Communication, Coordination and Networks

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Abstract

We study experimentally how the network structure and length of pre-play communication affect behavior and outcome in a multi-player coordination game with conflicting preferences. Network structure matters but the interaction between network and time effects is more subtle. Under each time treatment, substantial variations are observed in both the rate of coordination and distribution of coordinated outcomes across networks. But, increasing the communication length improves both efficiency and equity of coordination. In all treatments, coordination is mostly explained by convergence in communication. We also identify behaviors that explain variations in the distribution of coordinated outcomes both within and across networks.

JEL Classification: C70, C92, D61, D63, D82, D83

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1 Introduction

In numerous social and economic situations, individuals engage in pre-play communication to achieve coordination explicitly. Debating which restaurant to dine in, sharing information about the relative merits of competing compatibility standards for a new product and exchanging views about alternative public good projects or politicians in a local community all capture such efforts to resolve uncertainty inherent in coordination problems.

Despite the prevailing use of pre-play communication, however, our understanding of how its *structure* affects behaviors and outcomes remains incomplete. There is ample evidence that social networks play an important role in the formation of beliefs and opinions that shape individual choices (e.g. Goyal (2007) and Jackson (2008)). Workers rely on the existing communication protocol within a firm and its structure is often crucial for the determination of coordination outcomes for the firm (e.g. Chandler (1962) and Milgrom and Roberts (1992)). This paper investigates experimentally how the network structure of pre-play communication influences individuals' communication and coordination behaviors and, hence, the effectiveness of pre-play communication on coordination.

When networks play a central role in these settings, it is natural to question not only whether communication improves the chance of coordination but also how the benefits of coordination are distributed among individuals. In a given network, some individuals may occupy locations that enable them to derive greater strategic influence and payoffs than others.[1] We therefore explore both issues of *efficiency* and *equity* in the context of pre-play communication and coordination. Specifically, we consider as our underlying game a four-player extension of Battle of the Sexes with conflicting preferences about how to coordinate. Prior to playing the underlying game, the four players engage in multiple rounds, denoted by T, of structured pre-play communication in which they announce non-binding, hence cheap talk, messages about their intended actions in the underlying game.

While the standard analysis of cheap talk has mainly been concerned with the role of extra communication opportunities in achieving efficiency (e.g. Farrell (1987) and Rabin (1994)),[2] the key variable in our setup concerns the extent to which each player observes the past history of players' announcements, which we interpret as the network structure of pre-play communication. Specifically, at the beginning of each round of communication and the underlying game, a player observes past messages of another player if and only if there is an *undirected* edge between the two players. Four networks or undirected graphs are considered in our four-player setup, as illustrated by Figure 1 below. Nodes in each network, denoted by N, E, S and W, represent players.

- Figure 1 about here -

[1] For a related discussion on network structure and individual strategic advantage, see Jackson (2008).
[2] Also, see Aumann and Hart (2003) and Crawford (2007).

In the *complete* network, each player can communicate with every other player. In the *star* network, one central player (player E) can communicate with every other player while each of the other three players can communicate only with the central player. In the *kite* network, three players (players N, E and S) can communicate with each other, while the remaining player (player W) can communicate only with one of the first three players (player E). In the *line* network, two players (players E and W) can communicate with two other players and each of the two remaining players can communicate only with one of the first two players. The last three networks are sometimes referred to as *incomplete* networks.

Each network structure facilitates its own distinctive communication flows. Although there exist other four-player networks, the four networks we consider provide a rich enough ground to study the role of network structure of pre-play communication. Since we are interested in the issue of equity as well as efficiency, a particular attention will be given to the behavior of *hub* players in each of the three incomplete networks: E in the star and kite networks, E and W in the line network. These players occupy strategically influential locations in that some players rely entirely on their announcements to learn about others' intentions.

The games that we study allow a very rich set of histories and strategies, thereby admitting a large number of equilibria. Thus the theory does not provide strong predictions about which outcomes are likely to be observed in the experimental data. However, the network structure of pre-play communication assigns particular roles to players which may guide their behavior. To further this intuition, we focus on certain classes of equilibria in which the asymmetry in players' node characteristics translates into payoff asymmetry. In particular, we note that the complete symmetry of players in the underlying game can be broken by the network structure itself, and not by randomization, in the star and kite networks but not in the line network.[3] Also, the equilibrium analysis clarifies the sources of multiple equilibria in our setup; for instance, unlike in the two-player game studied by Farrell (1987) an "agreement" to coordinate on a particular action in the underlying game can take a variety of forms in our setup. These insights enable us to navigate a rich data set with the lens of theory.

In the experimental design, we consider treatments that combine the four networks and two different lengths of pre-play communication, $T = 2$ and $T = 5$. In addition, we consider the underlying game without communication. By varying both the network structure and

[3] In the star or kite network, one can construct a *symmetric* sequential equilibrium in which players with identical node characteristics play the same strategy (with respect to our labels) and the hub's favorite outcome occurs with probability 1. One such equilibrium is that the hub insists his favorite message/action throughout the entire game with the others gradually converging to coordinate accordingly. In the line network, however, symmetry requires randomization in the communication stage. Symmetry is a natural equilibrium restriction in our network setup.

length of communication, we examine how the network and time structure interact to determine subjects' communication behavior and influence coordination outcomes in terms of both efficiency and equity.

Our experimental results first establish a significant network effect on both efficiency and equity of the coordination outcome: both when $T = 2$ and when $T = 5$, significant differences in the coordination rate and the distribution of coordinated outcomes are observed across networks. However, the results also show that extra communication not only improves the chance of coordination but also reduces asymmetry in the distribution of coordinated outcomes. The details of these results are as follows:

- **Efficiency:** Both when $T = 2$ and $T = 5$, there is no significant difference in coordination rates between the complete, star and kite networks while coordination rate in the line network is significantly lower. In all networks, coordination rate is higher when $T = 5$ than when $T = 2$ but the increase is statistically significant only in the line network.

- **Equity:** Both when $T = 2$ and $T = 5$, coordination occurs most frequently in the hub's favorite outcome in the star and kite networks while coordinated outcomes appear to be uniformly distributed in the complete and line networks. Under each time treatment, the frequency of coordination on the hub's favorite outcome is greater in star than in kite; given star or kite, this frequency is lower when $T = 5$ than when $T = 2$.

We next examine the experimental data from pre-play communication. In all treatments, the subjects' announcements tend to converge but less than unanimity is usually sufficient to ensure corresponding coordination.

- **Communication dynamics:** In all treatments with pre-play communication, coordination rate is mostly explained by the frequency of convergence to super-majority or unanimity in the communication stage.

Finally, we look for regularities in the subjects' behavior that may explain the observations on the distribution of coordinated outcomes. Interestingly, our data reveal that the drop in the frequency of coordination on the hub's favorite outcome as we increase T appears to be induced by different behaviors across the star and kite networks. Also, we identify distinct behavior of players N and S in the kite network as responsible for the smaller asymmetry in the distribution of coordinated outcomes in the kite network. Here, we pay particular attention to finding evidence of "non-switching" behavior by the hub(s) in which this player insists his favorite message/action throughout the entire game.

- **Behavior:**

  - In the star network, the hub is highly likely to display non-switching behavior both when $T = 2$ and when $T = 5$. But, conditional on such behavior, the frequency of his favorite message/action is lower when $T = 5$ than when $T = 2$. In the kite network, the hub displays a strong tendency of non-switching only when $T = 2$.

  - Players N and S in the kite network conform less to the hub than other players in both star and kite networks.

  - There is evidence that all four players behave symmetrically in the complete and line networks.

The rest of the paper is organized as follows. The next section discusses the related literature. Section 3 describes our setup and presents some theoretical observations that guide our experimental design and data analysis. Section 4 outlines the research questions to be addressed with the experimental data. Section 5 describes the experimental design and procedures. Section 6 collects the experimental results, followed by some concluding remarks in Section 7.

2 Related Literature

Our paper contributes, above all, to the experimental literature on pre-play communication via cheap talk (see Crawford (1998) and Camerer (2003) for related surveys). A most closely related paper is Cooper, DeJong, Forsythe and Ross (1989) who consider the two-player Battle of the Sexes with cheap talk. They study two different communication structures: one-way communication versus two-way communication. In the former treatment only one player can send a message to the other player, whereas the two players send messages simultaneously to each other in the latter. They find that coordination rates are much higher in the one-way treatment than in the two-way treatment and also that the sender in the one-way treatment sends his favorite message, thereby inducing coordination on his favorite outcome, with a very large frequency. The two communication structures here can be interpreted as two possible (directed) networks with two players.[4] In contrast to their two-player setup, our multi-player setup enables us to consider a richer variety of networks. Also, their setup does not take account of how network effect may interact with the length of communication.

Pre-play communication in social networks has been studied elsewhere in theoretical models of Chwe (2000), Calvó-Armengol and de Martí (2007, 2009) and Galeotti, Ghiglino

[4] Cooper, DeJong, Forsythe and Ross (1992) and Burton, Loomes and Sefton (2005) also compare the two different communication structures in other coordination games.

and Squintani (2009), among others. In their setups, prior to playing the underlying game players simultaneously send messages about their private information to others whom they are linked with (possibly in a directed way). Chwe (2000) and Calvó-Armengol and de Martí (2007, 2009) consider coordination games with common interest and show that coordination can be achieved in networks with fewer links than the complete network. In a setup that allows for conflicting preferences, Galeotti, Ghiglino and Squintani (2009) examine how players' incentives to report the truth and their welfare are related to the network structure.[5] Thus, the central issue in these papers is the role of network structure on efficiency. In contrast, our paper deals with the distributional issue as well as efficiency. Moreover, unlike theirs, our setup allows for multiple rounds of communication, thereby shedding light on the effects of the dynamics of communication on efficiency and equity.

There is a large literature in sociology concerned with the impact of communication networks on group outcomes (see, for example, Wasserman and Faust (1994)). By focusing on the structural properties of networks, this literature proposes a number of indices that capture the relative importance of different nodes within a network and the network as a whole. One such notion that may be closely related to our analysis is that of *betweenness centrality* (Freeman (1977)).[6] A player, or a node, in a network is said to be *between* a pair of other nodes if the node falls between the pair of other nodes on the shortest path connecting them. A node located between other nodes controls the others' beliefs about what they cannot directly observe and, in this sense, a higher degree of betweenness makes the node more important.[7] Measures such as betweenness centrality, however, usually lack behavioral foundations based on individual incentives and, therefore, how they could be used for interpreting experimental data is not a straightforward issue.

Finally, our paper is related to a growing literature of network experiments in economics (see, for example, Kosfeld (2004) for a survey). Among them, Choi, Gale, Kariv and Palfrey (2009) also study experimentally the role of network structure on coordination.[8] They consider a class of monotone games that can be interpreted as dynamic public good games and use networks to describe a variety of information structures about the history of past contributions. Their findings suggest that network structure makes particular strategies salient, and this serves to reduce strategic uncertainty and hence facilitate efficient coordination.

[5] Hagenback and Koessler (2009) consider the issue of endogenous network formation in a coordination setup with pre-play communication.

[6] For other notions of centrality, see Chapter 5 of Wasserman and Faust (1994).

[7] This node centrality measure can be used to define centrality of a network. In our setup, the star network is most central, followed by kite, line and complete.

[8] Experimental studies on the relationship between network structure and coordination have also been conducted in other disciplines. See, for example, Kearns, Judd, Tan and Wortman (2009).

