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Network Experiments

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Abstract

This paper provides a survey of recent experimental work in economics focussing on social and economic networks. The experiments consider networks of coordination and cooperation, buyer-seller networks, and network formation.

1 Introduction

In recent years, economic research on networks has increased tremendously. By now there exists substantial evidence emphasizing the important role of networks on social and economic outcomes. Famous examples have pointed out network effects on job search (Holzer 1987, Montgomery 1991), trade (Lazerson 1993, Nishiguchi 1994), the granting of credit (McMillan and Woodruff 1999), mutual insurance (Fafchamps and Lund 2001) and welfare participation (Bertrand, Luttmer, and Mullainathan 2000).[1] While theoretical research on economic networks has received a lot of interest as well (see references in the subsequent sections), until very recently no experimental work on networks in economics existed. The number of network experiments

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[1]Outside economics the role of networks and social structure has earlier been emphasized by anthropologists (e.g., Lévi-Strauss 1963) and sociologists (e.g., Granovetter 1974).

is still very small but the literature is starting to grow. The aim of this paper is to provide an overview of existing experimental work and to suggest paths for interesting future research in this area.

Laboratory experiments present a useful and powerful technique to analyze economic questions. The main advantage of experiments lies in the ability to control variables (such as, e.g., costs, benefits, information, and timing) that possibly influence individual and aggregate behavior, something which is very hard and sometimes even impossible to achieve in the field. Together with theoretical models, in particular models based on game theory that provide the language for an exact formulation of hypotheses, controlled experiments are a key element for economics to become an empirical science. And, as one of the major contributors to economic theory writes in a recent paper, "moving from arm-chair theorizing to controlled laboratory experiments may be as important a step in the development of economics as it once was for the natural sciences to move from Aristotelian scholastic speculation to modern empirical science" (Weibull 2001).

Before experimental economists discovered networks, other social scientists already started to investigate network effects in various experimental settings. Perhaps the earliest network experiments are the "MIT experiments" of the social psychologist Alex Bavelas and his colleagues in the early 50's (Bavelas 1950, Leavitt 1951). In these experiments a group of individuals is assigned a problem to be solved. Typically, for this problem each individual receives a card showing different symbols. Individuals in a group have only one symbol in common and the problem is to discover that common symbol. Individuals can communicate by passing written messages to each other. Communication can only flow along an exogenously imposed network. Bavelas and his colleagues consider four different communication networks: the chain, the circle, the star, and the "Y". They find that groups who communicate via the star or the "Y" are fastest in solving the given problem. Moreover, they use the least number of messages and also make the fewest errors. On the other hand, individuals in the circle and the chain report highest average satisfaction during the experiment. Only the individual that acts as the center in the star reports higher satisfaction. As a consequence of these experiments Bavelas *et al.* call attention to the role of structural centrality for group efficiency. In subsequent years further studies have been conducted to investigate the effect of centrality on communication and organization networks (see Shaw 1964 for a critical review). Freeman (1979, 1980) clarifies the terminology by defining and testing the role of three different concepts of structural centrality.

Clearly, sociologists have long been interested in the role of networks, as well. Early experiments were conducted by Cook and Emerson (1978) and Cook, Emerson, Gilmore, and Yamagishi (1983), who are interested in the relation of power and social structure in exchange networks (see also the related theoretical work of Markovsky, Willer and Patton 1988). Recent articles by Bienenstock and Bonacich (1993, 1997) incorporate game theoretic concepts into the discussion.

In the subsequent sections I give an overview of present experimental work in economics focusing on networks. It seems convenient to organize the papers into four different categories, each of which shall be reviewed in a separate section. Section 2 starts with coordination networks. Section 3 and section 4 contain a discussion of cooperation networks and buyer-seller networks, respectively. Section 5 surveys experimental work on network formation. Clearly, this categorization is not the only one possible. Some of the papers that are presented in one section contain elements that are discussed in some of the other sections. Yet, I think that the categorization is helpful in organizing the present literature. In each section I first give a short overview of the theoretical work and then describe the experiments that have been conducted in the particular area.[2]

2 Coordination networks

2.1 Theory

Seminal work by Kandori, Mailath, and Rob (1993) and Young (1993) has triggered a lot of interest in the question of equilibrium selection in coordination games. Important research concerns the impact of different network structures on equilibrium selection and, if players can choose their network partners themselves, whether players will form networks that lead to play of the efficient Nash equilibrium in the coordination game.

Ellison (1993) and Morris (2000) analyze the role of local interaction networks for the spread of particular strategies in 2×2 coordination games, showing, e.g., how play converges to the risk-dominant equilibrium if players are located on a circle and interact with their two nearest neighbors. Similarly, convergence to the risk-dominant equilibrium is proven by Blume (1993) and Kosfeld (2002) for a population of players located on a d-dimensional lattice.

[2] I have included all experimental network papers that I know of. I am happy to learn of any other paper that is not yet considered in this survey.

In contrast, Ely (2002) and Bhaskar and Vega-Redondo (2002) show that once players are allowed to choose their partners themselves the situation looks very different. They introduce a number of locations where players can meet and play the coordination game with each other. Thus, at any time, players choose both a location and a strategy in the game. Under these conditions it is shown that risk dominance looses its selection force and that the population is most likely to coordinate on the efficient equilibrium. The reason is intuitive. Since players can freely choose their interaction partners, they are able to find partners that play the efficient equilibrium strategy and at the same time can avoid players that play the inefficient strategy. That the latter condition, i.e., the ability to avoid bad matches, is crucial, is emphasized by Mailath, Samuelson, and Shaked (2001), as well.

