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Call Me if You Can – An Experimental Investigation of Information Sharing in Knowledge Networks

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Christoph Helbach, Klemens Keldenich, Michael Rothgang,
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Call Me if You Can – An Experimental Investigation of Information Sharing in Knowledge Networks

Abstract

In the public promotion of R&D cluster and network formation, the following situation typically arises: An initial network structure has developed over a long time span and policy measures affect the structure of links between the actors. This new network structure influences the effectiveness of the information flow in a way that is not clear from the beginning. As analyzing the effects of a change in the network structure is difficult in the field, this paper uses a laboratory experiment to analyze how information is distributed in four different network structures. Networks are modeled as five-actor groups. Every individual represents a node and possesses some private information. The experimental results suggest that the different network structures do indeed influence the way information is exchanged. Both too many possible links (causing a coordination problem) and too few possible links (introducing bottlenecks) are harmful. The participants in all network structures learn over time and achieve a faster exchange of information in the later rounds. These results suggest that when influencing communication structures, one has to be careful to balance the positive and negative effects of adding more communication possibilities.

JEL Classification: C93, D70, D81

Keywords: Network; communication; laboratory experiment; information flow

April 2012

¹ Christoph Helbach, University of Duisburg-Essen; Klemens Keldenich and Guanzhong Yang, University of Duisburg-Essen and Ruhr Graduate School in Economics; Michael Rothgang, RWI. – We thank Jeannette Brosig-Koch as well as seminar participants at the University of Duisburg-Essen, the GfeW Conference 2011 in Nürnberg, and the Nordic Behavioral Economics Conference 2011 in Lund for helpful comments and suggestions. We thank the German Federal Ministry of Education and Research for financing the experiment within the project Ongoing Evaluation of the “Spitzencluster-Wettbewerb”. Zulfiya Davidova provided excellent research assistance. – All correspondence to: Klemens Keldenich, RGS Econ, c/o Chair for Economic Policy; University of Duisburg-Essen, Faculty of Economics, Universitätsstr. 12, 45117 Essen, Germany, Email: klemens.keldenich@ibes.uni-due.de.

1 Introduction

The efficiency of research networks and clusters (the latter being characterized by regional links) is dependent on the information flow between the actors involved. Network structures between firms or research institutions have usually developed over a longer time span to achieve a better research output through spillovers between the actors. Policy interventions aim to increase research output by funding cooperation which results in additional network links. While it is well established in the empirical literature that R&D actors increase their output by cooperating in networks, there are ambiguous results on the effects of public policies that aim to promote cluster and network formation (Martin et al., 2011). In particular, not much is known about the effects of different network structures on the efficiency of information flow.

The distribution of information is one aspect of interactive learning in R&D innovation systems (Soete et al., 2010). Presently, about 350 cluster or network organizations exist in Germany alone (Rothgang and Lageman, 2011). These organizations are mainly characterized by weak ties between the actors (Granovetter, 1973). However, current research policies influence network structures. One example of such an R&D program is the “Leading-Edge Cluster Competition”¹ in Germany that has changed the network structures substantially, leading to an increase in the concentration of the networks to a few actors (RWI et al., 2011). These observations are the starting point for the analysis at hand, which seeks to answer a general question: If the network structure is taken as given, how does this structure influence the information flow in the network? This question is of practical relevance not only in research cooperations but more generally in cases where network structures have evolved and the question arises whether they should be modified in order to ensure a more efficient information flow.

In network structures, each actor represents a node and the possible communication links represent lines between these nodes. Basic network structures are the star, where one node is linked to all other nodes but no other links exist; or the full network, where all nodes are linked to each other. Most of the existing literature is concerned either with network formation (see Section 2 for a brief overview of both the theoretical and experimental literature) or with the effect of network structure in strategic situations, i.e. where a payoff conflict between the actors exists. In contrast, the paper at hand examines a situation without payoff conflicts among the different agents in the network (reflecting a situation where success is only possible when all members achieve a high level of information) and with predetermined network structures. This is done by conducting a laboratory experiment where the participants are assigned to nodes in a network and have to master a task without payoff conflict. Using a laboratory experiment

¹The “Leading-Edge Cluster Competition” (“Spitzencluster-Wettbewerb”) was launched by the German Ministry of Education and Research in 2007. In this competition, research cooperation in regional partnerships (clusters) is fostered in order to improve innovation (see <http://www.bmbf.de/en/10726.php> for a detailed description of the competition). While the changes in network structure that take place after participation in the competition are observed, the basic research question remains, what influence these changes have on the efficiency of information flow between the actors involved.

allows the controlled variation of only the variable of interest - namely the network structure - while everything else is kept constant. In addition, agents can be randomly assigned to the different network structures. This way, it is easier to establish causality than in an empirical, non-experimental setting.

Which network is the most successful in terms of information sharing in the real world is not obvious: While many links between nodes of a network allow an efficient sharing of information, they also introduce a coordination problem even if each actor in the network is perfectly rational and the state of the world is common knowledge. Superfluous connections might be established or necessary connections might be delayed, leading to a general delay of the spread of relevant information. The paper at hand examines the causes of possible differences in the speed and efficiency of information sharing in different networks. Furthermore, the development of information sharing through several repetitions is studied to see if there are differences between experienced and inexperienced networks.

The paper proceeds as follows. A short literature summary is presented in Section 2. The experimental design is described in Section 3. In Section 4, the hypotheses are stated, while results are presented in Section 5. Section 6 concludes.

