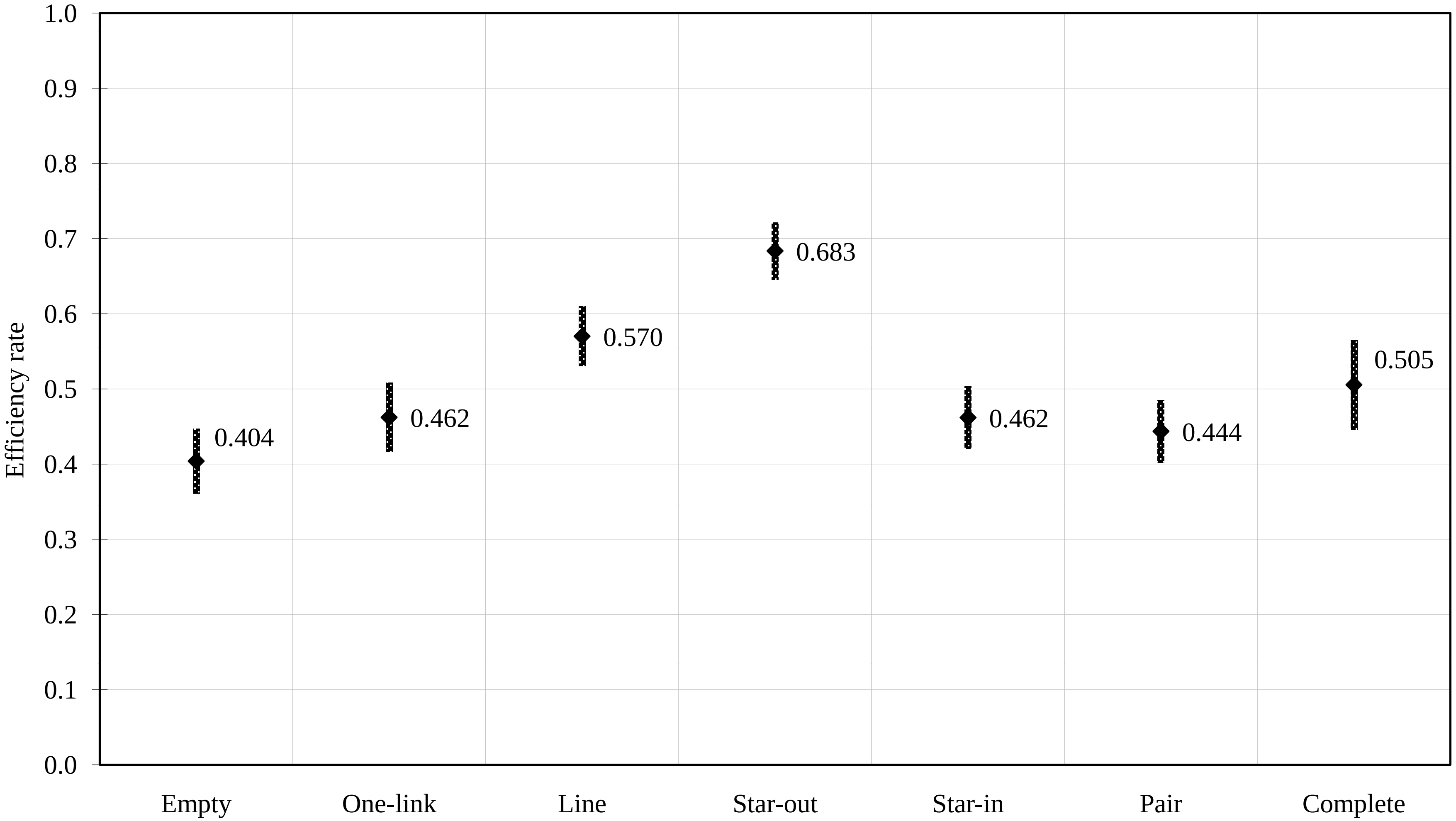

Figure 3. The frequencies of contributions across time for selected positions