Since migration is cost free in these models, an interesting and important question is what equilibrium will be selected when migration or the formation of links is costly. Goyal and Vega-Redondo (2000) present a first theoretical approach in this direction. They find that the cost of a link to another player plays a decisive — and somewhat counterintuitive — role for the selection of equilibrium. Only if costs are high enough, players coordinate on the efficient Nash equilibrium. If, however, costs are low the risk-dominant equilibrium is selected. Droste, Gilles, and Johnson (2000) consider a similar stochastic learning model. In their set-up players are located on a circle where they can form links to other players. Links to more distant players are assumed to be more costly. It is shown that, while in the medium run coexistence of both equilibrium strategies is possible, in the long run the risk-dominant equilibrium is selected.

2.2 Experiments

There exists a large experimental literature on coordination games (see, for example, Ochs 1995 for a review). The first experiment that considers the role of networks for coordination games, along the lines discussed above, is presented by Keser, Ehrhart, and Berninghaus (1998). In this experiment, the authors study the impact of local interaction as analyzed by Ellison (1993) and Morris (2000). They implement two different treatments. In the local-interaction treatment groups of eight players each interact around a circle. Players that are located next to each other play a coordination game for 20 periods. In this treatment Keser *et al.* find that play converges to the risk-dominant Nash equilibrium, as it is predicted by the theory. In contrast, once players interact in isolated groups of size three, which equals the neighborhood size in the local-interaction treatment, they find that play converges to the efficient Nash equilibrium. This finding is compatible with a similar experimental result of Van Huyck, Battalio, and Beil (1990) on coordination in small groups. In their second paper, Berninghaus, Ehrhart, and Keser (2002) put their result in a more general framework. In particular, they (i) modify the payoff function in the network-coordination-game, reducing the riskiness of the efficient Nash equilibrium, and (ii) vary the neighborhood structure that determines the way in which players locally interact. With regard to (i) they find that if the efficient Nash equilibrium becomes less risky, also populations that locally interact on a circle converge to efficient play in most of the cases. Varying the structure of the neighborhood, however, generates a converse effect. Precisely, in order to address point (ii) Berninghaus *et al.* compare two treatments, where in both treatments each player locally interacts with his four nearest neighbors. In one treatment players are located on a circle while in the second treatment players are located on a two-dimensional lattice.[3] Thus, the size of a player's neighborhood is kept constant across treatments and only the neighborhood structure differs. Given this experimental design, the authors find that play is more likely to converge to the risk-dominant equilibrium if players interact on the lattice than if they interact on the circle. This result is particularly interesting since subjects had exactly the same instructions in both treatments, i.e., they were not informed about the precise neighborhood structure of the population. One possible explanation the authors offer is the following: in the lattice treatment individual play is observed to be more changing than in the circle treatment. In consequence, risk dominance as an individual motive has more power in the lattice treatment than in the circle treatment. These findings offer an exciting starting point for further experimental (and theoretical) studies.

The local-interaction hypothesis is also tested in a recent preliminary experiment by Corbae and Duffy (2002). They look at groups of four players that are endowed with a network structure of either global interaction (the complete network), local interaction (the circle), or "marriage interaction". In the latter case the population is split into two isolated pairs of players, who interact with each other. Independent of the network, in each group subjects play ten periods of a coordination game, where the efficient Nash equilibrium is also risk-dominant. With the exception of one group, play is observed to converge to the efficient equilibrium. After these ten periods

[3] In fact, players interact on a torus, which, similar to the circle, has no boundaries.

subjects face a new game that differs from the previous game only with respect to the off-equilibrium payoff of the efficient Nash equilibrium strategy, which renders the inefficient Nash equilibrium risk-dominant. This game is played for ten periods. The hypothesis is that if no player is forced to play the inefficient equilibrium strategy, players will keep coordinating on the efficient equilibrium irrespective of the underlying interaction structure. Given the observations in the experiment (two groups for each network), this hypothesis is confirmed. Yet, if a single player in the group is forced to play the inefficient strategy, the hypothesis is that convergence to the inefficient equilibrium will be observed in the local- and in the marriage-interaction treatment but less so in the global-interaction treatment. Again, this hypothesis is confirmed by the data.

Corbae and Duffy also address the question what network will be formed if players can choose the network themselves. They again consider groups of four subjects who first interact on an exogenously imposed network structure for an initial phase of five periods. The network structure is either a global-, a local-, or a marriage-interaction network. Subjects play the same coordination game as in the second part of the exogenous-network treatment described before. After this initial phase, subjects can freely decide with whom of the other three subjects they want to interact in the subsequent periods. If two subjects mutually agree to interact, a link is formed between the two subjects.[4] For the next five periods all subjects that are directly linked play the coordination game. This procedure is repeated four times. So far, the analysis in the paper is still preliminary. Basically, no stable network structure seems to emerge. Perhaps the main finding is that groups starting with a network of marriage interaction show a high tendency to form the same network also in later periods. Clearly, further investigation of the data but also more experimental evidence is needed.

Cassar (2002) compares convergence to equilibrium across three different network structures: a local interaction network, a random network and a "small-world" network.[5] Small-world networks are obtained by starting from a circle and rewiring each link with probability p. A random network is a small-world network that is obtained by rewiring each link with probability 1. Intuitively, for intermediate p, small-world networks possess the nice feature of having a substantial degree of clustering, i.e., a large overlap of

[4]This assumption is based on the notion of pairwise stability defined by Jackson and Wolinsky (1996). See the section on network formation in this paper.