3 The Setup

3.1 The game

We study games in which multiple players share a common interest to coordinate but each player has his own preferred outcome. The following describes the *underlying game*. There are four players, indexed by $I = N, E, S, W$, and each player simultaneously and independently chooses an action, a_I, from a common set $\{n, e, s, w\}$. Let $a = (a_N, a_E, a_S, a_W)$ denote an action profile. A player obtains a positive payoff if all players choose a single common action. Otherwise, a player receives nothing. Each player has his preferred action corresponding to his *label*: player I obtains a higher payoff if all players choose action i. Player I's payoff, $u_I(a)$, is given by

$$u_I(a) = \begin{cases} 0 & \text{if} \quad a_I \neq a_J \text{ for some } J \neq I \\ k_1 & \text{if} \quad a_I = a_J \neq i \text{ for all } J \neq I \\ k_2 & \text{if} \quad a_I = a_J = i \text{ for all } J \neq I, \end{cases}$$

where $k_2 > k_1 > 0$. If there are only two players, the game corresponds to the well-known Battle of the Sexes. In this sense, the underlying game can be interpreted as a four-player version of Battle of the Sexes.

Prior to playing the underlying game, the players engage in finite periods of pre-play communication, sometimes referred to as the communication stage. Pre-play communication is cheap talk in the usual sense that it is non-binding and payoff-irrelevant. Let T denote the number of periods in the communication stage. In each period $t = 1, 2, ..., T$, each player I simultaneously and independently chooses a message, denoted by m_I^t, from the set $\{n, e, s, w\}$. A message therefore can be interpreted as the player's intended action. We shall sometimes refer to $T + 1$ as the period in which the players engage in the underlying game.

To complete the description of pre-play communication, we specify information available to each player at the beginning of each communication period. This is represented by an undirected graph, or *network*. We say that player I can communicate with player J if and only if there is an undirected edge or link between the two players, I and J. If player I can communicate with player J then, at the beginning of period $t + 1$, each of the two players knows the history of messages chosen by the other player up to, and including, period t. The network structure is common knowledge. As illustrated in Figure 1, we consider four networks: complete, star, kite and line.

The main objective of our analysis is to gain understanding of how network structure affects outcome and behavior. For this purpose, it will be helpful to identify some key positions in the incomplete networks. A *periphery* is a player who has only one link: N, S and W in the star network, W in the kite network, and N and S in the line network. A *hub* is a player who is linked to at least one periphery: E in the star network, E in the kite network, and E and W in the line network. We shall sometimes refer to the entire game that includes both the T-period communication stage with a given network and the subsequent underlying game simply as the game with the particular network.

3.2 Theoretical background

Our four-player games allow a very rich set of histories and strategies, thus admitting a large number of equilibria. Despite the multiplicity problem, however, theory points to some useful clues as to how one should analyze experimental data. In this section, we identify several such guidelines that will enable us to approach the data with the lens of theory.

Since we are interested in the impact of network structure on behavior and outcome, it is natural to adopt the notion of symmetry in equilibrium. In a given game with pre-play communication, we can identify players that occupy symmetric locations/nodes in the sense that, with appropriate re-labelling of the messages/actions, they are endowed with the same strategy set and any pair of such players exchanging their strategies exchange their payoffs as well. In the complete network game, all four players are symmetric; in the star network, each of the three peripheries, N, W and S, can only communicate with E and, hence, their strategies are identical mappings (from histories to messages/actions); in kite, N and S are similarly symmetric; and finally, line network is symmetric across the middle and has two pairs of symmetric players: E and W, and N and S. We shall consider symmetric (subgame perfect or sequential) equilibria in which players with identical node characteristics adopt symmetric strategies (relative to our labels).

Before we overview the issue of multiple equilibria in the games with pre-play communication, we first note that symmetry does not offer a unique prediction in our underlying game. To see this, it is easy to find a symmetric mixed-strategy Nash equilibrium in which each player plays his favorite action with probability $\frac{k_2}{3k_1+k_2}$ and each of the other three actions with equal probability $\frac{k_1}{3k_1+k_2}$. But, unlike the two-player game, there also exists a symmetric equilibrium in pure strategies in which each player plays his favorite action and thus coordination is not reached.[9]

In the games with pre-play communication multiple (symmetric) equilibria arise through a variety of patterns in the communication stage. Players randomize their messages in order to reach an "agreement" which will then induce the corresponding pure-strategy Nash equilibrium in the underlying game. With four players, however, an agreement can take a variety of forms. For instance, symmetric mixed-strategy equilibria can be constructed such

[9] Note however that the probability of coordination in the symmetric mixed-strategy equilibrium is negligible.

that not only unanimous announcement of a common message but also a super-majority outcome (i.e. all but one player choose the same message) or a majority outcome (i.e. only two players choose the same message) constitutes an agreement to achieve coordination. Another source of multiplicity of symmetric equilibria in our four-player games is the possibility of *partial* agreements. That is, the players may treat certain communication outcomes as an interim basis for further negotiation. A partial agreement could, for instance, narrow down the set of randomized messages in the continuation play, thereby increasing the likelihood of improved agreements and later coordination. In Appendix I, we provide detailed examples of multiple equilibria along these lines for the case of complete network. The equilibrium features that we address here are also present in games with other networks.[10]

As mentioned earlier, we are interested in the role of network structure on efficiency and equity of the coordination outcomes. For a given network, the likelihood of coordination depends, for instance, on the definition of agreement: a more strict form of agreement is indeed associated with a lower coordination rate in equilibrium (see Appendix I). Thus, the multiplicity problem makes it impossible to draw any conclusion about how network structure will affect efficiency.

We next discuss what game theory can tell us about the role of network structure on the issue of equity. In particular, we consider the set of symmetric equilibria in games with incomplete networks in which the hub acquires a higher benefit than the other players. This is because of the intuition that by strategically controlling the flow of information players with greater access to past play of a game may derive a greater payoff than those who observe less.

Our first observation shows that, in the star and kite networks, the complete symmetry of players in the underlying game can be broken by the network structure of pre-play communication.

Observation 1 *In the game with star or kite network, there exists a symmetric equilibrium in which coordination on action e occurs with probability 1. In the game with line network, there does not exist a symmetric equilibrium in which coordination on a particular action occurs with probability 1.*

The reasoning behind the statement is straightforward. In the star or kite network, for example, every player always playing message/action e can be supported as a symmetric sequential equilibrium. Player E's insistence on message e is met with the belief by each periphery that the others have also chosen the same message and will play action e in the underlying game; observation of any other messages by E triggers the (off-the-equilibrium)

[10] In the two-player game considered by Farrell (1987), these issues do not arise, and the restriction of symmetry delivers a unique equilibrium characterization.

belief that some other player has deviated, leading to coordination failure. Such an equilibrium is indeed symmetric across the peripheries. In the game with line network, however, symmetry cannot yield sure coordination on a particular outcome since that will require asymmetric behavior from one of the two pairs of symmetric players, E and W or N and S.

The above observation provides a sense in which the star and kite network structures serve the role of symmetry breaking such that disproportionate payoffs are conferred on the most central player, the hub. In contrast, in the line network, randomization is needed to break the symmetry across the two pairs of players. Our next observation demonstrates that, in all three networks, there exist alternative equilibrium dynamics, involving randomization, which generate outcome paths that confer asymmetric benefits on the hub(s).

Observation 2 *Consider the game with star, kite or line network. If $T \geq 3$, there exists a symmetric equilibrium with the following properties:*

1. *Coordination on each action occurs with positive probability.*

2. *Coordination on each hub's favorite action is most likely to occur.*

The details of the equilibria are provided in Appendix I. Let us briefly sketch the construction for the star network with $T = 3$. In period $t = 1$, each periphery randomizes among the entire message set; the hub, E, announces arbitrarily. In the next two periods, the peripheries play arbitrary messages while the hub reports a single message twice if there was a unanimous agreement among the peripheries on that message in $t = 1$ and any two different messages otherwise. Upon observing the same message from the hub in the last two periods of the communication stage, the players coordinate on the corresponding action in the underlying game; otherwise, they play their own favorite actions with probability 1.

As shown in Appendix I, the above behavior constitutes a sequential equilibrium with an appropriate off-the-equilibrium punishment scheme. Furthermore, the calculation of mixing probabilities in $t = 1$ reveals that, in equilibrium, coordination on the hub's favorite action, e, occurs more frequently than each of the other actions. It is important to note that, in this equilibrium, while each periphery announces his intended action the hub merely serves the role of information transmission; that is, his messages indicate different message profiles of only the other players that he is linked to.

Observations 1 and 2 offer further useful guidelines for our experimental design and analysis in the face of multiple equilibria. We are particularly interested in the question of whether the hub will enjoy disproportionate benefits due to his informational advantage. In the star and kite networks, such asymmetry in outcome can arise from several equilibrium dynamics. In the equilibria of Observation 2, the hub performs the role of information transmission, which is distinct from the behavior in the equilibria of Observation 1. In the line network, only randomization can induce similar asymmetric outcomes.[11]

4 Research Questions

We now list the set of questions that the previous theoretical discussion motivates in our experimental study. Our research questions are four-fold. The first two questions are concerned with the overall impact of the treatments (time and network effects) on the final outcome of the underlying coordination game along two central issues: efficiency and equity. The standard equilibrium analysis suggests that, for a given network, greater opportunities to communicate will improve the chance of coordination and hence payoffs but the multiplicity of equilibria makes it unclear if and how payoffs will depend on the network structure, or indeed what the combined effect of the length and network structure of communication will be. On the other hand, in an incomplete network, a hub player has more links than others and, therefore, we are interested in whether such informational advantage translates into asymmetric outcomes and, if so, whether the length of communication plays any role.

Question 1 (Efficiency) *How is the likelihood of coordination affected by the length and network structure of pre-play communication?*

Question 2 (Equity) *How is the distribution of coordinated outcomes affected by the length and network structure of pre-play communication?*

We observed in the previous section that the problem of multiple equilibria is caused primarily by different communication dynamics that are possible in equilibrium. This poses a challenge in interpreting the experimental data for the communication stage. Despite this, we want to find whether there are, on average, any regular patterns in the observed communication dynamics and how communication relates to coordination outcome. This motivates our next research question.

[11] There is an alternative equilibrium which confers larger payoffs to E and W in the line network. The two players randomize among just the two messages e and w such that an agreement results in their playing the corresponding pure strategy Nash equilibrium in the underlying game. N and S simply play the action corresponding to their hubs' messages in period T in the underlying game. Furthermore, randomization can also lead to symmetric outcomes/payoffs in all three networks. For example, let $T = 2$, and consider strategies with the following properties. All four players mix among the entire message set in $t = 1$ and the hub maintains/switches his message in $t = 2$ if there was an agreement/disagreement in $t = 1$. Non-switching leads to coordination and switching leads to coordination failure.

Question 3 (Communication dynamics) *How is the pattern of pre-play communication affected by the length and network structure of pre-play communication? What is the relationship between the dynamics of communication and the coordination outcome in each game?*

Our final question concerns the behavior of players at different locations within each network. The theoretical discussion in the previous section suggests that (i) subjects at different locations in a given network may serve distinct roles in communication and hence determination of the coordination outcome and, moreover, (ii) such behavioral patterns may depend on the treatment (i.e. network and time structures of communication) itself. Thus, we are interested in identifying any regular patterns in subjects' behavior and linking them to outcomes in communication and coordination.

Question 4 (Behavior) *Are there any regular and distinct patterns in subjects' behavior across treatments?*

5 Experimental Procedure

The experiment was run at the Experimental Laboratory of the Centre for Economic Learning and Social Evolution (ELSE) at University College London (UCL) between May 2008 and November 2008. The subjects in the experiment were recruited from an ELSE pool of UCL undergraduate students across all disciplines. Each subject participated in only one of the experimental sessions. After subjects read the instructions, the instructions were read aloud by an experimental administrator. Throughout the experiment we ensured anonymity and effective isolation of subjects in order to minimize any interpersonal influences that could stimulate cooperation. Each experimental session lasted between one hour and one and a half hours. The experiment was computerized and conducted using the experimental software z-Tree developed by Fischbacher (2007). Sample instructions are reported in Appendix II.