2 Literature on networks - knowledge transfer and formation

So far, very few experiments (in the field or in the laboratory) have addressed R&D networks and clusters and the related policy questions even though Sørensen et al. (2010) and Falk and Heckman (2009) argue that experiments are well suited to complement traditional methods like field research. Studies which have already used experiments to analyze R&D-related topics have been conducted by Giebe et al. (2006), who analyze the allocation of R&D subsidies in an experimental setting, and Gächter et al. (2010), who look at knowledge sharing in innovation networks. While the contributions mentioned focus on inefficiencies in selection processes and incentives for knowledge sharing, the paper at hand analyzes network structures and their role for the efficiency of information distribution within research networks.

In the empirical literature, learning and information transfer in R&D and the adoption of new technologies is discussed with respect to diffusion of technologies (Geroski, 2000; Hargreaves Heap and Parikh, 2005) and systems of innovations (Asheim and Coenen, 2005; Edquist, 2005). These studies show that transfer of technological information and knowledge in R&D in general and specifically in R&D networks and clusters follows rather complex patterns. Relevant dimensions of learning in cluster and network structures are interdependencies and interactions between the actors involved (business firms, universities, research institutes and other actors). These interdependencies lie behind network structures, asymmetric knowledge endowments and different resource bases of the actors involved and last but not least patterns of information transfer that exist in R&D clusters and networks.

A question that is closely related to our analysis, the development of network structures, has been addressed by several studies in theoretical models. These studies are relevant for our research question because they can give us hints on the characteristics and practical relevance of different network structures. Jackson and Wolinsky (1996) propose two specific models for the formation of networks and find that - depending on how the costs and benefits of connecting are allocated to the nodes - both the full network and the star network can be efficient and stable structures². Bala and Goyal (2000) use a different model to analyze the genesis of network structures where connections can be initiated by a single node, which then also has to bear all the incurred costs. This allows the modeling of network formation as a non-cooperative game. One notable result of their two-way model (where a connection gives access to the information to both nodes) is that the resulting networks are either empty or a star. In the star network, the central node bears the costs of initializing the connections.

The experimental economic literature on networks can be split into three broad areas³: Network formation, coordination networks, and cooperation networks. Again, the first area is the most interesting one for our concerns⁴ as it is informative for the decision about which network structures to study in our paper. Falk and Kosfeld (2003) explicitly test the model by Bala and Goyal (2000) and find that the Nash-Equilibrium predictions from this model (namely either an empty or star network) do not hold. Still, in a one-way model the predictions (which are then either empty or circle networks) do hold and the respective networks form. They go on to explain their divergent findings with social preferences which replace the standard, fully selfish preferences in the original model. Furthermore, Goeree et al. (2009) use a laboratory experiment to test the emergence of networks and augment the analysis by introducing different types of agents. They find that the resulting network structure strongly depends on the type of agent. The relation of costs and utility associated with a connection is the deciding factor. In particular, stars only develop with one “high utility” agent, not with homogeneous agents or with one “low cost” agent.

Besides economics, social psychology offers two early examples of the experimental analysis of different network structures: Bavelas (1950) and Leavitt (1951). The second paper is especially interesting as it has some similarities to the experiment proposed here. It also analyses the influence of network structures (namely circle, line, Y, and star) on information efficiency. Similar to our design, individuals represent the nodes in the network and can choose to send information along the links in the network. The experimental

²In a later model, Bloch and Jackson (2007) enrich this model by allowing players to use transfers (direct and indirect) in their bargaining process.

³This classification follows the survey by Kosfeld (2004).

⁴The literature on coordination networks is concerned with the effect of network structures when games have more than one equilibrium, e.g. a risk-dominant and a payoff-dominant one. The results are not clear cut, while Keser et al. (1998) find an influence of network structures on the resulting equilibrium, Boun My et al. (1999) do not (when comparing a circle with a full network). Cooperation networks in contrast use Prisoners’ Dilemma or Public Good games to look at the influence of network structure on cooperation. Kirchkamp and Nagel (2000) use a Prisoners’ Dilemma game and find less cooperation in a circle network; Carpenter et al. (2010) use Public Good games and find a large influence of network structure on efficiency.

design is also used by Guetzkow and Simon (1955), who include the full network in the analyzed network structures. Furthermore, their analysis adds a time dimension and finds that the full network is between the circle and the star network in terms of speed. While these studies have some aspects in common with the paper at hand, there are several crucial differences: They do not use monetary incentives, relying instead on the intrinsic motivation of the subjects. Furthermore, the subjects can write free-form messages, allowing mistakes in the information transmission. Finally, only male subjects are used and anonymity is not upheld.

3 Experimental design

3.1 General procedures

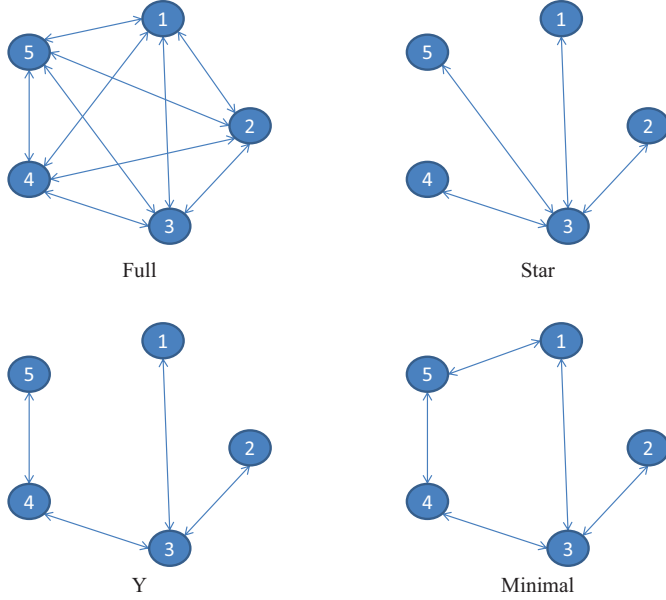
The experiment was conducted computer-based and took place at the “Essen laboratory for experimental economics” (elfe) at the University of Duisburg-Essen in July 2011. Participants were recruited via ORSEE (Greiner, 2004) and the attached subject pool. To program the experiment, the software z-Tree (Fischbacher, 2007) was used. In total, 16 sessions with 10 participants each were conducted. The participants were students from the University Duisburg-Essen with an average age of 24.2 years. The sessions lasted at most 90 minutes, the average payoff for the participants was EUR 19.60 with a minimum payoff of EUR 15.70 and a maximum payoff of EUR 23.40.