[5]Small-world networks are introduced by Watts and Strogatz (1998), see also Watts (1999).

neighborhoods, and yet only short paths connecting any two individuals in the network. In contrast, random networks have short connecting paths and low clustering, whereas the circle has high clustering but also long connecting paths. Generally, high clustering implies that interaction in the network resembles interaction in a closed group. On the other hand, short connecting paths suggest that contagious behavior can spread more easily.

In the experiment, Cassar considers groups of size 18, each group being connected according to one of the three network structures. In every group, subjects who are connected with each other play around 80 periods of a coordination game, where risk dominance and efficiency of equilibria conflict. The results show that in the small-world network subjects almost always converge to the efficient Nash equilibrium, while convergence is less likely (although still above 60 percent) in the other networks. Moreover, convergence to the efficient equilibrium is fastest in the small-world network, as well. These findings are consistent with the network effects suggested above.

Many questions concerning coordination networks remain still to be explored. For example, in order to test and better understand the importance of endogenous network formation on equilibrium selection it would be interesting to take the models of Ely (2002) and Bhaskar and Vega-Redondo (2002) into the laboratory. Similarly, the predictions of Goyal and Vega-Redondo (2000) and Droste, Gilles, and Johnson (2000) offer interesting theoretical benchmarks for empirical research. As the focus has been on theoretical modeling so far, there exists a wonderful collection of game theoretic predictions, but only few of them have been tested.

3 Cooperation networks

3.1 Theory

Eshel, Samuelson and Shaked (1998) show that cooperation in the prisoners' dilemma game can survive if players in a population locally interact with each other and adaptation is driven by imitation of successful behavior. The crucial effect of local interaction in this model is that it allows cooperative players to cluster together. The idea is the following. Since the positive externalities from cooperation are locally restricted, the interaction network reduces the possibility for other (more distant) players to exploit cooperation. In consequence, cooperators being surrounded by other cooperators can earn higher payoffs than defectors who are primarily surrounded by other defectors. Together with imitation this gives cooperation a chance to survive.

Related work include Nowak and May (1992) and Kirchkamp (2000).

Huck and Kosfeld (2001) use a similar local interaction framework to show how punishment of defection can survive and sustain cooperation in the prisoners' dilemma game. In their model some players in the population are so-called "social controllers" who punish defection by any neighbor. The effect of punishment is that first, it may deter defection, and second, it may induce other players to become social controllers, as well. The latter effect is called "socialization". Huck and Kosfeld show that if the socialization effect is strong enough, a condition which turns out to be relatively easy to be fulfilled, punishers can survive in the population. A crucial driving force behind this result is the fact that neighborhoods overlap in the given network structure. This allows punishment to diffuse in the population, similar to a contagion process (cf. Morris 2000). Finally, Huck and Kosfeld show that if punishers survive, they can generate a large degree of cooperation.

A recent theoretical paper considering endogenous cooperation networks is Vega-Redondo (2002), who studies the formation of networks among players bilaterally involved in infinitely repeated prisoners' dilemma games. In addition to specifying which pairs of players in the population play the game, in the model of Vega-Redondo a network also determines how strategic information diffuses among the players and how cooperation opportunities of the players are found. Assuming that payoffs in the prisoners' dilemma game fluctuate over time, Vega-Redondo analyzes the notion of pairwise-stable cooperation networks, where, intuitively, two players are directly connected with each other only if both players have an incentive to use the connection for cooperation in the prisoners' dilemma game. The main results are that players can sustain a dense social network, i.e., a network with sufficiently many individual connections, only if payoff volatility is not too high. Moreover, higher payoff volatility increases the cohesiveness of the network, i.e., the average distance between two players in the network declines as payoffs fluctuate more strongly.

3.2 Experiments

Although the experimental literature on cooperation in prisoners' dilemma games is extensive, there are only few recent papers considering the role of networks on cooperation. These are Kirchkamp and Nagel (2001), Cassar (2002) and Riedl and Ule (2002).

Kirchkamp and Nagel (2001) are interested in the prediction of Eshel *et al.* (1998) showing that cooperation can be sustained by local interaction and imitation. They consider a similar experimental design as Keser *et al.* (1998), which consists of two treatments. In the first treatment 18 subjects interact around a circle, each subject playing the prisoners' dilemma game with his four nearest neighbors, i.e., two neighbors to the left and two neighbors to the right. In the second treatment subjects interact in isolated groups of size five. Subjects play 80 periods in every treatment. In each period subjects observe the strategies and payoffs of each of their interaction partners. They must use the same strategy against all partners.

Different from the theoretical prediction, which says that there should be more cooperation in the local interaction treatment as subjects can learn from neighbors, Kirchkamp and Nagel find that cooperation rates are higher if subjects interact in isolated groups than if they locally interact on a circle. While initially, cooperation rates are close to 30 percent in both treatments, they decline to below five percent in the local interaction treatment. In contrast, cooperation rates stay at about the same level in the group treatment. This result clearly contradicts the theoretical prediction.

Cassar (2002) reports a similar decline in cooperation for the local interaction network, the small-world network, and the random network. She finds no major differences between these networks.