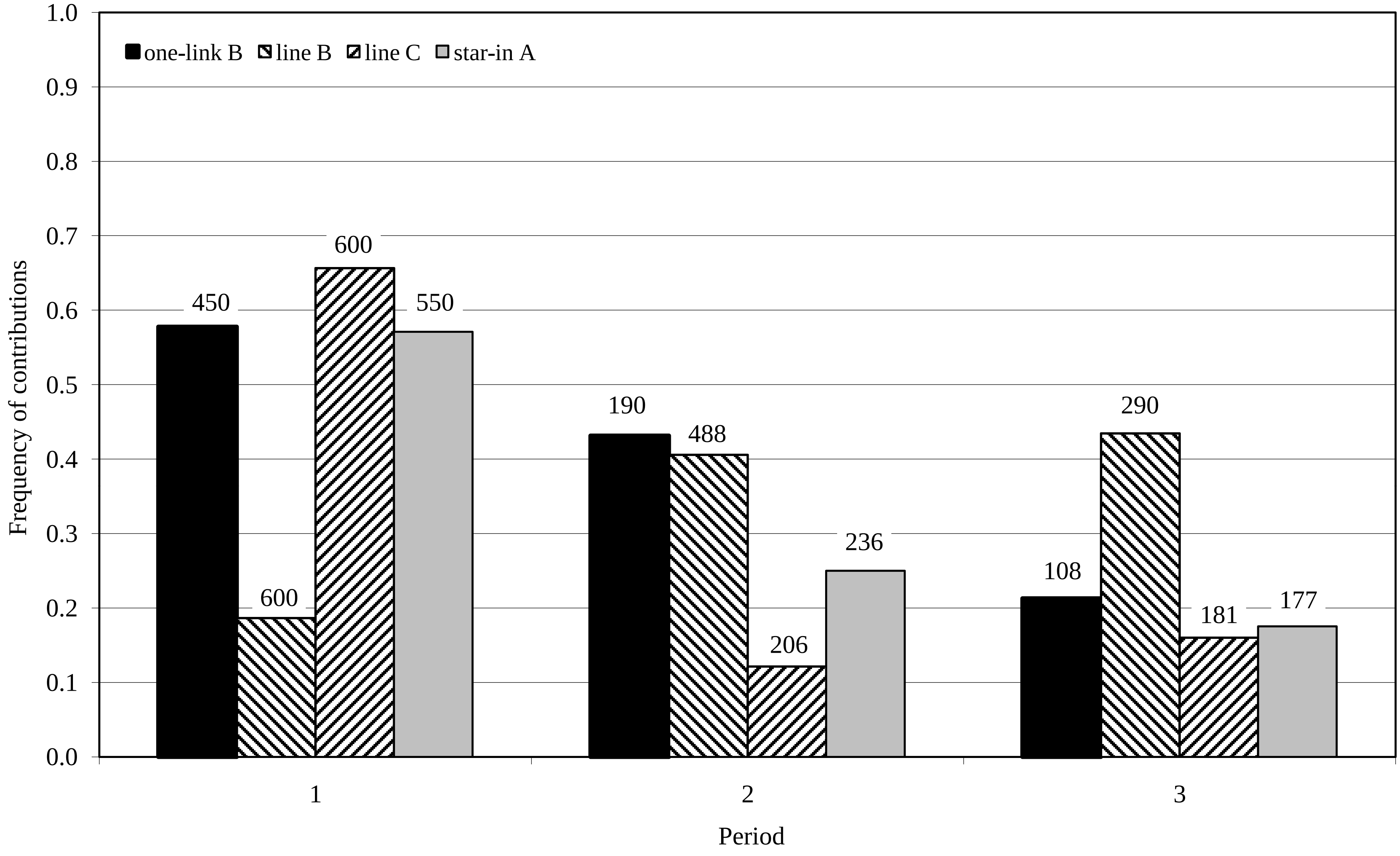

Figure 4. The frequencies of contribution at payoff-relevant states for selected positions