We studied the game with four network structures (complete, star, kite and line networks) and two lengths of pre-play communication ($T = 2$ (short) and $T = 5$ (long)), in addition to the one-shot game with no communication ($T = 0$). A single treatment consisting of a pair of network and T was used for each session and each treatment was used for one session. Thus, there were in total 9 experimental sessions. Either 16 or 20 subjects participated in each session which consisted of 20 independent rounds, except for the no-communication treatment which consisted of 30 rounds. In each session, the network positions were labeled N, E, S, or W. One fourth of the subjects were randomly designated as type-N participants, one fourth as type-E participants, one fourth as type-S participants and one fourth as type-W participants. Each subject's type remained constant throughout the session. In each round, the subjects were randomly formed into four-person groups. The groups formed in each round were independent of the groups formed in any of the other rounds.

The table below summarizes the experimental design and the number of observations in each treatment. The first number in each cell is the number of subjects and the second is the number of observations per treatment/session.

	Network			
Communication length	Complete	Star	Kite	Line
Short ($T = 2$)	16 / 80	16 / 80	16 / 80	16 / 80
Long ($T = 5$)	20 / 100	16 / 80	20 / 100	16 / 80
No ($T = 0$)	20 / 150			

Each round was divided into two stages: a communication stage, which consists of T (either 2 or 5) decision-turns, and an action stage, which consists of a single decision-turn. In the no-communication treatment, there was only an action stage in each round. In the action stage, four actions were available: n, e, s and w. The communication stage that preceded the action stage involved each participant sending messages. In each decision-turn of the communication stage each participant was asked to choose a message from n, e, s and w, which were labeled by the same letters as the actions available in the action stage. It was illustrated that a message may indicate a subject's intended action in the subsequent action stage but the subject does not have to follow that message when it comes to making an action choice. When every participant in the group had made his or her decision, each participant received the messages chosen by the participants to whom he or she was connected in the network. This completed the first decision-turn of the communication stage. This process was repeated in the remaining decision-turns of the communication stage.

When the communication stage ended, each participant was asked to choose an action out of the four possible actions without knowing the actions selected by other participants. After every participant made a decision in the action stage, the computer informed subjects of the actions chosen by all the participants in the group and their earnings. It was illustrated and emphasized that the earnings in each round are determined only by the actions chosen in the action stage and the messages chosen in the preceding communication stage are entirely irrelevant to earnings. After each subject observed the results of the first round, the second round started with the computer randomly forming new groups of four participants with distinct types. This process was repeated until all 20 rounds were completed.

Earnings were calculated in terms of tokens and then exchanged into British pounds, where each token was worth £0.50. The earnings in each round were determined as follows.

If all participants in the group chose a common action, a participant whose label corresponded to the letter of the common action received 3 tokens while the other participants received 1 token each. Otherwise, all participants received zero token. Thus, the total payment to a subject was equal to £0.50 times the total number of tokens earned over 20 rounds (30 rounds in the one-shot game treatment), plus a £5 participation fee. The average payment was about £13. Subjects received their payments privately at the end of the session.

6 Experimental Results

6.1 Coordination outcomes

We begin our analysis of the experimental data by examining the final outcomes of coordination in each treatment. As summarized in Section 4, the focus of our interest lies in the impact of our treatments on both efficiency and equity of final coordination outcomes. To address the issue of efficiency, we consider the *rate* of coordination; for equity, we examine the *distribution* of coordinated actions.

Table 1 below reports coordination rates across treatments (the top panel) and results of the chi-square nonparametric test that compare coordination rates between each pair of treatments (the bottom panel).

- *Table 1 about here* -

We first check whether communication is indeed effective. The coordination rate in the treatment without communication is 0.05, while the coordination rates in treatments with communication vary from 0.28 to 0.73. The difference between the no-communication treatment and each communication treatment is highly significant (p-value in each comparison is far below 0.001). Thus, we can conclude that communication is an effective means of achieving coordination.

Next, we compare coordination rates across networks for a given length of the communication stage T. When $T = 2$, coordination rates in the first three networks range from 0.56 to 0.65, while coordination rate in the line network is 0.28. When $T = 5$, coordination is achieved in the complete, star and kite networks with similar frequencies ranging from 0.68 to 0.73, while coordination rate in the line network is 0.50. The nonparametric tests (lighter-shaded cells) reveal no significant differences in coordination rate among the complete, star and kite networks both when $T = 2$ and when $T = 5$. However, coordination rate in the line network is significantly lower than in the other three networks both when $T = 2$ and when $T = 5$.

We also check if a longer communication stage increases the likelihood of coordination within a network. A first glance at the top panel of Table 1 suggests that this is indeed the case for every network; the increases in coordination rate from $T = 2$ to $T = 5$ are 0.05 (complete), 0.09 (star), 0.12 (kite) and 0.22 (line). However, results of the pair-wise nonparametric test in the bottom panel (darker-shaded cells) show that these differences are in fact not statistically significant with the usual significance levels in the complete, star and kite networks. This suggests that the value of communication is mostly realized by two rounds of communication in the three networks. In contrast, the likelihood of coordination increases significantly in the line network from $T = 2$ to $T = 5$.

These findings are summarized below.

Result 1 (Efficiency) *1. Coordination rates are higher in treatments with communication than in the treatment with no communication.*

2. Given any time treatment T, coordination rates are not statistically different across the complete, star and kite networks, while coordination rate in the line network is significantly lower than in the other three networks.

3. Given any network treatment, coordination rate increases from $T = 2$ to $T = 5$, although the differences are not statistically significant in the complete, star and kite networks.

Our next Table summarizes the distribution of coordinated outcomes in the underlying game along with the number of corresponding observations. The number in parentheses in the last column presents a p-value from the chi-square nonparametric test for uniform distribution.

- *Table 2 about here* -

There are considerable variations in the frequency of each coordinated outcome, n, e, s or w, across treatments. In order to further clarify our results, we present the observations across networks for each T in Figures 2A and 2B.

- *Figure 2A and 2B about here* -

In Table 2 and Figures 2A-B, we observe a notable effect of network structure on the distribution of coordinated outcomes. First, both when $T = 2$ and when $T = 5$, if coordination were to occur in the star and kite networks, it would most likely to fall on action e, the hub's favorite action, while the distribution of coordination actions is not statistically different from the uniform distribution in the complete and line networks. Given our intuitions and the equilibrium analysis of Section 3.2 above (Observations 1-2), it is indeed interesting to confirm the strategic advantage of the hub in the star and kite networks; furthermore, just as the theory suggests, the outcomes in the complete network turn out to be symmetric. Also interesting, in light of Observation 2, is that the two hubs, E and W, in the line network do not actually obtain greater benefits.

Second, both when $T = 2$ and when $T = 5$, the likelihood of coordination on action e is higher in the star network than in the kite network. This appears to suggest that an additional link between N and S in the kite network compared to the star network reduces the hub player E's strategic advantage. We shall further investigate this issue in Section 6.3 below.

Third, there is a strong evidence of time effect in the star and kite networks. Here, the longer the players engage in cheap talk, the less frequently is that they coordinate on action e. Furthermore, in the star network, the likelihood of coordination on each of the other three actions appears to increase by equal proportion as we go from $T = 2$ to $T = 5$; in the kite network, on the other hand, the decrease in the likelihood of coordination on the hub E's favorite action is matched mainly by an increase in the likelihood of the periphery W's favorite action.

In summary the data support the following results.

Result 2 (Equity) 1. *Both when $T = 2$ and when $T = 5$, the distribution of coordinated actions is highly concentrated on action e in the star and kite networks, whereas the distribution does not differ statistically from the uniform distribution in the complete and line networks.*

2. *Given any T, the frequency of coordination on action e is higher in the star network than in the kite network; given star or kite, this frequency is lower when $T = 5$ than when $T = 2$.*

Despite the multiplicity of equilibria, our experimental results strongly support regularity of certain patterns in outcomes. The network structure of communication indeed matters for both efficiency and equity of coordination outcomes. However, the length of communication also plays an important role. Our results suggest that allowing the players to communicate longer will not only improve efficiency but also make the coordination outcome more equitable in the networks that produce asymmetric coordination outcomes.

6.2 Communication and coordination

We next examine the play of the communication stage and relate the dynamics of communication to coordination outcomes. First, we consider the form of "agreement" that leads to coordination. Table 3 presents the likelihood of coordination (on any action) in the underlying game contingent on each possible outcome in the last period of the communication stage, together with the number of observations for each communication outcome. In the complete network, communication outcomes are divided into five categories: unanimity, super-majority, majority, tied-majority and complete disagreement. Unanimity is an outcome in which all four players announce the same message; super-majority is an outcome in which all but one player choose the same message; majority is an outcome in which only two players announce the same message; tied-majority is an outcome with two distinct pairs of two players who choose the same message; and complete disagreement is an outcome in which each player announces a distinct message. In the incomplete (star, kite and line) networks, we divide super-majority and majority further by identifying whether such an outcome includes the hub player(s). For example, a super-majority outcome NES in the star network represents players N, E, and S choosing the same message in period T.[12]

- Table 3 about here -

There is a strong relation between what happens in the last period of the communication stage and coordination across all treatments: a wider consensus improves the chance of coordination. Unanimity leads to coordination almost with certainty in all treatments. Super-majority (including the hub(s) in the incomplete networks) is very likely to induce coordination in most of the treatments, one possible exception being the line network with $T = 2$ where the coordination rate contingent on super-majority in period T is 0.35.[13]

On the other hand, we observe high frequencies of unanimity and super-majority in the last period of communication, especially in the complete, star and kite networks. For instance, in the complete network, the subjects reach super-majority or unanimity by period T in 69% of observations when $T = 2$ and 88% of observations when $T = 5$. This therefore leads us to our next Table, which reports the frequency of unanimity or super-majority occurring in each period $t \leq T$.

- Table 4 about here -

There is a clear pattern of convergence towards "agreement", i.e. unanimity or super-majority, in all treatments. The chance of an agreement in the first period is low, ranging from 0.04 (line network with $T = 5$) and 0.29 (star network with $T = 2$), but it increases monotonically over time in all treatments. Moreover, in all treatments, the chance of eventual coordination (the last column) is mostly explained by the chance of successfully

[12] Due to small number of observations, tied-majority and complete disagreement are treated as one outcome in each of the incomplete networks.

[13] Notice also that, in each of the incomplete networks, almost all super-majority outcomes in period T include the hub(s).

reaching such an agreement. This implies that the role of network structure in determining efficiency of outcome indeed depends on how well it facilitates the flow of information and hence the formation of agreement among the players.

Another interesting observation is related to the role of extra communication. Notice first that the marginal increase in the proportion of agreement across two periods (the number in parentheses) is larger when $T = 2$ than when $T = 5$ in each network. More interestingly, the improvement in coordination rate as we go from $T = 2$ to $T = 5$ is larger in the networks that are less effective in inducing agreement.

We summarize these results below.

Result 3

1. *In all treatments, the coordination rate is mostly explained by the frequency of convergence to super-majority or unanimity in the communication stage.*
2. *The increase in coordination rate from $T = 2$ to $T = 5$ is greater in a network with lower frequency of convergence.*

6.3 Behavior in the star and kite networks

The distributions of coordinated outcomes in the star and kite networks turn out to be highly asymmetric in favor of the hub, player E, but extra communication reduces such asymmetry. Also, given T, the degree of inequity is greater in the star than in the kite network. In order to identify any behavioral patterns responsible for these observations, we compare strategies by nodes.