A possible explanation for the instability of cooperation in these networks is that subjects do not learn the way it is assumed by models of imitation. Indeed, Kirchkamp and Nagel find that in both treatments learning is not driven by imitation of neighbors' successful strategies, but mainly by positive reinforcement of one's own successful strategies. Hence, the main mechanism which makes cooperation survive on the circle but not in isolated groups does not seem to be at work in the laboratory. This alone, however, does not explain why subjects cooperate more in the group treatment, since the success, and hence the reinforcement of one's own strategy to cooperate should be the same (namely, zero) in both treatments. Yet, the surprising and interesting finding is that the strategy to cooperate increases one's own payoff in groups but not on the circle. Subjects seem to interact more in a reciprocal manner, i.e., they cooperate more if others cooperate, when they interact in isolated groups, than if they interact in locally overlapping groups of the same size. So far it remains unclear what precisely generates this result, whether it is some sort of strategic reasoning that plays a role, as suggested by Kirchkamp and Nagel, or other more psychological factors. It thus presents an interesting problem for future research.

The experiment of Riedl and Ule (2002) considers a different question. They are interested in endogenous network formation when players play a repeated prisoners' dilemma game, as, e.g., studied in the model of Vega-Redondo (2002). Riedl and Ule take groups of size six. In the control treatment of their experiment the network structure is exogenously fixed to the complete network, i.e., each subject plays the prisoners' dilemma game against every other group member. In the other treatments subjects decide whether to form links with other group members. A link is established if both parties agree to form a link (pairwise stability, cf. Jackson and Wolinsky 1996). Links are cost free. Each pair that is linked plays the prisoners' dilemma game. If some party rejects a link both parties earn an outside-option payoff. Subjects have to choose the same strategy against all partners. Every treatment consists of 60 periods of play.

The analysis presented in Riedl and Ule (2002) is still preliminary. However, some interesting results can already be summarized. First, cooperation rates are significantly higher in the endogenous-network treatments compared to the exogenous-network treatment. While initially, cooperation rates are around and beyond fifty percent in all treatments, cooperation declines if the network is fixed, whereas cooperation remains stable almost until the end if subjects can choose their partners themselves. Only in the final five periods cooperation decreases also in the endogenous-network treatments. Second, cooperation rates are highest if the outside-option payoff lies between the Nash-equilibrium and the cooperation payoff in the prisoners' dilemma game and subjects can observe the strategies of all other subjects in the group.[6] Assuming that some of the subjects are reciprocators, who cooperate if others cooperate as well, this suggests that the value of the outside option might serve as a signaling device for cooperative play. Third, cooperators are more likely to propose links to subjects who cooperated in the previous period than to previous-period defectors. This holds, even if the outside-option payoff is lower than the Nash-equilibrium payoff, i.e., when exclusion of defectors is costly. This result calls to mind an interesting finding of Ehrhart and Keser (1999), who study a public goods experiment where subjects have the possibility to change groups. They observe that the more cooperative subjects are on the run from the less cooperative subjects who follow the former around.

The results of Riedl and Ule clearly show that the fact whether the interaction network is exogenous or endogenous plays an important role for the degree of cooperation in prisoners' dilemma like situations. In particular, the possibility to exclude players who defect, even if this is costly, turns out to be

[6] Hauk and Nagel (2001) find a similar increase in cooperation rates in a related prisoners' dilemma experiment with the possibility of partner choice. In this experiment, however, no networks are considered.

a powerful instrument having striking effects on behavior. It is illuminating to compare this finding to a recent experiment by Brown, Falk, and Fehr (2002), who do not study network formation explicitly, but allow subjects to form bilateral relations in a two-person incomplete contract setting. They also find that the threat to terminate a relation represents a powerful discipline device, which induces partners to cooperate and consequently enhances efficiency.

4 Buyer-seller networks

4.1 Theory

Buyer-seller networks represent an area where both theoretical and experimental research in economics has been initiated recently.

Kranton and Minehart (2001) are interested in the individual motives of buyers and sellers to form particular network structures, as documented, e.g., in the Japanese electronics industry (Nishigushi 1994) and the Italian garment industry (Lazerson 1993). In particular, they ask what may lead buyers and sellers to establish links to multiple trading partners, and whether these networks can be expected to be efficient.

To answer these questions they consider a number of buyers and sellers, where each seller has an indivisible object for sale and buyers have i.i.d. random valuations for the object. A buyer can purchase from a seller if and only if the two are linked. Links are established by the buyers, who face costs for these links.[7] Transactions and prices are determined by an English, i.e., ascending-bid, auction. Buyers drop out of the bidding as the price exceeds their valuation. This process continues until demand equals supply. Kranton and Minehart show that competition generates an efficient allocation of goods in the network. Furthermore, prices reflect the link pattern in the sense that a buyer's profit equals the marginal social value of his participation in the network. From this it follows that efficient network structures are always an equilibrium outcome.

The model of Kranton and Minehart (2001) emphasizes two reasons why buyer-seller networks may emerge, one economic, the other strategic. First, networks may allow buyers and sellers to pool uncertainty in demand, which in the present model is caused by buyers' random valuations. Second, multiple links of a trader can enhance the competitive position of this trader.

[7] Jackson (2001) generalizes the model such that links are costly to buyers and sellers.

Network effects on competition are also addressed in the network model of Corominas-Bosch (1999). However, different from the model of Kranton and Minehart (2001), in this model prices are determined by a bargaining process rather than an English auction, and a buyer's valuation of the seller's good is certain. Again, a link between two trading partners is necessary for possible transaction. Consequently, if an individual has several links, he has several possible partners he can trade with. Thus, the network structure directly determines the bargaining power of individual players.

Bargaining follows a variation of the Rubinstein alternating-offer protocol. In the first period each seller calls out a price. Buyers then simultaneously choose to accept at most one of the prices offered by a seller to whom they are linked, with ties broken randomly. If a buyer and a seller trade their links are removed from the network. In the next period the situation reverses and buyers call out prices, which are then accepted or rejected by the sellers connected to them. This process repeats itself until all remaining buyers and sellers are not linked to each other. Future periods are discounted according to a common discount factor.