3.2 Treatments

This study aims to investigate networks without payoff conflicts, where every member of the network has the same goal. This goal is defined as the maximum information level for the network, i.e. every member of the network holds all available information. The network structure, i.e. the links along which information exchange is possible, determine several properties of the networks⁵. These properties then allow theoretical predictions which network structure will perform better in terms of information dispersal. From both the theoretical literature on network formation and the actually existing networks in the “Leading-Edge Cluster Competition”, three interesting network structures are identified: Full, Star, and Y. A fourth network structure - called Minimal - is used due to its unique properties (see Section 4 for a detailed explanation). Figure 1 shows these four network structures. In total, 32 independent observations (one observation consists of one network with five subjects each) were gathered, 8 in each treatment.

⁵ A note on terminology: Links denote the channels through which information exchange is generally possible; connections denote those instances when a contact was actually established.

FIGURE 1: Network structures



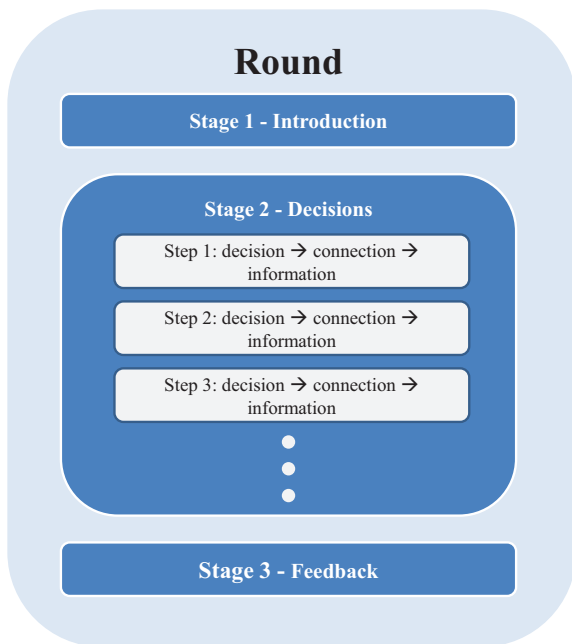
3.3 Course of the experiment

The experiment uses five-person networks⁶, where each node in the network is an individual subject. A between-subject design is employed where each subject only participates in one treatment. The detailed course of events in the experiment is as follows: Upon entering the laboratory, the subjects are randomly allocated to 10 closed and sound-protected cabins. They receive the instructions (see the Appendix for the translated instructions, all treatments used the same instructions) and have the opportunity to ask questions, which are answered privately by the experimenter. When all subjects have indicated that they have understood the instructions, they have to answer a set of 7 control questions, mainly concerned with the general setup of the experiment and the payoff rules. After all subjects have answered the questions correctly, the experiment itself starts. The experiment consists of 10 rounds with three stages each. For the repetition, a partner matching is employed, i.e. the same network stays together for all 10 rounds. The number of repetitions is chosen such that a convergence of play should be possible for the subjects and learning can be analyzed. Figure 2 provides a graphical overview of one round's timing.

In the first stage, each subject receives a different piece of private information. This information allocation is common knowledge for all subjects. The subjects are informed about the network they are

⁶Five-person networks are used because they are the smallest possible networks where reaching full information is not trivial. As this is the first study to analyze the influence of exogenous network structures, this is a natural starting point and allows the clearest identification of the information exchange in the network.

FIGURE 2: Experimental design - timing



in, and their position in this network. Figure 3 shows a screenshot⁷.

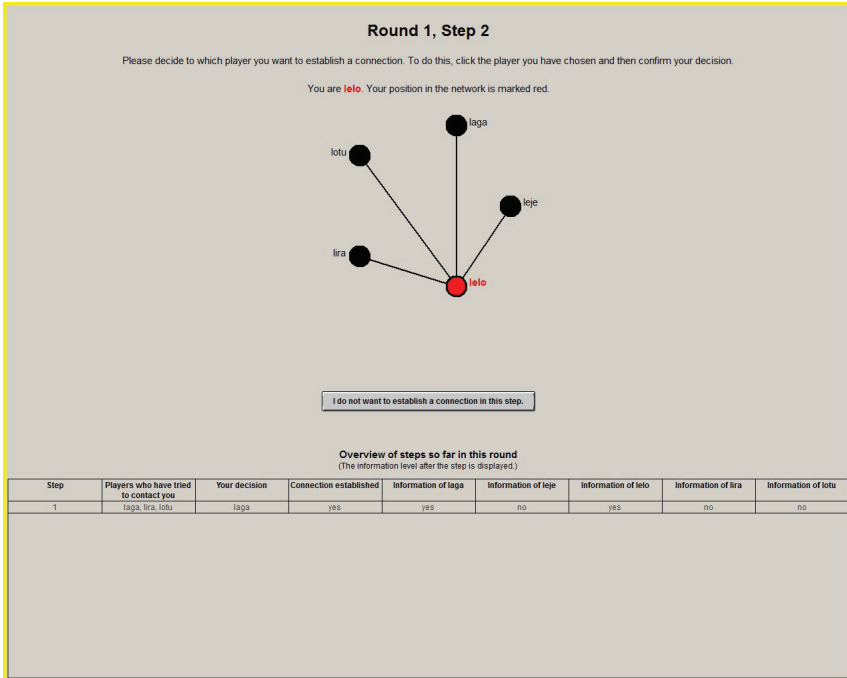
The second stage is divided into discrete steps. During each step, all subjects can choose one node (or none at all) to connect with. If two subjects select each other, the connection is established and all information both nodes possess is exchanged. If no decisions coincide, no connections are formed. This procedure is repeated until every subject has all available information. From step 2 onwards, the following information is additionally displayed for the subjects: The pieces of information they already possess, the decisions they have made during the current period, and (if applicable) the subject(s) who has (have) tried to contact them in the last step. The design takes great care to avoid any focal points which might influence who is contacted: The network is displayed at a slightly skewed angle, such that there is no clear focal point. The different nodes in the network are given the names “lotu”, “laja”, “leje”, “lira”, and “lelo” which have been created in such a way as to make ordering them difficult (as opposed to numbers or letters, for example)⁸.