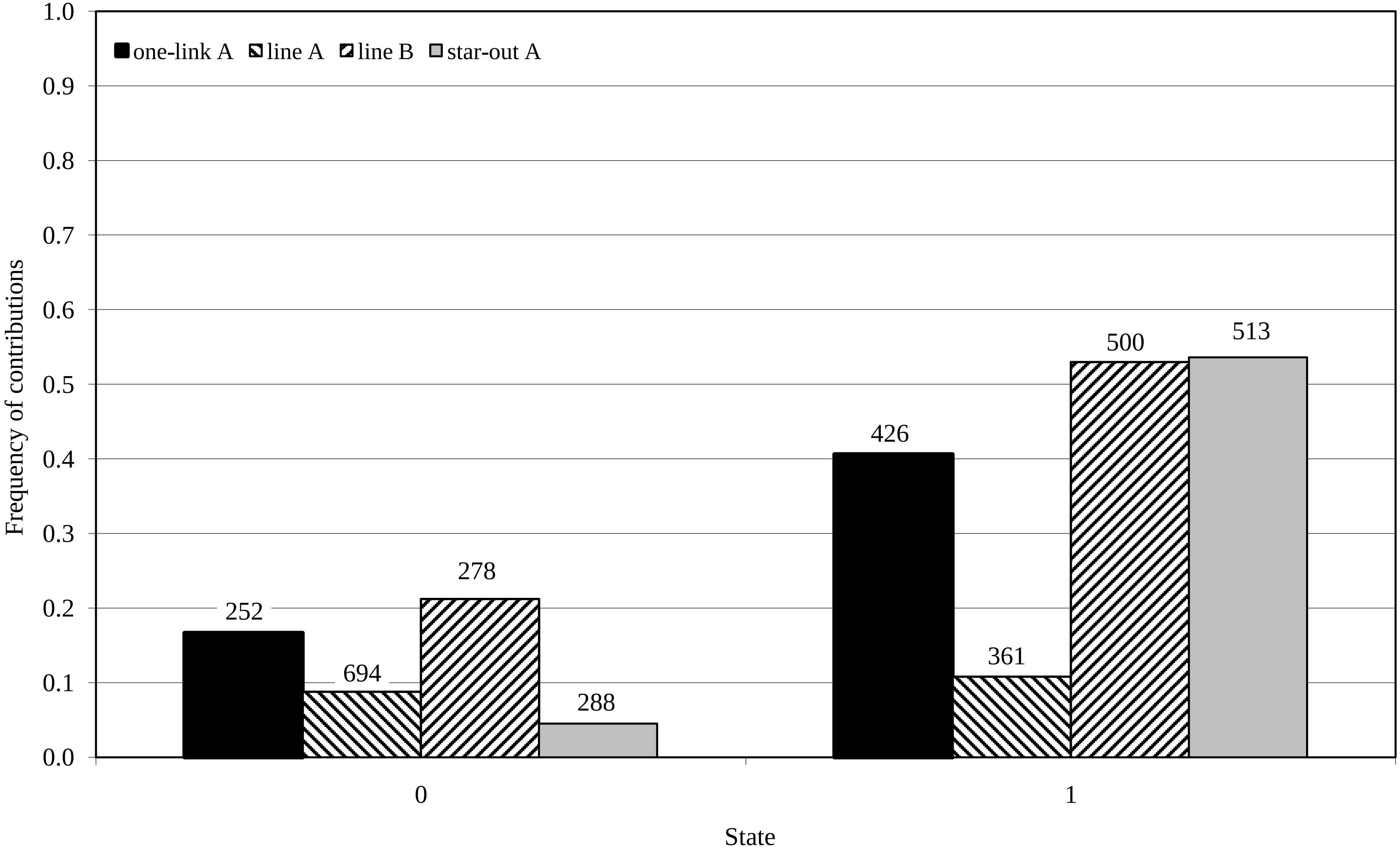

Figure 5. The total contributions across time in the star-out network by subjects in positions *B* and *C*