Corominas-Bosch shows that depending on the given network structure the subgame-perfect equilibrium of the bargaining game has the following properties. If the network is "competitive" the short side of the market receives all surplus. For example, if there is only one buyer who is linked to two sellers, competition between the sellers will reduce the price such that the buyer extracts all surplus. This is reversed for a single seller who is linked to two buyers. If, however, the network is "even", i.e., the number of buyers and sellers linked to each other is the same, traders split the surplus evenly. In the case of a single seller linked to a single buyer this result corresponds exactly to the Rubinstein bargaining model. Corominas-Bosch then shows that any network can be decomposed into a union of subnetworks that are either competitive or even, plus some extra links. Furthermore, subgame-perfect equilibrium outcomes of the bargaining game are such that all the surplus is given to the short side of the market in every competitive subnetwork, while the surplus is divided evenly in every even subnetwork.

4.2 Experiments

The model of Corominas-Bosch (1999) has recently been tested by Charness, Corominas-Bosch, and Frechette (2001), who are particularly interested in the predictive power of the subgame-perfect equilibrium outcome in competitive versus even buyer-seller networks. In the initial phase of their experiment subjects interact on either one of two different network structures: a three-player network, where a single buyer is connected to two sellers, or a four-player network, where two buyers and two sellers are each connected to each other. The three-player network is competitive whereas the four-player network is even. In both networks subjects are engaged in alternating bargaining over five to six rounds. Sellers start offering a proposal to divide 2500 with any of their linked buyers, who then simultaneously decide to accept at most one of the proposals. If a transaction is made, the corresponding pair of a buyer and a seller is removed from the network. The game proceeds to the second round if any links remain. In the second round buyers offer a division of 2400 to all of their linked sellers, who choose to accept or not to accept any of these offers. If needed, a third round is implemented, etc. A coin is flipped to determine whether bargaining ends after five or six rounds. All unmatched subjects receive 200. This bargaining protocol is repeated for four periods with subjects' roles reversed after each period.

After the fourth period the second phase of the experiment begins, in which the two separate networks are merged to obtain a single seven-player network. This is done by adding a link either from the short (i.e., buyer) side or from the long (i.e., seller) side of the competitive network to the corresponding other side of the even network, respectively. If the two networks are connected via the short side of the competitive network, theory predicts that equilibrium-outcomes remain the same for each player. If, however, the two networks are connected via the long side of the competitive network, the new seven-player network becomes competitive. Consequently, equilibrium-outcome predictions change for all subjects from the former even subnetwork. The second phase of the experiment consists of six periods of bargaining, each containing again up to six alternating rounds.

Charness *et al.* find that while exact equilibrium-point predictions fail, qualitatively the behavior in the experiment is consistent with theoretical predictions. For example, seller's payoffs are lower in the competitive three-player network than in the even four-player network. Hence, buyers seem to successfully make use of their bargaining power. Furthermore, the way in which the two subnetworks are connected with each other has a significant effect on what bargaining outcomes are realized in subsequent periods. Theory predicts that payoffs between buyers and sellers in the four-player subnetwork should diverge if the large network becomes competitive, while they should be roughly the same if the subnetwork remains even. This prediction is well confirmed by the data.

The fact that any precise equilibrium prediction fails, may be due to insufficient time for the subjects to learn. However, as Charness *et al.* show, the willingness to offer or accept certain shares is strongly affected by allocations in the past. Subjects learn from each other and develop a social norm for appropriate bargaining outcomes. This suggests that learning may not necessarily lead into the direction predicted by the theory. Finally, that bargaining outcomes tend to be less extreme than predicted by standard economic theory is consistent with extensive experimental research on ultimatum and dictator games (see Roth 1995, Camerer and Thaler 1995). In these games observations can be explained by assuming that players' behavior is driven by considerations of fairness and equity (e.g., Fehr and Schmidt 1999). It seems obvious that fairness considerations may also play a role in the present experiment of a buyer-seller network. However, the precise interaction between network structure, bargaining power and fairness considerations needs yet to be studied (with this regard see also the related experimental work by Roth, Prasnikar, Okuno-Fujiwara, and Zamir 1991 and Fischbacher, Fong, and Fehr 2003).

5 Network formation

5.1 Theory

Next to the effects on coordination, cooperation, and bargaining, one of the most important questions is how networks emerge. In recent years, several theoretical approaches have been proposed to address this question, using techniques from cooperative and non-cooperative game theory.[8]

The paper of Myerson (1977) is, probably, one of the first important contributions to this literature. Myerson analyzes a cooperative game that is enriched by a network structure describing the possibilities for communication or cooperation among different players. Individuals can act as a coalition if and only if they are connected through links in the network. While this idea constitutes an important step forward, it leaves several issues unsolved. Because the value function is still defined on coalitions and not on the network directly, the theory does not distinguish between different networks that connect the same players but differ in the way these players are connected. In consequence, many interesting details of the network formation process, for example costs and benefits of particular links, can not be analyzed in the

[8]See Jackson (2003) for a detailed survey of the theoretical literature on network formation.

model.

Jackson and Wolinsky (1996) follow a different approach. They consider value functions that are defined on networks directly. The main issue they address is the conflict between efficiency, i.e., value maximization, and stability. With regard to the latter they analyze the notion of pairwise stability, which assumes that links are formed if and only if both players that are connected by that link agree to form the link. On the other hand, links are severed if any of the two individuals decides to do so.