In the third and final stage, the payoffs for the subjects, which are the same for each subject, are computed. Each network starts with EUR 18 per round. From this amount, costs for each step used

⁷The screenshot is translated from the original German.

⁸To test if there really is no “focal point” contained in the name or the geographical position of the nodes, an exact χ^2 -test is employed to compare the frequency of choices in the very first decision of the Full network. The relative frequencies are not significantly ($p > 0.1$) different from a uniform distribution.

FIGURE 3: Screenshot of the decision screen



and each connection established are subtracted where one step costs EUR 0.30 and one connection costs EUR 0.80⁹. Note that connection attempts that do not result in a connection are costless¹⁰. The network payoff is divided evenly among the members. There is therefore no payoff conflict between the subjects, as the incentives for the group and each individual are perfectly aligned. Throughout the whole experiment, anonymity is maintained and no communication is possible, except through the described mechanism.

At the end of each round, all own connections are displayed to the members of the network once again. For the final payoff, the payoffs from all 10 rounds are summed up. At the end of the experiment, a questionnaire is filled out by the participants, asking for demographics (like sex, age, study subject), school grades (final cumulative high school GPA¹¹, last math grade, last German grade), and several questions about their behavior during the experiment (see Section 5 for more details of these questions).

⁹These costs were chosen in a way to achieve a reasonable average payoff (as compared to opportunity costs) for the participants.

¹⁰The round is ended automatically if the subjects have reached a 0 payoff, i.e. if they needed so many steps and connections that the costs exceed EUR 18. This occurred only once; this group was excluded from the analysis.

¹¹The German “Abiturnote” is used, which is a weighted average of grades received in the last two school years and the main measurement used for university admissions.

3.4 Experimental design and characteristics of network and cluster organizations

The experimental design mirrors several characteristics of real world R&D network and cluster organizations. In these organizations, there are many weak ties, i.e. indirect contacts or contacts that are not very intensive in respect to number of interactions. Likewise, contacts in the experiment at hand are highly formalized and indirect contacts play a significant role. Of course, different degrees of the strength of the contacts are still possible. These can be influenced by the exogenously given network structure and the endogenously developed routines. Both in the experiment and in existing R&D clusters, information exchange takes place repeatedly, allowing for the emergence of communication patterns as well as improving efficiency through learning.

Furthermore, many cluster and network organizations operate under one common goal or strategy, for which the exchange of information is necessary. This is especially the case if firms and research institutes combine their knowledge to solve precompetitive research topics (Rothgang et al., 2011). Similarly, the incentives for all actors in the experiment are identical. In addition, the relation of the costs for steps and connections in the experiment was chosen to reflect the situation in reality, where a connection - i.e. a visit to a cooperation partner in a research project - is more costly than a unit of time per se. Finally, three of the network structures used in the experiment (Star, Y, and Full) are - as already mentioned - often found in cluster organizations, e.g. in the "Leading-Edge Cluster Competition" in Germany.

4 Hypotheses and benchmarks

4.1 General network characteristics

First, there are some generally descriptive properties of the networks. These are the total number of links in the network, the average number of links per network node, and the variance of the number of links per node; see Table 1.

Furthermore, the following properties can be defined: The minimal number of connections needed to give every node all of the information, the minimal number of steps needed to give every node all of the information, and the number of nodes that on average do not communicate through the optimal path to complete information even though they could. This last property serves as a measure of how much coordination is needed in the network to reach the optimal path. In the Full network, for example, subjects only need 6 connections in 4 steps to establish full information, making a maximum profit of EUR 12 for the group possible¹². However, on average 1.5 nodes do not communicate along an optimal

¹²See Figures A - D in the Appendix for concrete examples of an optimal path for every network.

path indicating a notable coordination problem.

TABLE 1: Network properties

Properties	Full	Star	Y	Minimal
Number of links	10	4	4	5
Average number of links	4	1.6	1.6	1.8
Variance of links	0	1.8	1.44	0.2
<i>Best possible result</i>				
Connections needed	6	7	7	6
Steps needed	4	7	5	4
Nodes not communicating	1.5	0	0.8	1.25
<i>Random</i>				
Average connections	11.56	15.66	18.27	15.24
Variance of connections	9.18	28.72	48.45	24.75
Average steps	28.98	39.15	36.54	29.66
Variance of steps	111.71	237.08	238.41	133.01

Source: Own calculations, simulation results after 100,000 runs.

As achieving the optimal possible outcome is very demanding for the ability of the individual nodes to form the correct connections (especially in the networks where there is a coordination problem), it is also useful to look at a lower benchmark. To this end, purely random behavior by the nodes is simulated. From this simulation, the following network properties are derived (after 100,000 repetitions): The average number and the variance of connections needed to achieve full information and the average number and the variance of steps needed to achieve full information. Table 1 gives all these properties for the networks which are considered for this study.