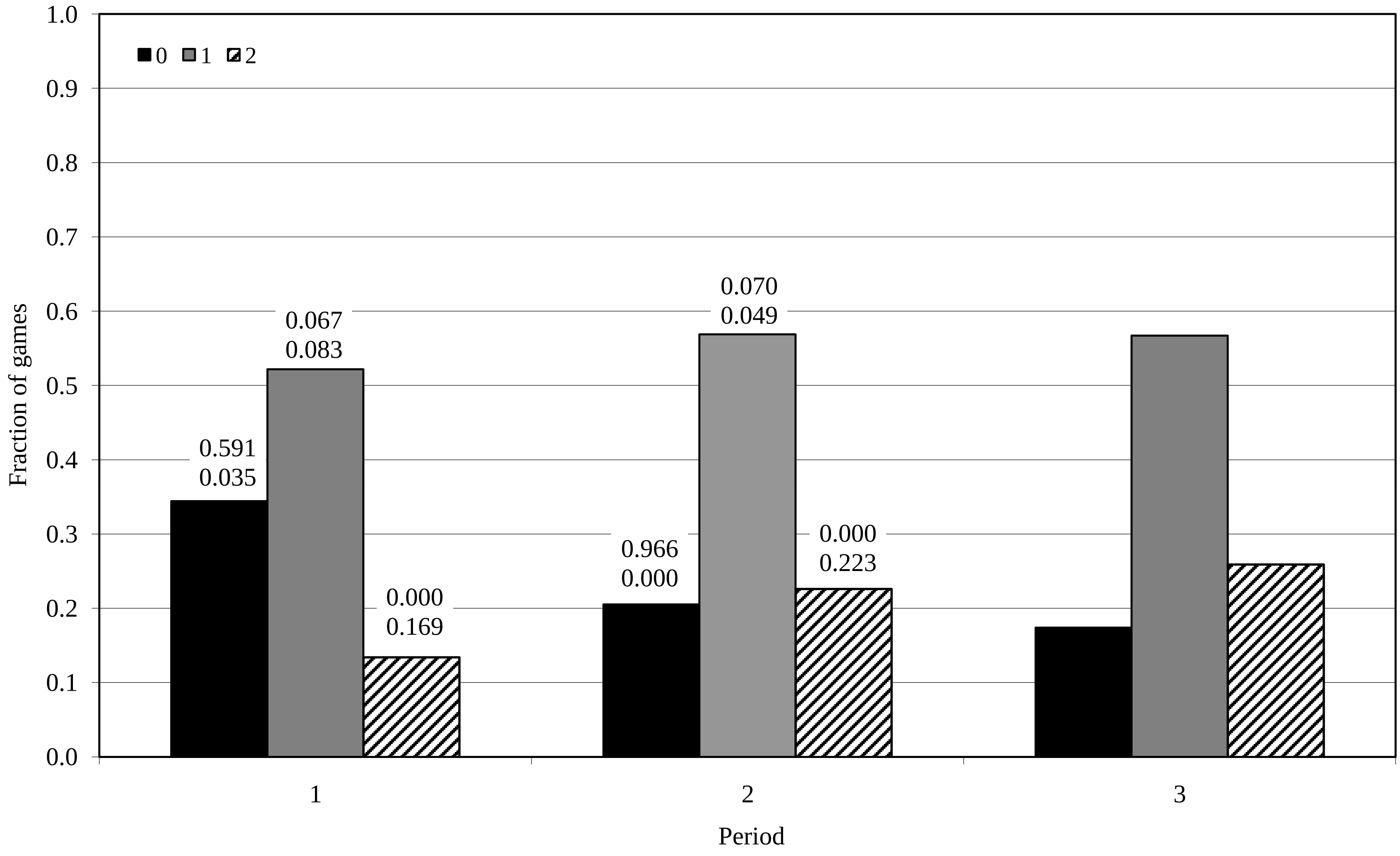

Figure 6. Efficiency in the star-in network conditional on the timing of contribution of position-*A* subjects