A particular network model they consider is the so-called connections model, where individuals receive benefits from being connected to other individuals and bear costs for maintaining direct links. Jackson and Wolinsky show that the set of efficient networks reduces to only three different types of networks: the complete network if costs are low, the star network if costs are intermediate, and the empty network if costs are high. While the complete and the empty network are pairwise stable if they are efficient, the star network may fail to be pairwise stable. As Jackson and Wolinsky show, this conflict between efficiency on the one hand and pairwise stability on the other, is no unique feature of the connections model but extends to more general network settings, as well.

The work of Myerson (1977) and Jackson and Wolinsky (1996) has attracted much interest in economic models of network formation. Subsequent models include Aumann and Myerson (1988), Dutta and Mutuswami (1997), Dutta, van den Nouweland, and Tijs (1998), Slikker and van den Nouweland (2000) and Johnson and Gilles (2000). All these models study the formation of networks in a static setting. Watts (2001) departs from this tradition and analyzes the connections model in a dynamic setting, where individuals meet over time and decide to form or sever links between each other. Similarly, Jackson and Watts (2001) consider the evolution of more general network models.

Somewhat parallel to the above literature that has clear origins in cooperative game theory, Bala and Goyal (2000a,b) develop models of network formation that use tools from non-cooperative game theory. Rather than considering pairwise stability, Bala and Goyal assume that individuals can form and sever links unilaterally, i.e., in particular no mutual consent is needed to form a link between two individuals. Clearly, this assumption changes the incentives of the players, hence the analysis in Bala and Goyal (2000a,b) differs substantially from the analysis in the models mentioned above. A central implication of unilateral link formation is that with regard to stability it leads to the concept of Nash equilibrium. Papers that follow a similar methodological approach include Goyal and Moraga-Gonzalez (2001), Goyal and Joshi (2002), Haller and Sarangi (2001) and Sarangi, Kannan, and Ray (2003).

The main idea of the network model in Bala and Goyal (2000a) is similar to the connections model of Jackson and Wolinsky (1996): players earn benefits from being connected to other players and bear costs for maintaining direct links. Benefits are regarded as resulting from valuable, non-rival information that flows through the network. Bala and Goyal distinguish between two different scenarios of information flow. In the first scenario (the 1-way flow model) information flows only to the player who maintains the link. In the second scenario (the 2-way flow model) information flows both ways. Independent of the information flow, Bala and Goyal assume that players simultaneously decide with whom to form a direct link, a link being costly to the individual who forms it.

Assuming that information flows through the network with no decay, Bala and Goyal prove that Nash equilibria of the network-formation game look as follows.[9] In the 1-way flow model a Nash equilibrium is either the empty network, where no player maintains any connection to any other player, or minimally connected, i.e., it has a unique component that splits if one link is severed. Analogously, in the 2-way flow model a Nash equilibrium is either the empty network or minimally 2-way connected, i.e., it has a unique component, no cycle, and no two individuals both maintain a link with each other. Intuitively, in both models a network is Nash if (i) either none or all players are connected and (ii) no redundant links are maintained.

Depending on the number of players the number of Nash (equilibrium) networks can be quite large. Therefore, a reasonable refinement to consider is the notion of strict Nash equilibrium, where each player plays his unique best response to the strategy profile of the other players. As it turns out, the set of strict Nash networks is much more restrictive. In the 1-way flow model Bala and Goyal show that the only strict Nash networks are the empty network and the circle (or, as Bala and Goyal call it, the wheel). In the 2-way flow model only the empty network and the center-sponsored star are strict Nash networks. The center-sponsored star is the network, where one individual (the center) maintains a direct link to every other individual, and no other individual maintains any link.

Both the circle and the center-sponsored star are shown to be efficient networks, where efficiency is defined in terms of maximizing the sum of play-

[9]Bala and Goyal prove also results for the general case, where they allow for decay. However, results are more clear-cut if no decay exists.

ers' payoffs. Thus, contrary to the model of Jackson and Wolinsky (1996), in the model of Bala and Goyal (2000a) no conflict between efficiency and stability exists. This suggests that the circle and the center-sponsored star may serve as a powerful prediction for network formation.

5.2 Experiments

Recent economic experiments that consider network formation are Deck and Johnson (2002), Callander and Plott (2003), and Falk and Kosfeld (2003). Vanin (2002) presents a pilot study for the model of Jackson and Wolinsky (1996). In his experiment three groups of four subjects each collectively bargain about what network to form. Links between two subjects are established based on pairwise stability, i.e., bilateral agreement is required. Each group forms a network in three different scenarios: the connections model with and without side payments and the co-author model.[10] Vanin finds that groups tend to form pairwise unstable but efficient networks both in the co-author model and, two out of three times, also in the connections model with side payments. In the connections model without side payments groups form networks that are inefficient but equalize payoffs among the subjects.

The experimental study of Deck and Johnson (2002) is inspired by the network-formation model of Johnson and Gilles (2000), which introduces a spatial cost topology in the connections model of Jackson and Wolinsky (1996). In this model players are located on a line and the cost for a direct connection between two players monotonically increases with the distance between the two players. Deck and Johnson are interested in a comparison of three different institutions for network formation in this model, and consequently implement one treatment for each institution. In the first institution, called "Split", players select those direct links, for which they are willing to pay exactly half of the cost. If both players agree to pay half of the cost of their connecting link, the link is formed. The second institution, "Primary", allows players to bid between zero and the total cost of a link for all their direct links. Finally, in the institution "Secondary" players can bid for all possible links. In particular, they can bid for a link between any two of the other players. Under the latter institutions, a link is formed if and only if the total sum of players' bids for that link exceeds the cost of the link. Deck and Johnson use the notion of Nash equilibrium as a stability concept for a

[10] The co-author model assumes that an additional link generates a negative externality on individuals already connected. Jackson and Wolinsky (1996) show that pairwise stable networks are generally over-connected and hence inefficient in this model.

network.