Note that for the networks without any coordination problem (Star and Y), the best achievable outcomes can be expected when players are fully rational. In the Minimal network, where there is only a slight coordination problem, optimal play would result in 4.5 steps and 6 connections¹³. The severity of the coordination problem in the Full network, however, will make it very unlikely that the best possible result is achieved¹⁴.

4.2 Hypotheses on treatment effects

As mentioned in Section 1, a conflict exists between more possibilities to exchange information and possible coordination problems. This conflict is smallest in the Minimal network, as this structure is chosen so that all information can be exchanged as quickly as possible with the smallest number of links. The coordination problem can be expected to have the largest negative influence at the beginning of the experiment, as the players have not yet gained any experience. This leads an ordering of the networks

¹³See the Appendix for a detailed derivation. If the additional assumption is made that a group is able to repeat the optimal result if it has reached it once, the steps needed decrease to 4.09 per round if all ten rounds are examined.

¹⁴It is furthermore very difficult to assess rationality in the Full network from simply observing decisions. As players usually do not know which information the other players have, in most cases it is impossible for them to exclude one potential node completely. Instead, most decisions they can make are rational with a positive probability, depending on the expected allocation of information.

according to the severity of the coordination problem. In particular, the Full network can be expected to perform worst.

Assuming that the coordination problem gets less influential in the course of the 10 rounds, the Full network should improve. At the same time, the Star network should perform relatively worse due to its efficiency constraints. Combining these arguments and looking at the whole experiment the following hypothesis is derived:

H1: *“Among the four different networks, the order of networks in terms of average profit over all rounds will be as follows: Minimal = Y > Full = Star.”*

This hypothesis might also serve as an indicator of how severe the coordination problem really is. If e.g. the Star network is more successful than one of the others, the benefit given by the higher number of links is not high enough to overcome the coordination problem.

4.3 Learning and convergence

As the game is repeated ten times with the same group, one can observe whether learning occurs i.e. if the participants achieve a higher profit in the later rounds. The game itself is not trivial for the participants to master, therefore one might expect that they do not achieve the best possible result in the very first rounds, leading to the second hypothesis:

H2: *“In all four networks, the participants will achieve a higher profit in the last five rounds than in the first five rounds.”*

Another way to look at the development of results over time is to analyze whether a convergence of play can be observed, i.e. if the changes in behavior from round to round become less or even disappear. To do this, several possible strategies can be used. First, the number of consecutive rounds - counting from the last round - with the same result in terms of connections and periods can be counted. The higher this number, the earlier an equilibrium (as in a situation with resistance to change) is reached. If this number is 1, the group has not converged to a certain pattern of behavior at all. This serves therefore as an aggregate measure of convergence in the groups.

Second, the individual decisions can be analyzed by looking at the share of identical individual decisions from one round to the next in one single step. If, e.g., one subject chooses the same connection in the first step in every round, her behavior is very stable. Looking at this share on a group level gives a good idea how far this group has converged to one path of connections.

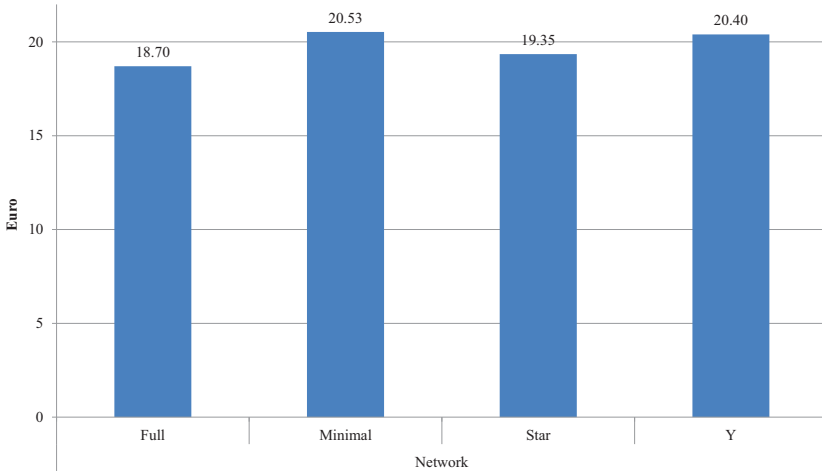
Finally, one can again count consecutive runs from the end in which a group behaved identically in a certain step. E.g., if every group member makes the same decision in step two in the last five rounds, this might serve as an indicator of a relatively high convergence in that group.

5 Results

5.1 Treatment effects

First, the differences in behavior and outcome between the treatments are analyzed. Figure 4 shows the average profit the different network structures achieved in all ten rounds. At first glance, the Minimal and Y networks manage to reach a higher profit than the other two structures, especially in the later rounds. The total profit (over all 10 rounds) for the networks are EUR 18.70 for the Full, EUR 19.35 for the Star, EUR 20.40 for the Y, and EUR 20.53 for the Minimal network. A Kruskal-Wallis test confirms that there is a significant difference in profit between the treatments ($p=0.026$)¹⁵.