Hub The equilibrium constructions of Section 3.2 suggest a number of strategies of the hub that can result in this player obtaining disproportionately large payoffs. We focus on identifying one such strategy. Akin to Observation 1, *non-switching* behavior refers to the case in which a subject with the role of a hub chooses his initial message constantly throughout the entire game (including the underlying game); any other observed behavior is referred to as *switching* behavior. Table 5A presents the frequencies of non-switching and switching behaviors in the star and kite networks, together with the frequency of the hub initially choosing his own favorite message conditional on each category (in parentheses).

- Table 5A about here -

Table 5B shows how reluctant the hub is to switch from his initial message when he finds himself in conflict with every other player in $t = 1$, together with the number of observations (in parentheses).

- Table 5B about here -

These two tables report a marked difference in the hub's behavior across the star and kite networks. First, the hub in the star network exhibits a strong tendency to insist his initial message (even after complete disagreement) throughout the game *both* when $T = 2$ and when $T = 5$, while the hub in the kite network shows such tendency only when $T = 2$. Second, conditional on non-switching, the hub in the star network chooses his own favorite message/action with a significantly larger frequency when $T = 2$ than when $T = 5$, while the corresponding frequencies in the kite network are almost the same.

Next, Table 5C presents the distribution of coordinated actions in the underlying game, conditional on the hub's behavior.

- *Table 5C about here* -

There are a couple of notable patterns here. First, in both time treatments for the star network, coordination occurs mostly when the hub does not switch from his initial message: 0.96 (= 49/51) when $T = 2$ and 0.93 (= 54/58) when $T = 5$. A similar pattern is established in the kite network with $T = 2$: 0.89 (= 40/45). However, in the kite network with $T = 5$, coordination is more likely to occur when the hub switches from his initial message: 0.66 (= 45/68). Second, when coordination occurs with non-switching behavior, it mostly falls on action e, the hub's favorite action. This holds even true in the kite network with $T = 5$. When coordination results from switching, however, the distribution of coordinated actions is not concentrated on action e. In particular, in the kite network with $T = 5$, coordination appears to be slightly more likely to occur on action w.

Putting these observations together, we can conclude that the positive time effect on equity in the star and kite networks is driven by different behaviors across the two networks. This is summarized below.

Result 4 *1. In the star network, the hub displays a strong tendency of non-switching behavior both when $T = 2$ and when $T = 5$. But, conditional on non-switching, the hub is less likely to choose his own favorite message/action when $T = 5$ than when $T = 2$.*

2. In the kite network, the hub displays a strong tendency of non-switching behavior when $T = 2$ but the frequency of switching behavior is greater than that of non-swithcing when $T = 5$. Both when $T = 2$ and when $T = 5$, non-switching behavior is associated with a high concentration of coordination on action e while switching behavior does not result in the likelihood of coordination on action e being greater than on other actions.

N and S in the kite network Now that we have identified how increasing the length of communication generates more equitable outcomes in the star and kite networks, it remains to investigate why the hub's advantage is lower in the kite than in the star network for each T. Since the only structural difference between the two networks is the additional link between players N and S in the kite network, behavior of these players should hold key to answering this question. But, in order to address these two players, we must first consider how other nodes behave in the two networks.

Table 6 below presents the behavior of *peripheries* in the star, kite and line networks. Since information about past play of the game flows to a periphery only through the hub that he is linked to, it is natural to examine a periphery's willingness to *conform* to the hub. For this purpose, we divide the relevant histories of observations at the beginning of each period $t \leq T + 1$ (including the action stage) into whether or not a periphery's message in the previous period coincided with the message chosen by the hub.

- Table 6 about here -

The following patterns are observed in all treatments. Not surprisingly, at a history in which the periphery and hub chose a common message (the bottom panel of Table 6) the periphery continues to choose the same message almost surely. At other histories with disagreements, the periphery's tendency to copy the hub's previous message increases significantly in period $t = T$ of the entire game. Also, for a given network, this probability is higher at the end of the game with $T = 5$ than with $T = 2$. The probability of conformity, i.e. following the hub's message when their messages conflicted in the previous period, at the action stage is high in both star and kite: 0.65 (star) and 0.64 (kite) when $T = 2$; 0.70 (star) and 0.79 (kite) when $T = 5$.[14]

Let us now compare these observations with the behavior of N and S in the kite network. We examine the histories at which either of the two players is in disagreement with the hub, E. Since N and S can observe each other's past messages, the relevant histories at the beginning of $t \leq T + 1$ are partitioned into the following three sets about the three players' messages in $t - 1$: (i) N and S played the same message different from E's message; (ii) all three players played distinct messages; and (iii) either N or S played the same message as E. Table 7 presents the behavior of players N and S in the kite network at these histories.

- Table 7 about here -

[14] The corresponding probabilities for the line network are somewhat smaller. This may explain the relatively low coordination rates in the treatments with line network. See Section 6.4 below for further discussion on the behavior in the line network.

The difference in behavior between these two players and a periphery is most clearly seen by the decisions made by N and S contingent on the first type of histories. Here, in both time treatments, the two players are much more likely to stick with their own previous message than to conform with the hub. In this case, the probability that either N or S switches to the hub's message when playing the underlying game is just 0.29 when $T = 2$ and 0.28 when $T = 5$. Even when all three players played differently, the probability of conformity is significantly lower when $T = 5$ (equal to 0.54), compared to the corresponding tendency exhibited by the periphery, W, in the same treatment (equal to 0.79) as seen in the previous table. But, when one of N and S agreed with E in the previous period, the other player is likely to conform to E. Together with the high tendency of conformity by the peripheries in the star and kite networks (Table 6), these observations (Table 7) lead to the following result.

Result 5 *Both when $T = 2$ and when $T = 5$, players N and S in the kite network are less likely to conform to the hub than the peripheries in the star and kite networks.*

We have already seen that, when $T = 2$, the hub in both star and kite networks exhibits non-switching behavior (Result 4) and also such behavior is very frequently accompanied by the hub's own favorite message/action (Table 5A). Thus, Result 5 gives an explanation for why under this time treatment the distribution of coordinated outcomes is less asymmetric in the kite network than in the star network. Furthermore, Result 5 suggests that the less conforming behavior of N and S is what induces the hub in the kite network to switch his messages much more frequently when $T = 5$, which in turn reduces the hub's payoff advantage.

6.4 Behavior in the complete and line networks

Another interesting feature of Result 2 in Section 6.1 is the symmetry of coordinated outcomes in the complete and line networks. On the one hand, the observations in the complete network support the symmetric equilibrium as a useful framework to approach our games that are fraught with multiple equilibria; on the other hand, one wonders why in the line network the two hubs, E and W, do not enjoy greater benefits than the two peripheries, N and S. In this section, we engage in a more detailed examination of the subjects' behavior in these two networks.

Table 8 presents the frequency of each message played by each subject in the first period of communication, together with the frequency of each action in the no communication treatment.

- Table 8 about here -

In all reported treatments, all four players appear to randomize over the entire message set, each attaching the greatest weight on his own favorite message. As expected, the frequency of playing one's own favorite message is higher in treatments with communication than the treatment without communication. Interestingly, however, there appears to be no significant difference in the reported frequencies across the complete and line networks under both time treatments. In particular, for each corresponding treatment, the frequencies of playing messages other than one's own favorite are fairly evenly distributed.

We next examine what the communication evolves into. Specifically, we consider the distribution of messages in the last period of the communication stage conditional on an agreement (i.e. unanimity or super-majority) having been reached.[15]

- Table 9 about here -

The reported distributions are all fairly close to be uniform. Given the observations of Table 8, this indicates that the subjects behave symmetrically not just in the first period but throughout the communication stage. This gives our final result.

Result 6 *Both when $T = 2$ and when $T = 5$, there is evidence indicating that all four players in the complete and line networks behave symmetrically.*

7 Conclusion

We have explored the role of network structure and length of pre-play communication in a coordination game with conflicting preferences, which can be naturally interpreted as an extension of Battle of the Sexes. By introducing network variations, we have been able to address not only the issue of efficiency, which has been the focus of standard cheap-talk literature, but also the issue of equity. Our main conclusion is that network structure has important implications on behavior and outcome, and on both issues of efficiency and equity. In particular, we have identified how certain network structures break the symmetry of players in the underlying game and confer strategic edge, and hence higher payoff, to some players. Nonetheless, the extent of such strategic advantage depends on the length of communication. When communication lasts longer, this advantage becomes weaker, which in turn makes coordination outcomes more equitable.

In this paper, we have chosen one particular underlying game to investigate the role of network structure of pre-play communication. Our approach can be applied to study different games, for instance, other coordination games such as ones with Pareto-ranked equilibria. Cooper, De Jong, Forsythe and Ross (1989, 1992) provide experimental evidence

[15] Super-majority in the line network includes both E and W.

that one-way communication is more effective in Battle of the Sexes, whereas two-way communication is more effective in Stag Hunt. Their findings with two-player games suggest that network structure of pre-play communication generate different implications in different coordination games. Extending our analysis to other classes of underlying game may also call for an even richer set of network variations, for instance, including directed, as well as undirected, graphs. Another potentially interesting extension is to consider cheap talk games with incomplete information (pioneered by Crawford and Sobel (1982)). We shall leave these issues for future research.

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Appendix I - Equilibrium Constructions

1. Complete network

Symmetric equilibria with alternative definitions of agreement Consider the following strategy profile:

- $t = 1$

  Each player $I \in \{N, E, S, W\}$ plays each message $j \in \{n, e, s, w\}$, $j \neq i$, with probability q_1 and message i with probability $1 - 3q_1$;

- $t = 2, \ldots, T$

  If there was an "agreement" in $t - 1$ (we define an "agreement" below), each I plays the corresponding message with probability 1; otherwise, I plays each message $j \neq i$ with probability q_t and message i with probability $1 - 3q_t$;

- $t = T + 1$ (underlying game)

  If there was an "agreement" in T, each I plays the corresponding action with probability 1; otherwise, I plays action i with probability $\frac{k_2}{3k_1+k_2}$ and each $j \neq i$ with probability $\frac{k_1}{3k_1+k_2}$.[16]

An "agreement" in period t takes one of three forms - (i) unanimity; (ii) unanimity and super-majority; or (iii) unanimity, super-majority and majority (each of these terms are defined in the main text above). We next describe a recursive process that gives the equilibrium mixing probabilities q_t under each agreement form. For $t = 1, \ldots, T + 1$, let u_t denote the equilibrium continuation payoff to each player at the beginning of period t, conditional on no agreement having been reached.

(i) Unanimity

For each $t = 1, \ldots, T$, the following indifference condition characterizes the equilibrium:

$$u_t = q_t^3 k_2 + (1 - q_t^3)u_{t+1} = q_t^2(1 - 3q_t)k_1 + [1 - q_t^2(1 - 3q_t)]u_{t+1}.$$

Letting $k_1 = 1$ and $k_2 = 3$ as in the experiments, we obtain a recursive equation

[16] Any observed deviation during the communication stage is punished by continuation play of the pure strategy Nash equilibrium of the underlying game in which each player I plays action i for sure.

system

$$q_t = \frac{1-u_{t+1}}{6-4u_{t+1}}$$
$$u_t = 3q_t^3 + (1-q_t^3)u_{t+1}$$
$$u_{T+1} = \frac{1}{72}.$$

Let the probability of agreement/coordination at t be denoted by μ_t. We have $\mu_t = 4q_t^3(1-3q_t)$. The probability of coordination is then equal to

$$\mu_1 + (1-\mu_1)\mu_2 + \cdots + \prod_{t=1}^{T}(1-\mu_t)\mu_{T+1}. \tag{1}$$

(*ii*) Super-majority

Fix any $t \leq T$, and suppose that there was no agreement in $t-1$. Given symmetry, without loss of generality, consider player N playing message n and any other message, say, e. For each case, we summarize all possible events and their likelihoods, together with the corresponding continuation payoffs:

- N chooses n.

outcome	likelihood	continuation payoff
unanimity (on n)	q_t^3	3
super-majority on n	$3\left(q_t^2 - q_t^3\right)$	3
super-majority not on n	$3(1-3q_t)q_t^2$	1
disagreement	$1-q_t^2(6-11q_t)$	u_{t+1}

- N chooses e.

outcome	likelihood	continuation payoff
unanimity (on e)	$q_t^2(1-3q_t)$	1
super-majority on n	q_t^3	3
super-majority on e	$2q_t(1-3q_t)(1-q_t)+3q_t^3$	1
super-majority on w or s	$2(1-3q_t)q_t^2$	1
disagreement	$1-2q_t+5q_t^2-q_t^3$	u_{t+1}

This sets up the indifference equation and a recursive system, similarly to the unanimity case above. We can also compute the probability of agreement at $t \leq T$ to be $4\left[(1-3q_t)(3q_t^2-2q_t^3)+3q_t^4\right]$ (the corresponding probability for $T+1$ is $\frac{1}{108}$).