In each treatment of the experiment subjects consecutively interact in three different payoff environments, two of them involving groups of five players. In the third environment players interact in pairs. In the following, I focus on the five player environments only. A particular feature of the experimental design of Deck and Johnson is that the situation is described to the subjects as a decision task faced by managers of a train station. Precisely, in the experiment a subject is in the role of a station manager, who has to decide (i.e., to bid) on the connections between different stations. Just like in the connections model, the value of a network to a station manager is determined by the minimum number of stops a fictitious passenger would have to make on his trips from the manager's station to the other stations. In the first payoff environment, the parametrization is such that the unique efficient network requires each player to be directly connected to his nearest and to his second nearest neighbor(s). This network is supportable by a Nash equilibrium under all three institutions. In the second payoff environment, parameters are chosen such that the chain is the unique efficient network, where each player is connected to his nearest neighbor only. The chain is supportable by a Nash equilibrium only under the Primary and the Secondary institution, but not under the Split institution.

Subjects play 15 periods of the first environment, following 10 periods of the second environment. The results reported in the paper are based on the last two thirds of all periods in each environment. Deck and Johnson find that in the first environment the Primary institution performs best, yielding an average level of efficiency of 89 percent while Split and Secondary, on average, achieve an efficiency of 83 percent and 81 percent, respectively. The authors explain their result as follows: while in all treatments subjects form too many of the long links, connecting stations that are far away from each other, in the Primary treatment subjects are more successful in forming the necessary short links. In the second environment all three institutions show a similarly bad performance. No group achieves a positive surplus under any institution. Note that in this environment, the chain is the unique efficient network, where a significant percentage of the network's value is provided by indirect links. Since subjects do not succeed in coordinating on this network, the authors conclude that network formation driven by individual decision-making is a difficult process that is likely to produce inefficient outcomes. However, in the analyzed environment the individual strategy to form a chain is a high-risk strategy that is likely to generate a negative payoff to each player if players do not successfully coordinate. It remains to be shown whether it is the individual decision-making itself or rather the riskiness of the efficient equilibrium-strategy that leads to the coordination failure. In fact, the studies of Callander and Plott (2003) and Falk and Kosfeld (2003) show that if this riskiness is reduced, individuals are well able to coordinate on an efficient network. These studies are discussed in the remainder of the paper.

Callander and Plott (2003) report on — as they call it — an "exploratory" experiment, in which they study the evolution of information networks under various treatment conditions. In each treatment they consider groups of six players. The first treatment involves between 10 and 20 periods of a 1-way flow network-formation game à la Bala and Goyal (2000a), using a random stopping rule to determine the end of the experiment. In this experiment, subjects sit together in a room. In each period, after each subject has recorded his direct connections payoffs in the resulting network are calculated. Precisely, different physical signs are placed in front of each subject that represent individual links and are used to determine subjects' profits. Costs and benefits in this treatment are such that the unique strict Nash network prediction is the circle, which is also efficient. In the second treatment that is studied by Callander and Plott, individual decisions are made via the computer. Moreover, whereas in the first treatment the decision making of the subjects is simultaneous, in the second treatment decisions are made continuously over two minute rounds, where choices can be adjusted repeatedly in real time. Subjects are continuously updated about the choices of the other group members and each choice adjustment is costly. Each session lasts between 15 and 20 rounds, using again a random stopping rule to determine the end of a session. Different games are played in this treatment. At the beginning, each session starts with a 1-way flow network-formation game with benefits being slightly different from the game played in the first treatment but the theoretical prediction being the same (i.e., the circle). In case subjects form the same network for three consecutive periods the game is changed in such a way that from then on direct links to nearest neighbors are twice as costly than links to other subjects.[11] This modification has the effect that only particular circles, where no nearest neighbors are directly connected, are efficient. If under the new setting subjects form again the same network for three consecutive periods, the game is changed yet another time. Precisely, one subject is selected to/from which direct links are free. This renders the circle inefficient and predicts a star network as the unique

[11]This is the opposite of what is assumed in the model of Johnson and Gilles (2000).

efficient (and strict Nash) network. Subjects are not informed about the potential change of the games at the beginning of the experiment.

The main findings of Callander and Plott are as follows: first, in both treatments networks often converge to Nash equilibrium. If convergence is observed, in all cases except for one group subjects form the efficient and strict Nash network, which is the circle.[12] Second, decision making with real-time choice adjustment facilitates the coordination on a Nash network. While in the first treatment two out of five groups eventually converge to Nash, in the second treatment six out of seven groups eventually form a Nash network. At the individual level, Callander and Plott reject the hypothesis that subjects adjust their strategies based on a best-response rule with additional error term. Instead, the authors conclude that many subjects seem to exhibit so-called "simple strategic behavior", meaning that subjects form exactly one direct link that is part of a focal (e.g., a clockwise) circle network.

The experiment of Callander and Plott (2003) is inspired by the network-formation model of Bala and Goyal (2003a). The authors, however, consider only the 1-way flow model and in this model only treatments, where the circle is the unique efficient strict Nash network. Falk and Kosfeld (2003) present a more detailed analysis of the Bala-Goyal model, where both 1-way and 2-way flow networks are studied and several treatment conditions are implemented yielding different theoretical predictions.