FIGURE 4: Average total profit by treatment



Performing then pairwise Mann-Whitney-U tests (again for average profit over all 10 rounds) reveals that Minimal and Y are both significantly higher than Full and Star; while there is no difference between Minimal and Y on the one hand and Full and Star on the other hand¹⁶. Looking at these results, hypothesis H1 cannot be rejected: While the Minimal network is indeed the most efficient one, it is no different to the Y network. Similarly, Full and Star perform similarly, showing that both too many links

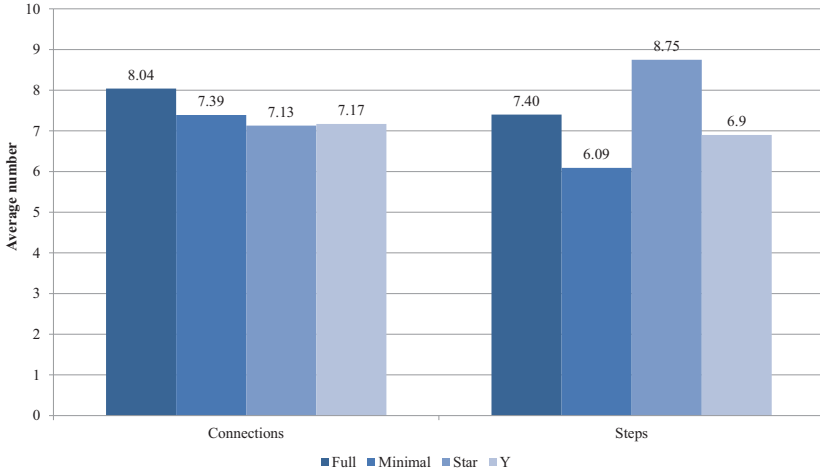
¹⁵If not indicated otherwise, all tests are two-sided and exact.

¹⁶The p-values for the pairwise comparisons are as follows: Star vs. Y: 0.015; Star vs. Minimal: 0.040; Full vs. Y: 0.038; Full vs. Minimal: 0.072; all other comparisons are insignificant with $p>0.1$.

and very restricted communication channels are harmful.

As profit is just a linear combination of steps and connections needed per round, the question remains as to which of the two variables drives this result. Figure 5 shows the average number of steps and connections needed to achieve full information in each round. The numbers for connections are 8.04 for the Full, 7.39 for the Minimal, 7.17 for the Y, and 7.13 for the Star network. Here, the one clear difference seems to be that groups playing in the full network seem to need more connections than the groups playing in the other networks. Again using pairwise Mann-Whitney-U tests, this is confirmed, as the Full network needs significantly more connections on average than the other three networks¹⁷.

FIGURE 5: Average total connections and steps by treatment



The second driving factor for profit are the steps needed. The picture is somewhat different compared to the connections: The Star network is now the one needing more steps than the others; the numbers are 8.75 for the Star, 7.40 for the Full, 6.90 for the Y, and 6.09 for the Minimal network¹⁸. Looking back at the differences in profit, the lower profit by the Full network is driven by too many connections, while the lower profit of the Star network is driven by too many steps. The most likely explanation in case of the Full network is the coordination problem. Every node in this network structure has four links, making it hard to establish any connection in the first place. This amplifies the problem for the individual nodes to pick useful connections, driving up the total number of connections. In the case of the Star network, the many steps at the beginning are likely due to getting familiar with the decision situation (this is of course similar for all networks). The difference, however, stems from the natural limit in steps: in the

¹⁷P-Values are as follows: Full vs. Star: 0.000; Full vs. Y: 0.001, Full vs. Minimal: 0.058; all other comparisons are insignificant with $p > 0.1$.

¹⁸This is again confirmed by using pairwise Mann-Whitney-U tests (The p-values are as follows: Star vs. Full: 0.099; Star vs. Y: 0.007; Star vs. Minimal: 0.000; all other comparisons are insignificant with $p > 0.1$.)

Star network, the smallest number of steps which is possible to achieve is seven, as opposed to four in the Full and Minimal networks and five in the Y network. This means that even when all networks move towards these limits in the rounds, the Star networks will still need more steps on average.

After the experiment, subjects filled out a questionnaire with the following information¹⁹: demographic information, school grades, questions concerning their strategies in the experiment, and questions concerning their satisfaction with the experiment²⁰. However, of special interest from the questionnaire variables is the subjective happiness with the process, quantified by asking for the number of rounds in which the subjects were satisfied with the results. This is especially relevant from a practical point of view. Thinking back to the evaluation of R&D clusters, the perception of the participants might be just as important as the actual results of the cooperation. Using Spearman correlation coefficients for every network separately reveals that while the number of connections is not correlated to the overall satisfaction ($p > 0.1$ for all networks), the number of steps is negatively correlated in all networks ($p < 0.1$). This is somewhat surprising, as the payoff is per definition negatively correlated to both connections and steps. Indeed, connections are even more costly than steps. A possible explanation is that subjects value the (successful) connections per se and see them as progress towards the common goal of information exchange. In addition, they may not be able to identify unnecessary connections. A second possible explanation is that participants not only take the monetary costs of steps into account, but are also generally impatient and attach costs to waiting until the round is finished.

5.2 Treatment effects over time

The next step in the analysis is to see whether the treatment effects described in the previous section change in the course of the 10 rounds. Figure 6 shows the average profit of the different networks in all ten rounds.

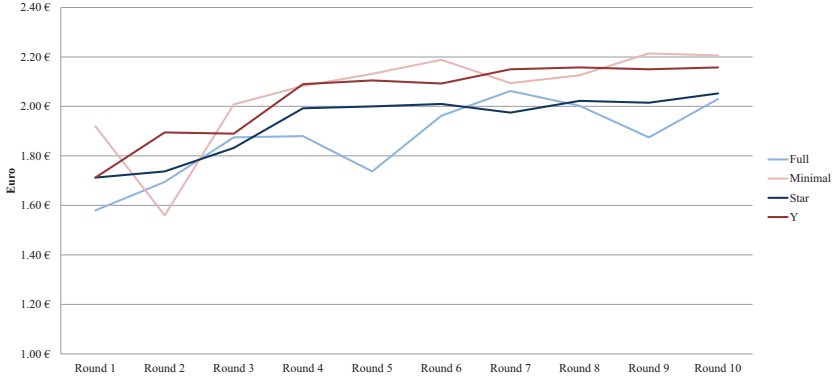
To see if there is a difference in the networks, the results from the first five rounds are compared to the results from the last five rounds. In the first five rounds, hardly any clear pattern can be seen in the average profit, testing for pairwise differences shows that only one difference - Minimal achieving a higher profit than Full - is significant (comparing the average profit of the first five rounds, $p = 0.044$). The pattern becomes clearer when looking at the last five rounds, however. The average profit of the last five rounds is significantly higher for Y and Minimal than for Full and Star²¹. The overall pattern of treatment differences is therefore driven by the results in the last five rounds.