(*iii*) Majority

Fix any $t \leq T$, and suppose that there was no agreement in $t-1$. Given symmetry, consider player N playing message n or any other message, say, e. For each case, we summarize all possible events and their likelihoods, together with the corresponding continuation payoffs:

- N chooses n.

outcome	likelihood	continuation payoff
unanimity (on n)	q_t^3	3
super-majority on n	$3\left(q_t^2 - q_t^3\right)$	3
super-majority not on n	$3(1-3q_t)q_t^2$	1
majority on n	$9q_t^3 + 6q_t^2(1-3q_t) + 3q_t(1-3q_t)^2$	3
majority not on n	$6\left[q_t^3 + q_t^2(1-3q_t) + q_t(1-3q_t)^2\right]$	1
disagreement	$1 - 9q_t + 36q_t^2 - 49q_t^3$	u_{t+1}

- N chooses e.

outcome	likelihood	continuation payoff
unanimity (on e)	$q_t^2(1-3q_t)$	1
super-majority on n	q_t^3	3
super-majority on e	$2q_t(1-3q_t)(1-q_t) + 3q_t^3$	1
super-majority on w or s	$2(1-3q_t)q_t^2$	1
majority on n	$2q_t^2(1-q_t)$	3
majority on e	$1 - 7q_t + 22q_t^2 - 22q_t^3$	1
majority on w or s	$2q_t(1-3q_t+2q_t^2)$	1
disagreement	$3q_t - 13q_t^2 + 19q_t^3$	u_{t+1}

This sets up the indifference equation and a recursive system. We can also compute the probability of agreement at $t \leq T$ to be $4q_t\left(3 - 18q_t + 49q_t^2 - 51q_t^3\right)$.

In the following table, we report some key features of the symmetric equilibrium above, for different definitions of an agreement and communication lengths. Given the payoffs used the experimental design ($k_1 = 1$ and $k_2 = 3$), we simulate for each game (i) the probability of coordination in the underlying game (as in (1) above and its counterparts in equilibria with other agreement forms) and (ii) the probability with which each player announces his favorite message/action in the first period of communication. In the table below, each row gives these probabilities calculated from the three equilibria for the game with pre-communication length T.

	Unanimity		Super-majority		Majority	
T	Coord prob	Mix prob	Coord prob	Mix prob	Coord prob	Mix prob
1	0.018	0.502	0.133	0.589	0.576	0.774
2	0.027	0.505	0.228	0.627	0.663	0.942
3	0.036	0.507	0.302	0.662	0.667	0.997
4	0.045	0.509	0.359	0.694	0.667	0.999
5	0.053	0.512	0.404	0.723	0.667	1.000

A symmetric equilibrium with partial/interim agreements Suppose that $T = 2$. As in the experiments, $k_1 = 1$ and $k_2 = 3$. We establish the following symmetric mixed strategy equilibrium:

- $t = 1$

  Each player $I \in \{N, E, S, W\}$ plays each $j \in \{n, e, s, w\}$, $j \neq i$, with probability q and i with probability $1 - 3q$.

- $t = 2$

  (1) If there was super-majority or unanimity in $t = 1$, each I plays the corresponding message with probability 1.

  (2) If there was majority and message i was played in $t = 1$, each I plays message i with probability $1 - 2x$ and each of the other two previously played messages with probability x.

  (3) If there was majority and message i was not played in $t = 1$, each I plays each of the three previously played messages with probability $\frac{1}{3}$.

  (4) If there was tied-majority and message i was played in $t = 1$, each I plays message i with probability $1 - y$ and the other previously played message with probability y.

  (5) If there was tied-majority and message i was not played in $t = 1$, each I plays each of the two previously played messages with equal probability;

  (6) if there was complete disagreement in $t = 1$, each I plays message i with probability $1 - 3z$ and each of the other three messages with probability z.

- underlying game

  If there was super-majority or unanimity in $t = 2$, each I plays the corresponding pure-strategy Nash equilibrium; otherwise, each I plays the symmetric mixed-strategy Nash equilibrium (yielding each player a payoff of $\frac{1}{72}$).[17]

In order to establish this equilibrium, let us first go through each continuation game at $t = 2$ (numbered as above). We compute the mixing probabilities and continuation payoffs that support subgame perfectness.

(1) The specified continuation strategies are clearly optimal.

(2) Given symmetry, without loss of generality, consider player N and suppose that the messages played in the previous period are n, e and s. Let u_x refer to the player's expected continuation payoff in this case.

If he chooses message n, his expected payoff amounts to

$$u_x = 3 \times \underbrace{\frac{x^2}{3}}_{\text{unanimity on } n} + 3 \times \underbrace{\frac{2x}{3}}_{\text{super-majority on } n} + \underbrace{\frac{2x(1-2x)}{3}}_{\text{super-majority on } e \text{ or } s} + \frac{1}{72} \times \underbrace{\left(1 - \frac{4x}{3} + x^2\right)}_{\text{otherwise}}$$

If he chooses e, the expected payoff is

$$u_x = \underbrace{\frac{x\,(1-2x)}{3}}_{\text{unanimity on } e} + 3 \times \underbrace{\frac{x^2}{3}}_{\text{super-majority on } n} + \underbrace{\frac{1-x}{3}}_{\text{super-majority on } e} + \underbrace{\frac{x(1-2x)}{3}}_{\text{super-majority on } s} + \frac{1}{72} \times \underbrace{\left(\frac{2}{3} - \frac{x}{3} + x^2\right)}_{\text{otherwise}}.$$

Thus, we obtain $x = 0.141717$ and $u_x = 0.38276$.

(3) Consider player N, and suppose that the messages played in the previous period are e, s and w. Let u'_x refer to the expected continuation payoff in this case.

If he chooses e, then we have

$$u'_x = \underbrace{x^2(1-2x)}_{\text{unanimity on } e} + \underbrace{2\left[x\,(1-2x)\,(1-x) + x^3\right]}_{\text{super-majority on } e} + \underbrace{2x^2\,(1-2x)}_{\text{super-majority on } s \text{ or } w} + \frac{1}{72} \times \underbrace{\left(1 - 2x + 3x^2\right)}_{\text{otherwise}}.$$

Substituting for x calculated above, we obtain that $u'_x = 0.23397$.

(4) Consider player N, and suppose that the messages played in the previous period are n and e. Let u_y refer to the expected continuation payoff in this case.

[17] Any observed deviation in period 2 is punished by continuation play of the pure strategy NE of the underlying game in which each player plays his favorite action for sure.

If he chooses message n, we have

$$u_y = 3 \times \underbrace{\frac{y}{4}}_{\text{unanimity on } n} + 3 \times \underbrace{\left(\frac{y}{2} + \frac{1-y}{4}\right)}_{\text{super-majority on } n} + \underbrace{\frac{1-y}{4}}_{\text{super-majority on } e} + \frac{1}{72} \times \underbrace{\frac{2-y}{4}}_{\text{otherwise}} \tag{2}$$

If he chooses e, the expected payoff is

$$u_y = \underbrace{\frac{1-y}{4}}_{\text{unanimity on } e} + 3 \times \underbrace{\frac{y}{4}}_{\text{super-majority on } n} + \underbrace{\left(\frac{1-y}{2} + \frac{y}{4}\right)}_{\text{super-majority on } e} + \frac{1}{72} \times \underbrace{\frac{1+y}{4}}_{\text{otherwise}} \tag{3}$$

However, (2) can be rewritten as $\frac{145}{144} + \frac{359}{288}y$, which is strictly larger than 1 for any $y \in [0, 1]$. Thus, we obtain that $y = 0$ and $u_y = 1.00694$.

(5) Consider player N, and suppose that the messages played in the previous period are e and w. Let u'_y refer to the expected continuation payoff in this case.

If he chooses e, then

$$u'_y = \underbrace{\frac{y\,(1-y)}{2}}_{\text{unanimity on } e} + \underbrace{\frac{1-y+y^2}{2}}_{\text{super-majority on } e} + \underbrace{\frac{y(1-y)}{2}}_{\text{super-majority on } w} + \frac{1}{72} \times \underbrace{\frac{1-y+y^2}{2}}_{\text{otherwise}}.$$

Given $y = 0$, we obtain $u'_y = 0.50694$.

(6) Consider player N. Let u'_z refer to the expected continuation payoff in this case.

If he chooses message, then

$$u_z = 3z^3 + 9(z^2 - z^3) + 3z^2(1-3z) + \frac{1}{72}\left[1 - z^2(6-11z)\right]$$

If he chooses any of the other messages, say e, then

$$u_z = z^2(1-3z) + 3z^3 + \left[2z^2(1-3z) + 2z(1-z)(1-3z) + 3z^3\right] + \frac{1}{72}\left[1 - z(2-5z+z^2)\right].$$

We therefore obtain $z = 0.13691$ and $u_z = 0.19915$.

Next, let us consider each player's incentives in $t = 1$, given the continuation payoffs computed above. First, suppose that player N plays message n. We summarize all the possible events and their likelihoods in $t = 1$ as well as the corresponding continuation payoffs in the first of two tables below. Second, suppose that player N plays any other action, say, e. The second table below summarizes all the possible events, their likelihoods and continuation payoffs.

A simulation exercise from these figures demonstrates that there exists a unique $q \in \left(0, \frac{1}{3}\right)$ that solves the indifference condition and it amounts to $q = 0.122713$. The equilibrium payoff to each player is 0.495797.

<u>N chooses n.</u>

outcome in $t = 1$	likelihood	continuation payoff
unanimity (on n)	q^3	3
super-majority on n	$3(q^2 - q^3)$	3
super-majority not on n	$3q^2(1 - 3q)$	1
majority on n	$9q^3 + 6q^2(1 - 3q) + 3q(1 - 3q)^2$	u_x
majority on e	$2q^3 + 2q^2(1 - 3q) + 2q(1 - 3q)^2$	u_x
majority on s	$2q^3 + 2q^2(1 - 3q) + 2q(1 - 3q)^2$	u_x
majority on w	$2q^3 + 2q^2(1 - 3q) + 2q(1 - 3q)^2$	u_x
tied-majority (on n)	$3[q^3 + 2q^2(1 - 3q)]$	u_y
complete disagreement	$2q^3 + 3q^2(1 - 3q) + (1 - 3q)^3$	u_z

<u>N chooses e.</u>

outcome in $t = 1$	likelihood	continuation payoff
unanimity (on e)	$q^2(1 - 3q)$	1
super-majority on n	q^3	3
super-majority on e	$3q^3 + 4q^2(1 - 3q) + 2q(1 - 3q)^2$	1
super-majority on s	$q^2(1 - 3q)$	1
super-majority on w	$q^2(1 - 3q)$	1
majority on n	$2q^2(1 - q)$	u_x
majority on e and n played by no-one	$2q^3 + 3q^2(1 - 3q) + (1 - 3q)^3$	u'_x
majority on e but n played by someone	$2q(1 - 2q)^2 + 4q^3$	u_x
majority on s and n played by no-one	$q(1 - 3q)^2 + q^2(1 - 3q) + q^3$	u'_x
majority on s but n played by someone	$q^3 + 2q^2(1 - 3q)$	u_x
majority on w and n played by no-one	$q(1 - 3q)^2 + q^2(1 - 3q) + q^3$	u'_x
majority on w but n played by someone	$q^3 + 2q^2(1 - 3q)$	u_x
tied-majority, not including n	$2q^3 + 2q^2(1 - 3q) + 2q(1 - 3q)^2$	u_y
tied-majority, including n	$2q^3 + q^2(1 - 3q)$	u'_y
complete disagreement	$3q^3 + q(1 - 3q)(1 - q)$	u_z

2. Incomplete networks

Star and kite networks The following construction is for the star network. It is straightforward to extend it to the kite network. Also, without loss of generality, suppose that $T = 3$. Consider the following strategies. Beliefs are Bayesian whenever possible.