In their experiment, Falk and Kosfeld (2003) consider groups of four. In every period subjects anonymously and independently decide with whom of the other group members they want to form a direct link. After decisions are made subjects learn the realized network and earn a payoff that depends on the number of links they form and the number of group members to whom they are connected in that period. Groups stay together for five periods, after which they are randomly recomposed. Overall, subjects play 15 periods of the network formation game and participate in three different groups.

The experiment consists of five treatments, three 1-way flow and two 2-way flow treatments. In every treatment the benefit from an additional (direct or indirect) connection is equal to 10. In the 1-way flow model the cost of a direct link is either 5, 15, or 25. In the 2-way flow model the cost of a direct link is either 5 or 15. Table 1 shows the predictions of the Bala and Goyal model based on strict Nash equilibrium and efficiency in the five different treatments of the experiment.

[12]Only one group participated in the final parameter setting of the second treatment. No convergence was observed in this case.

	1-way flow			2-way flow	
Cost of connection	5	15	25	5	15
Strict Nash network	circle	circle, $\emptyset$	circle, $\emptyset$	cs-star	$\emptyset$
Efficient network	circle	circle	circle	m2c	m2c

Note: In all treatments the benefit from an additional connection is equal to 10. ($\emptyset$ = empty network, cs-star = center-sponsored star, m2c = minimally 2-way connected.)

Table 1: Treatments and predictions in Falk and Kosfeld (2003).

The circle is a strict Nash network in all 1-way flow treatments. For costs of a direct link equal to 5 it is the unique strict Nash network, while for costs equal to 15 or 25 the empty network is also a strict Nash network. In all 1-way flow treatments the circle is the unique efficient network. In the 2-way flow model the center-sponsored star is the unique strict Nash network if costs equal 5 and the empty network is the unique strict Nash network if costs equal 15. In both treatments, efficient networks are those that are minimally 2-way connected. This includes the center-sponsored star but not the empty network.

Falk and Kosfeld (2003) derive several results. Their main finding is the following. While in the 1-way flow model more than fifty percent of the networks formed by the subjects are strict Nash networks (i.e., either the circle or the empty network), in the 2-way flow model no strict Nash network (i.e., neither the center-sponsored star nor the empty network) is formed at all. Hence, there is a significant difference between the two scenarios of information flow. Whereas the notion of strict Nash equilibrium serves as a good prediction in the 1-way flow scenario, it has no predictive power at all in the 2-way flow scenario. This difference is no artefact of the refinement of strict Nash equilibrium, but remains true if we look at all Nash networks instead. Although subjects form Nash networks in the 2-way flow model, they do so significantly less than in the 1-way flow model.

What explanation can be offered to account for this finding? One reason might be that the 2-way flow model is more complex and that it might take more time for the subjects to coordinate on equilibrium. However, simulations of Bala and Goyal (2002a) suggest that convergence times of both models are similar if subjects have the chance to revise their strategy in every period, as is the case in the experiment. Moreover, following the complexity argument, one should not see any difference in behavior once an equilibrium is reached. However, Falk and Kosfeld do find such difference in the data. Given that subjects form a Nash network in period t, the probability to form a Nash network in period $t + 1$ is significantly smaller in the 2-way flow model than in the 1-way flow model. Thus, even if subjects succeed in coordinating on a Nash network, equilibria are less stable in the 2-way flow model.

Another explanation might be that the behavior of the subjects in the experiment is guided by fairness considerations. Note that a crucial difference between the 1-way and the 2-flow model is that in the first model every subject has to form a link if he wants to receive any benefits from the network. In contrast, in the 2-way flow model a subject can earn large benefits even if he does not form a link himself. As a consequence, in equilibrium payoffs are very unequal. For example, in the center-sponsored star the individual in the center, who maintains all links, earns a payoff of 25, while individuals on the periphery earn a payoff of 40. If subjects dislike unequal payoffs (as, e.g., in Fehr and Schmidt 1999), they may be unwilling to form such networks.

In Falk and Kosfeld (2003) this argument is tested by a probit regression measuring the impact of payoff inequity on inertia. The latter is defined as any instance where a subject plays the same strategy as in the previous period. Payoff inequity is measured by the sum of absolute payoff differences between once own and the other players' payoff. Controlling for best replies, it is found that payoff inequity has a significantly negative impact on inertia. The higher the payoff inequity between subjects in a given network is, the less willing subjects are to maintain that network, even if (according to monetary rewards) the maintenance of the network is an individual best reply. As Nash networks in the 2-way flow model generate higher payoff inequity than in the 1-way flow model, this implies that subjects form less Nash networks in the 2-way compared to the 1-way flow model, which is exactly what is found in the experiment.

One conclusion from this result is that networks have to be fairness compatible in order to be stable. Otherwise the notion of Nash equilibrium together with standard money-maximizing preferences generates wrong predictions. A second implication is that mechanisms that help overcome the conflict between fairness and stability (e.g., compensation of the central player or rotation within the network) may play an important role in the formation and maintenance of social networks. In the experiment subjects did not have such possibilities. In reality, however, there are many of these possibilities, and, as evidence from sociology, psychology, and anthropology suggests, these mechanisms are widely used. Clearly, these mechanisms provide an interesting area for further experimental research, too.

6 Conclusion

The experiments discussed in this paper belong to a recent wave in experimental economics focusing on social and economic networks. Present work emphasizes individual incentives for network formation, as well as network effects on equilibrium selection, competition, and cooperation. Given the interest in the topic and the existing theoretical literature in this area, it seems clear that more experimental studies are on the way.

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