¹⁹See Table A in the Appendix for a complete list of questions.

²⁰There is no difference according to a Kruska-Wallis test between treatments in average age, average number of semesters, average math grade (scaled to reflect different kinds of course), average German grade (scaled to reflect different kinds of course), number of males in the group, and number of economists in the group.

²¹The p-values are as follows: Y vs. Full: 0.049; Y vs. Star: 0.000; Minimal vs. Full: 0.099; Minimal vs. Star: 0.003; all other comparisons are insignificant with $p > 0.1$.

FIGURE 6: Average profit by treatment, all 10 rounds



Summarizing treatment effects, the Minimal and the Y networks are better in terms of profit than the Star and Full networks. This difference is due to the high number of connections in the Full network and the high number of steps in the Star network. These results are mainly driven by the behavior in the second half of the experiment.

5.3 Learning and convergence

The structure of the experiment also enables the dynamic process the different networks go through to be analyzed. This is also interesting with regard to practical applications of the research question. R&D networks, for example, in most cases exist for a longer time period. Usually, the interaction among the different agents is repeated with the same information structure. To see whether groups improve their performance during the course of the experiment, the first five rounds are compared to the last five rounds for each treatment. Looking at Figures 6, 7, and 8, the decisions on average seem to improve, with the groups needing fewer steps and connections and therefore achieving a higher profit in later rounds.

This is confirmed by a Wilcoxon-Signed-Rank testing for differences in the steps needed to achieve full information in each network (All p-values are < 0.02). For the other target variables profit and connections, only the Y network improves significantly when comparing the first half of the experiment to the second half ($p = 0.031$). Hypothesis H2 therefore can be partially rejected: subjects do indeed need fewer steps in later rounds, but only one network structure (Y) also shows significant differences in profit and connections.

FIGURE 7: Average connections by treatment, all 10 rounds

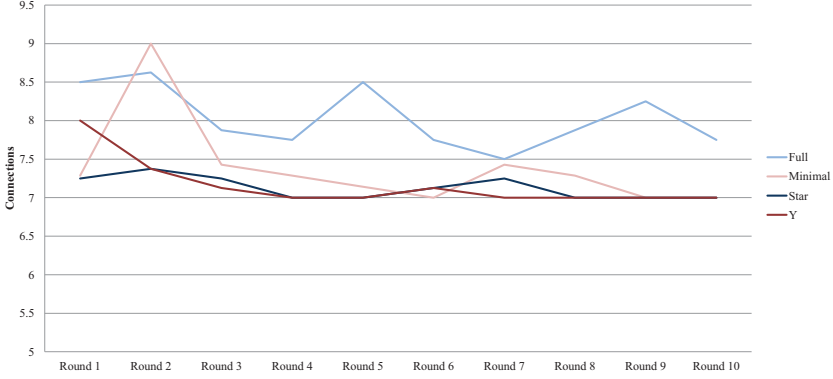
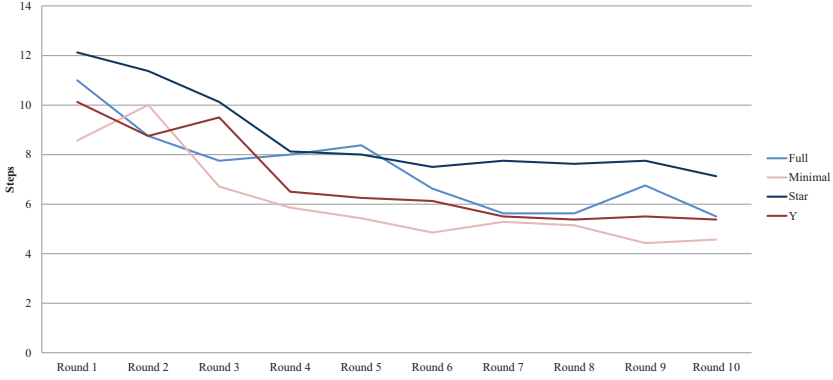


FIGURE 8: Average steps by treatment, all 10 rounds



Section 4.2 describes three different ways to look at possible convergence over time in the networks. Using the first method, one looks at the number of consecutive rounds (counted from the end) with the identical result. On average, these are 2.25 in the Star network, 4.5 in the Y network, 2.25 in the Full network, and 3.43 in the Minimal network. Testing these results with pairwise Mann-Whitney-U tests, groups in the Y network converge significantly faster than those in the Star ($p=0.027$) and Full ($p=0.038$) network, but not than those in the Minimal network. Further significant differences cannot be found.

The second method uses the average ratios of all decisions in step 1 to 4 which were identical in the same step of consecutive rounds. Comparing Star, Y, and Minimal, no statistically significant differences can be found. Only the Full network shows less convergence compared to the other network structures: compared to the Star and Y network in steps 3, 4, and the average of the first four steps and compared to the Minimal network only in step 4.

Finally, the last method investigates in how many consecutive runs - counted from the end - a group's

decision is exactly identical in step 1 to step 4. The differences in this number between the network structures are not significantly different (using a Kruskal-Wallis test). However, this number increases from the first five rounds to the last five rounds in all networks, indicating that all networks do indeed move into the direction of equilibrium behavior in the course of the 10 rounds.