- $t = 1$

  The hub, player E, mixes among the four messages with arbitrary probabilities. Each $J \neq E$ plays message j with probability p, each $k \neq j, e$ with probability q and message e with probability r (such that $p + 2q + r = 1$).

- $t = 2$ and $t = 3$

  If in $t = 1$ the other three players all played the same message (an "agreement") then, in both $t = 2$ and $t = 3$, E announces that message; otherwise, E announces two (arbitrary) different messages in $t = 2$ and $t = 3$. Each $J \neq E$ makes arbitrary announcements in $t = 2$ and $t = 3$.

- underlying game

  - If there was an agreement in $t = 1$ and he played as above in $t = 2, 3$, E plays the corresponding action with probability 1; if there was no agreement in $t = 1$ but he deviated from above by playing the same message, i, in $t = 2, 3$, E plays every $j \neq i$ each with probability $\frac{1}{3}$; otherwise, E plays e with probability 1.
  - If E announced the same message, i, in $t = 2, 3$ and he himself played i in $t = 1$, each $J \neq E$ plays i with probability 1;

    If E announced the same message, i, in $t = 2, 3$ but he himself did not play i in $t = 1$ and $i \neq j$, each $J \neq E$ plays j with probability 1;

    If E announced the same message, i, in $t = 2, 3$ but he himself did not play i in $t = 1$ and $i = j$, each $J \neq E$ plays e with probability 1;

    Otherwise, each $J \neq E$ plays j with probability 1.

To establish that the strategies constitute an equilibrium, note first that, in equilibrium, the indifference condition of each $J \neq E$ is given by

$$k_2 q^2 = k_1 pq = k_1 r^2$$

where the first term is the expected payoff from playing own favorite message, the second is the expected payoff from playing one of two other messages except for e and the final is the expected payoff from playing message e. It is straightforward to solve for the three probabilities:

$$p = \frac{k_2}{2k_1 + \sqrt{k_1 k_2} + k_2}, \ q = \frac{k_1}{2k_1 + \sqrt{k_1 k_2} + k_2}, \ r = \frac{\sqrt{k_1 k_2}}{2k_1 + \sqrt{k_1 k_2} + k_2}.$$

Since $k_2 > k_1$, this implies that $p > r > q$. Moreover, the probability of coordination on e (which is equal to r^3) is greater than that on any other action (equal to pq^2). It is straightforward to check that deviations are not profitable for E under any off-the-equilibrium beliefs.

Line network Slight modification to the strategies constructed for the star (kite) network above will deliver an analogous equilibrium for the line network. Consider the following strategies. Beliefs are Bayesian whenever possible.

- $t = 1$

  Players E and W, mix among the four messages with arbitrary probabilities. Each $J \in \{N, S\}$ plays message j with probability p, each of e and w with probability q and the remaining message with probability r (such that $p + 2q + r = 1$).

- $t = 2$

  Player E (W) plays the message played by N (S) in $t = 1$. Players N and S play arbitrarily.

- $t = 3$

  Player E (W) plays the message that he played in $t = 2$ if W (E) played the same message in $t = 2$; otherwise, he plays a different message. Players N and S play arbitrarily.

- underlying game

  – If both he and player W (E) played the same message in $t = 2$ and $t = 3$ and that message was played by N (S) in $t = 1$, player E (W) plays the corresponding action for sure;

    If both he and player W (E) played the same message in $t = 2$ and $t = 3$ but that message was not played by N (S) in $t = 1$, E (W) plays the message of N (S) in $t = 1$ for sure;

    Otherwise, he plays e (w) for sure.

– If E (W) plays the same message in $t = 2$ and $t = 3$ and that message is the message that he himself played in $t = 1$, N (S) plays the corresponding action for sure;

  If E (W) plays the same message in $t = 2$ and $t = 3$ but that message is not what he himself played in $t = 1$, N (S) plays an action that corresponds to neither his message in $t = 1$ nor the message of E (W) in $t = 2, 3$ for sure;

  Otherwise, he plays n (s) for sure.

To compute equilibrium mixing probabilities at $t = 1$, consider N. His indifference condition is:

$$k_2 r = k_1 q = k_1 p,$$

which implies that $p = q = \frac{3}{10}$ and $r = \frac{1}{10}$. Clearly, the probability of coordination on action e or w is higher than that on n or s.

Appendix II

Sample instructions: kite network with T = 2

Instructions

This is an experiment in the economics of decision-making. A research foundation has provided funds for conducting this research. Your earnings will depend partly on your decisions and partly on the decisions of the other participants in the experiments. If you follow the instructions and make careful decisions, you may earn a considerable amount of money.

At this point, check the name of the computer you are using as it appears on the top of the monitor. At the end of the experiment, you should use your computer name to claim your earnings. At this time, you will receive £5 as a participation fee (simply for showing up on time). Details of how you will make decisions will be provided below.

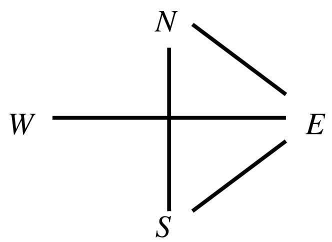
During the experiment we will speak in terms of experimental tokens instead of pounds. Your earnings will be calculated in terms of tokens and then exchanged at the end of the experiment into pounds at the following rate:

2 Tokens = 1 Pound

In this experiment, you will participate in 20 independent and identical (of the same form) rounds, each divided into two stages: a communication stage, which consists of 2 decision-turns, and an action stage, which consists of a single decision-turn. In each round you will be assigned to a position in a four-person network. In each decision-turn of a communication stage, you will be able to communicate with the other participants to whom you are connected in the network. That is, you will be able to send a message to the connected participants and receive messages from them.

Before the first round, you will be randomly assigned to one of the four network positions labeled *N*, *W*, *S*, or *E*. One fourth of the participants in the room will be designated as type-*N* participants, one fourth as type-*W* participants, one fourth as type-*S* participants and one fourth as type-*E* participants. Your type (*N*, *W*, *S*, or *E*) depends solely upon chance and will remain constant in all rounds throughout the experiment.

When you are asked to send your first message, the network and your type will be displayed at the top left hand side of the screen (see Attachment 1). It is also illustrated in the diagram below. A line segment between any two types indicates that the two types are connected and that they can communicate with each other: each can send a message to the other and receive a message from the other.



Note that in the network used in this experiment, type-*E* participants can communicate with all the other types (*N*, *W*, and *S*) and type-*W* participants can communicate only with type-*E*, while type-*N* participants can communicate with type-*E* and type-*S*, and type-*S* participants can communicate with type-*E* and type-*N*.

A decision round

Next, we will describe in detail the process that will be repeated in all 20 rounds. Each round starts by having the computer randomly form four-person groups by selecting one participant of type-*N*, one of type-*W*, one of type-*S* and one of type-*E*, per group.

The groups formed in each round depend solely upon chance and are independent of the groups formed in any of the other rounds. That is, in any group each participant of type-*N* is equally likely to be chosen for that group, and similarly with participants of type-*W*, type-*S* and type-*E*. Groups are formed by the computer.

Each round in a group consists of two stages: first, communication stage, and second, action stage. Your final earnings will depend only on what you choose and what others in your group choose in the action stage. Four actions, *n*, *w*, *s* and *e*, are available in the action stage. The communication stage that precedes the action stage involves each participant sending messages. Four messages are available in the communication stage, and they shall be labeled by the same letters, *n*, *w*, *s* and *e*, as the actions available in the action stage. A message may indicate your intended action in the subsequent action stage. However, you do not have to follow your message when it comes to making an action choice. We now describe each of these two stages in more detail.

A communication stage

The communication stage itself consists of two decision-turns. At the beginning of the first decision-turn, you will be asked to choose a message – *n*, *w*, *s* or *e*. You will see four boxes, each labeled with a possible message, at the bottom left hand side of the screen. When you are ready to make your decision, simply use the mouse to click on one of them. You will then see a small pop-up window asking you to confirm your decision (see Attachment 2).

Once everyone in your group has confirmed a decision, type-*E* participant in your group will receive the messages chosen by all the other types (type-*N*, type-*W*, and type-*S*) and type-*W* participant in your group will receive only the message chosen by type-*E*, while type-*N* participant in your group will receive the messages chosen by type-*E* and type-*S*, and type-*S* participants in your group will receive the messages chosen by type-*E* and type-*N*. For example, if you are type-*N* participant, you will be informed of which message each of type-*E* and type-*S* participants has chosen. This information is displayed at the middle right hand side of the screen (see Attachment 1). This completes the first of five decision-turns in the communication stage of this round.

This process will be repeated in the second decision-turn of the communication stage. Note again that when everyone in your group has made a decision in each decision-turn, your chosen message will be sent to each type participant in your group to whom you are connected. Likewise, you will receive the messages chosen by all the other type participants to whom you are connected.

An action stage

When the communication stage ends, each participant in your group will be asked to choose one action out of the four possible actions, *n*, *w*, *s*, or *e*, without knowing the action selected by each other. You will see four boxes, each labeled with a possible action, at the bottom left hand side of the screen (see Attachment 3). When you are ready to make your decision, simply use the mouse to click on one of them. This will end the action stage. When the action stage ends, the computer will inform everyone the choices of actions made by all the participants in your group and the earnings (see Attachment 4).

After you observe the results of the first round, the second round will start the computer randomly forming new groups of four participants. The process will be repeated until all the 20 independent and identical rounds are completed. At the end of the last round, you will be informed the experiment has ended.

<u>Earnings</u>

Your earnings in each round are determined solely by the action you choose and the actions the other participants in your group choose in the action stage. The messages you and other type participants have chosen in the preceding communication stage are irrelevant to earnings.

- If all the participants in your group choose action *n*, type-*N* participant in your group will receive 3 tokens and each of the other types (type-*W*, type-*S*, and type-*E*) in your group will receive 1 token.
- If all the participants in your group choose action *w*, type-*W* participant in your group will receive 3 tokens and each of the other types (type-*N*, type-*S*, and type-*E*) in your group will receive 1 token.
- If all the participants in your group choose action *s*, type-*S* participant in your group will receive 3 tokens and each of the other types (type-*N*, type-*W*, and type-*E*) in your group will receive 1 token.
- If all the participants in your group choose action *e*, type-*E* participant in your group will receive 3 tokens and each of the other types (type-*N*, type-*W*, and type-*S*) in your group will receive 1 token.
- Otherwise, that is, if all the participants in your group do not choose a common action, every participant in your group will receive 0 token.

For example, if type-*S* participant chooses action *s* and all the other types choose action *n*, every participant will receive 0 token. This information on earnings is displayed at the top right hand side of the screens in both the communication stage and action stage (see Attachment 1 and 3).

Your final earnings in the experiment will be the sum of your earnings over the 20 rounds. At the end of the experiment, the tokens will be converted into money. You will receive your payment as you leave the experiment.

<u>Rules</u>

Please do not talk with anyone during the experiment. We ask everyone to remain silent until the end of the last round.

Your participation in the experiment and any information about your earnings will be kept strictly confidential. Your payments receipt is the only place in which your name is recorded.

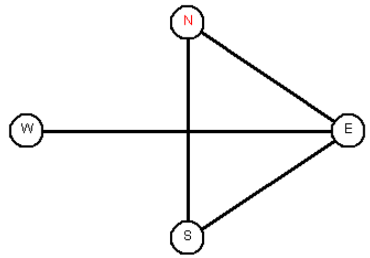
If there are no further questions, you are ready to start. An instructor will activate your program.

Attachment 1

Round

1 of 20

Stage 1 - Communication



You are a type- N participant

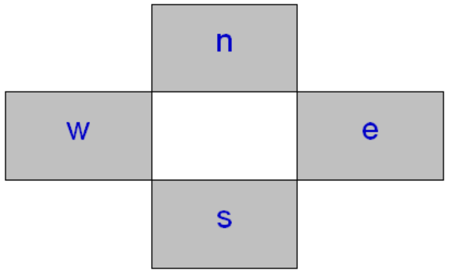
Payoffs in Stage 2

	N	E	S	W
All choose action n	3	1	1	1
All choose action e	1	3	1	1
All choose action s	1	1	3	1
All choose action w	1	1	1	3
Otherwise	0	0	0	0

Messages in Stage 1

Turn	N	E	S	W
1	s	s	e	?

Please send other participants connected to you a message which may indicate your intended action in Stage 2

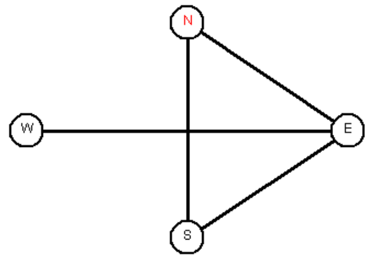


Attachment 2

Round

1 of 20

Stage 1 - Communication



You are a type- N participant

Payoffs in Stage 2

	N	E	S	W
All choose action n	3	1	1	1
All choose action e	1	3	1	1
All choose action s	1	1	3	1
All choose action w	1	1	1	3
Otherwise	0	0	0	0

Messages in Stage 1

Turn	N	E	S	W
1	s	s	e	?

Please send other participants connected to you a message which may indicate your intended action in Stage 2

Are you sure you wish to choose a message of n?

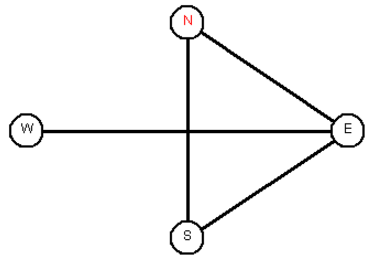
YES NO

Attachment 3

Round

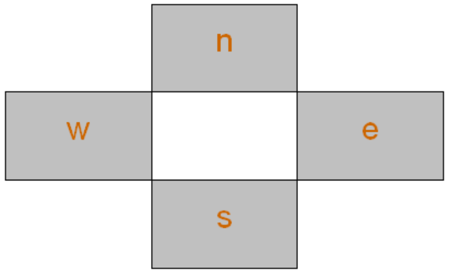
1 of 20

Stage 2 - Action



You are a type- N participant

Please choose your action



Payoffs in Stage 2

	N	E	S	W
All choose action n	3	1	1	1
All choose action e	1	3	1	1
All choose action s	1	1	3	1
All choose action w	1	1	1	3
Otherwise	0	0	0	0

Messages in Stage 1

Turn	N	E	S	W
1	s	s	e	?
2	n	e	n	?

Attachment 4

Round

1 of 20

You are a type-N participant. You chose the action n.

Action choices and payoffs of your group in this round are summarized below:

	N	E	S	W
Action	n	n	s	n
Payoff	0	0	0	0

Your total earnings so far are 0.

OK

Table 1. Frequencies of coordination

Network	T	Coord. freq.	# of obs
Complete	2	0.65	80
	5	0.70	100
Star	2	0.64	80
	5	0.73	80
Kite	2	0.56	80
	5	0.68	100
Line	2	0.28	80
	5	0.50	80
No communication		0.05	150

Chi-square nonparametric tests on coordination rates

		Complete		Star		Kite		Line		No com-munication
		2	5	2	5	2	5	2	5	
Complete	2	--	0.48	0.87	0.31	0.26	0.67	0.00	0.06	0.00
	5	--	--	0.37	0.71	0.06	0.76	0.00	0.01	0.00
Star	2	--	--	--	0.24	0.33	0.55	0.00	0.08	0.00
	5	--	--	--	--	0.03	0.51	0.00	0.00	0.00
Kite	2	--	--	--	--	--	0.11	0.00	0.43	0.00
	5	--	--	--	--	--	--	0.00	0.01	0.00
Line	2	--	--	--	--	--	--	--	0.01	0.00
	5	--	--	--	--	--	--	--	--	0.00
No communication		--	--	--	--	--	--	--	--	--

Notes: Each cell reports the *p* -value from nonparametric test on coordination rates between two treatments. A darker-shaded cell represents a pair-wise nonparametric test between T=2 and T=5 within a network; a lighter-shaded cell represents a pair-wise nonparametric test between two networks given T.

Table 2. Frequencies of coordinated actions

Network	T	Action *n*	*e*	*s*	*w*	# of obs. (p-value)
Complete	2	0.19	0.33	0.23	0.25	52 (0.25)
	5	0.24	0.27	0.24	0.24	70 (0.96)
Star	2	0.10	0.76	0.06	0.08	51 (0.00)
	5	0.19	0.45	0.19	0.17	58 (0.00)
Kite	2	0.18	0.56	0.16	0.11	45 (0.00)
	5	0.16	0.34	0.21	0.29	68 (0.05)
Line	2	0.27	0.27	0.18	0.27	22 (0.49)
	5	0.23	0.30	0.18	0.30	40 (0.25)
No communication	--	0.75	0.25	0.00	0.00	8 (0.00)

Note: A p-value is from the chi-square nonparametric test with null hypothesis that the action frequencies are uniformly distributed.

Table 3. Relation between last-period communication and coordination

Table 3A. Complete

Outcome	T = 2 Coord. freq.	T = 2 # of obs.	T = 5 Coord. freq.	T = 5 # of obs.
Unanimity	0.95	22	0.95	41
Super-majority	0.73	33	0.62	47
Majority	0.47	15	0.13	8
Tied-majority	0.00	8	0.00	2
Complete disagreement	0.00	2	0.50	2
Total	0.65	80	0.70	100

Table 3B. Star

Outcome		T = 2 Coord. freq.	T = 2 # of obs.	T = 5 Coord. freq.	T = 5 # of obs.
Unanimity		0.95	20	0.88	25
Super-majority	*NES/ NEW/ ESW*	0.66	32	0.86	35
	NSW	0.00	2	0.00	1
Majority	*NE/ EW/ ES*	0.40	20	0.38	13
	NS/ NW/ SW	1.00	1	0.00	2
Others		0.40	5	0.25	4
Total		0.64	80	0.73	80

Table 3C. Kite

Outcome		T = 2 Coord. freq.	T = 2 # of obs.	T = 5 Coord. freq.	T = 5 # of obs.
Unanimity		0.89	9	1.00	33
Super-majority	*NES/ NEW/ ESW*	0.89	28	0.74	38
	NSW	--	0	0.00	1
Majority	*NE/ EW/ ES*	0.50	18	0.33	15
	NS/ NW/ SW	0.00	9	0.00	3
Others		0.19	16	0.10	10
Total		0.56	80	0.68	100

Table 3D. Line

Outcome		T = 2 Coord. freq.	T = 2 # of obs.	T = 5 Coord. freq.	T = 5 # of obs.
Unanimity		1.00	11	1.00	24
Super-majority	*NEW/ ESW*	0.35	20	0.64	22
	NSW/ NES	0.33	6	0.00	2
Majority	*EW*	0.50	4	0.00	2
	NW/ ES/ NE/ SW	0.00	22	0.00	10
	NS	0.00	3	0.50	2
Others		0.00	14	0.06	18
Total		0.28	80	0.50	80

Table 4. Frequencies of unanimity and super-majority

Network	T	Time (t) 1	2	3	4	5	Coord. freq.
Complete	2	0.15 (--)	0.69 (0.54)	--	--	--	0.65
	5	0.09 (--)	0.42 (0.33)	0.61 (0.19)	0.73 (0.12)	0.88 (0.15)	0.70
Star	2	0.29 (--)	0.65 (0.36)	--	--	--	0.64
	5	0.13 (--)	0.36 (0.24)	0.51 (0.15)	0.60 (0.09)	0.75 (0.15)	0.73
Kite	2	0.08 (--)	0.46 (0.38)	--	--	--	0.56
	5	0.05 (--)	0.16 (0.11)	0.26 (0.10)	0.41 (0.15)	0.71 (0.30)	0.68
Line	2	0.05 (--)	0.39 (0.34)	--	--	--	0.28
	5	0.04 (--)	0.15 (0.11)	0.25 (0.10)	0.39 (0.15)	0.58 (0.19)	0.50

Notes: (1) A number in parentheses is the marginal change from period *t-1* to period *t*. (2) For incomplete networks, we consider only super-majority including the hub(s).

Table 5A. Behavior of the hub

Network	T	non-switching	switching
Star	2	0.91 (0.78)	0.09 (0.57)
	5	0.89 (0.54)	0.11 (0.44)
Kite	2	0.85 (0.72)	0.15 (0.75)
	5	0.41 (0.73)	0.59 (0.68)

Table 5B. Frequencies of non-switching by the hub after initial disagreement

Network	T	Freq.
Star	2	0.81 (21)
	5	0.87 (30)
Kite	2	0.69 (39)
	5	0.36 (61)

Table 5C. Frequencies of coordinated actions conditional on non-switching / switching

Network	T	Switching	N	E	S	W	Total
Star	2	No	4	38	3	4	49
		Yes	1	1	0	0	2
	5	No	10	25	10	9	54
		Yes	1	1	1	1	4
Kite	2	No	8	25	4	3	40
		Yes	0	0	3	2	5
	5	No	3	16	2	2	23
		Yes	8	7	12	18	45

Table 6. Behavior of the periphery: $m_I^t = m_H^{t-1}$

			Time *(t)*				
Message in *t-1*	Network	T	2	3	4	5	6
$m_I^{t-1} \neq m_H^{t-1}$	Star	2	0.50 (157)	0.65 (91)	--	--	--
		5	0.27 (180)	0.16 (140)	0.15 (121)	0.32 (107)	0.70 (79)
	Kite	2	0.18 (67)	0.64 (55)	--	--	--
		5	0.13 (80)	0.10 (80)	0.11 (72)	0.62(53)	0.79 (24)
	Line	2	0.40 (126)	0.44 (75)	--	--	--
		5	0.18 (141)	0.13 (117)	0.24 (102)	0.44 (77)	0.58 (53)
$m_I^{t-1} = m_H^{t-1}$	Star	2	0.99 (83)	0.99 (149)	--	--	--
		5	1.00 (60)	0.98 (100)	0.99 (119)	1.00 (133)	0.98 (161)
	Kite	2	1.00 (13)	1.00 (25)	--	--	--
		5	0.95 (20)	1.00 (20)	1.00 (28)	1.00 (47)	1.00 (76)
	Line	2	1.00 (34)	1.00 (85)	--	--	--
		5	0.89 (19)	0.93 (43)	1.00 (58)	0.99 (83)	1.00 (017)

Notes: (1) A number in parentheses is the number of observations. (2) *I* is a periphery - *N/S/W* in star, *W* in kite, *N/S* in line. *H* is the hub that *I* is linked to - *E* in star and kite, *E/W* in line. (3) Message or action of periphery *I* (hub *H*) in period *t* is denoted by m_I^t (m_H^t). (4) The action stage is referred to as $t = T+1$. $T = 2, 5$.

Table 7. Behavior of players N and S in the kite network

($I \neq J = N$ or S)			Time (t)				
Message in (t-1)	Behavior in t	T	2	3	4	5	6
$m_I^{t-1} = m_J^{t-1} \neq m_E^{t-1}$	$m_I^t = m_I^{t-1}$	2	0.93 (14)	0.71 (14)	--	--	--
		5	0.87 (30)	0.96 (24)	0.93 (28)	0.86 (28)	0.72 (18)
	$m_I^t = m_E^{t-1}$	2	0.07 (14)	0.29 (14)	--	--	--
		5	0.03 (30)	0.04 (24)	0.00 (28)	0.14 (28)	0.28 (18)
$m_I^{t-1} \neq m_J^{t-1} \neq m_E^{t-1}$	$m_I^t = m_I^{t-1}$	2	0.65 (84)	0.28 (32)	--	--	--
		5	0.90 (124)	0.84 (124)	0.82 (94)	0.58 (64)	0.42 (26)
	$m_I^t = m_E^{t-1}$	2	0.30 (84)	0.72 (32)	--	--	--
		5	0.03 (124)	0.09 (124)	0.05 (94)	0.30 (64)	0.54 (26)
$m_I^{t-1} \neq m_J^{t-1} = m_E^{t-1}$	$m_I^t = m_I^{t-1}$	2	0.18 (28)	0.03 (30)	--	--	--
		5	0.55 (22)	0.67 (12)	0.79 (19)	0.63 (24)	0.24 (33)
	$m_I^t = m_E^{t-1}$	2	0.79 (28)	0.97 (30)	--	--	--
		5	0.45 (22)	0.25 (12)	0.16 (19)	0.33 (24)	0.73 (33)

Notes: (1) Player I's message or action in t is denoted by m_I^t. (2) A number in parentheses is the number of observations.

Table 8. Behavior in the first period: complete, line and no-communication treatments

Complete, T = 2		Message in $t = 1$			
		n	*e*	*s*	*w*
Type	*N*	0.43	0.19	0.18	0.21
	E	0.09	0.75	0.08	0.09
	S	0.14	0.10	0.65	0.11
	W	0.09	0.04	0.10	0.78

Complete, T = 5		Message in $t = 1$			
		n	*e*	*s*	*w*
Type	*N*	0.62	0.19	0.09	0.10
	E	0.05	0.85	0.04	0.06
	S	0.08	0.09	0.64	0.19
	W	0.13	0.13	0.21	0.53

Line, T = 2		Message at t = 1			
		n	*e*	*s*	*w*
Type	*N*	0.61	0.16	0.06	0.16
	E	0.13	0.60	0.13	0.15
	S	0.19	0.14	0.61	0.06
	W	0.15	0.03	0.05	0.78

Line, T = 5		Message at t = 1			
		n	*e*	*s*	*w*
Type	*N*	0.80	0.06	0.06	0.08
	E	0.06	0.65	0.13	0.16
	S	0.08	0.06	0.84	0.03
	W	0.09	0.09	0.11	0.71

No communication		Action			
		n	*e*	*s*	*w*
Type	*N*	0.47	0.24	0.19	0.09
	E	0.25	0.47	0.20	0.07
	S	0.34	0.23	0.33	0.10
	W	0.25	0.37	0.13	0.25

Table 9. Frequencies of messages under agreement in the last period of communication

		message				
		n	*e*	*s*	*w*	# of obs.
Complete	2	0.15	0.25	0.25	0.35	55
	5	0.24	0.25	0.26	0.25	88
Line	2	0.20	0.26	0.17	0.37	35
	5	0.20	0.27	0.18	0.35	49

Note: Agreement in the complete network is defined as either unanimity or super-majority; agreement in the line network refers to a consensus between E and W.

Figure 1. Communication Networks

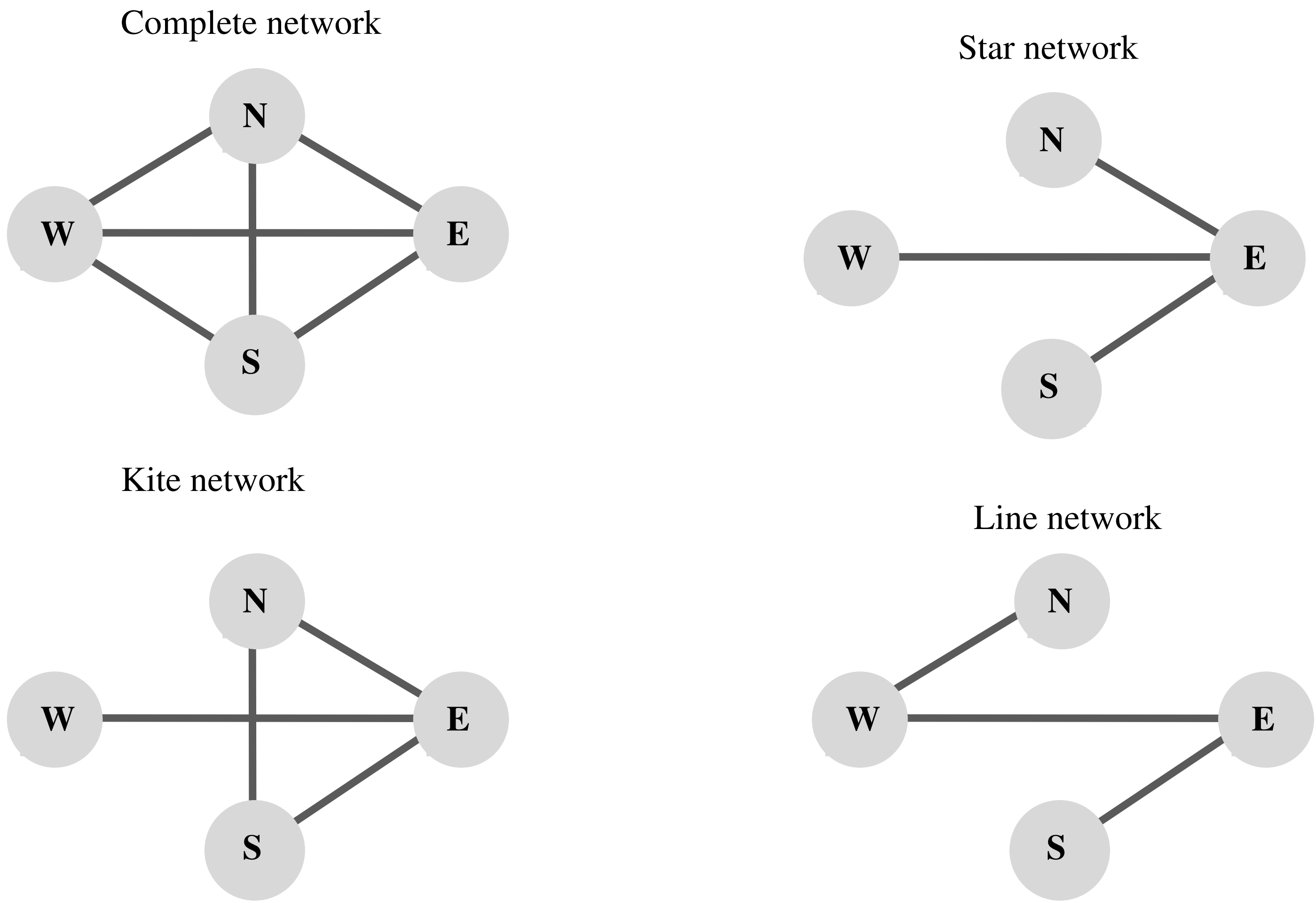


Figure 2A. Frequencies of Coordinated Actions in the Networks with T = 2

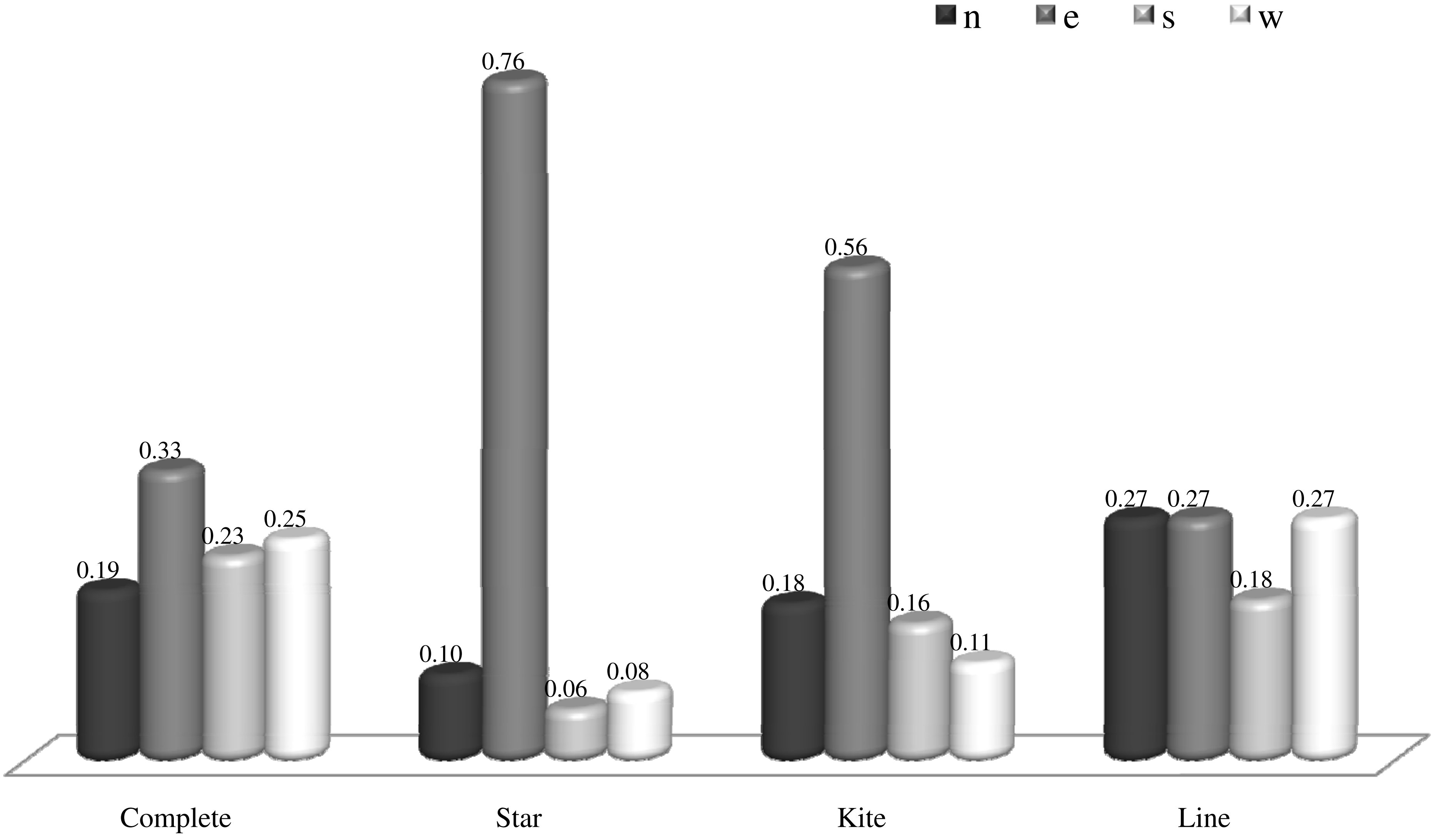


Figure 2B. Frequencies of Coordinated Actions in the Networks with T = 5