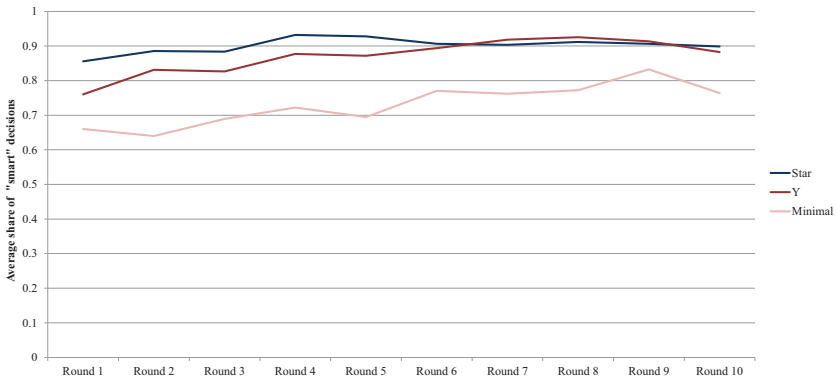
Summarizing the results on the dynamics from the experiment, all networks need fewer steps in the later rounds, while only the Y network also improves in profit and connections. Regarding convergence, the results are not as clear cut and depend on the method used. However, it seems that most do indeed converge to some equilibrium behavior in the later rounds.

5.4 Individual decision making

In addition to the aggregate behavior analyzed in the preceding sections, one can also look at individual decision making in the networks. To this end, the networks where there is no (or only a very small) coordination problem - i.e. Star, Y, and Minimal - are analyzed separately from the Full network which suffers from a large coordination problem.

In the first three networks mentioned, it is possible to classify individual decisions as “smart” (i.e. maximizing the expected payoff) as the coordination problem is not so severe²². Figure 9 shows the share of “smart” decisions by all subjects in the three different networks.

FIGURE 9: Average share of “smart” decisions



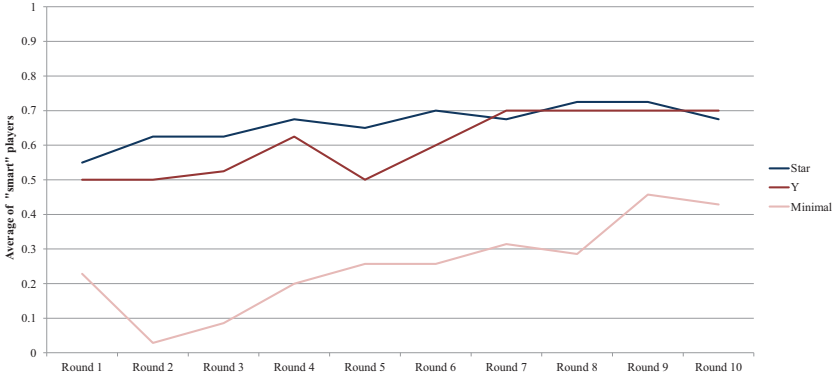
Reflecting the slight difference in their coordination problem, subjects in the Y and Star networks make the fewest mistakes and consistently play “smart”, while subjects in the Minimal network make “smart” decisions somewhat less frequently. Still, the overall share of “smart” play is pretty high, with a slight trend towards better decision-making in the later rounds. This reflects the aggregate results of

²²To avoid classification errors, the coding was done by two persons separately. Figure E in the Appendix shows the share of identical classifications between the two coders.

higher average payoffs in the later rounds as subjects learn to avoid mistakes in the later rounds and therefore make better decisions. The scope for this learning is largest in the Minimal network, resulting in a clearer upward trend.

A second way to look at the individual decisions is to classify the subjects into “smart” and “non-smart” players. A subject is classified as “smart” if at least 90% of her decisions are “smart”. Using this classification makes it possible to see whether the results described above are driven by single subjects or whether all subjects behave the same. Figure 10 shows the share of “smart” players in the different networks.

FIGURE 10: Average share of “smart” players



Again, Y and Star are different from Minimal, with a consistently higher share of “smart” players. All networks again exhibit an upward trend, pointing again to the fact that subjects learn to avoid mistakes in the course of the 10 rounds. Another interesting observation is that for the Star and Y networks, there is hardly any improvement in the last four rounds. One possible explanation would be that all subjects capable of understanding the situation have done so by round six and are therefore classified as “smart”, while the rest of the players keep on making mistakes even through repetition of the game.

The Full network suffers from a severe coordination problem, so it is hardly surprising that the best achievable outcome is not realized. There are mainly two pieces of information which might serve as a guide for the players in the decision situation: The connection attempts of the other players in the preceding step and the player(s) whose information they are still missing. To see if players actually use these information (and which is more important), two simple heuristics are investigated:

1. Connect with somebody whose information is still missing. If you already have all the information, choose randomly (called “No info”).
2. Connect with somebody who has tried to connect with you in the preceding period. If nobody tried

to connect with you, choose randomly (called “Call back”)²³.

For both of these heuristics, two rules additionally hold: subjects never call themselves (which is the equivalent of not trying to establish any connections) and never try to contact the subject with whom they have just established a connection. Table 2 shows the simulated results from these heuristics and as a comparison the actual results from the first two rounds²⁴.

TABLE 2: Heuristics in the Full network

Heuristics	Connections	Steps
No Info	9.10	12.90
Call Back	10.40	18.23
<i>Actual results</i>		
Round 1	8.50	11.00
Round 2	8.63	8.75

Source: Own calculations, simulation results after 100,000 runs.

In addition to this aggregate view of behavior in the Full network, all individual decisions were classified as either compatible with the two heuristics or not. This results in a share of 0.66 of decisions that are compatible with the “Call back” heuristics and a share of 0.86 decisions that are compatible with the “No info” heuristic in the first round. Taking these two approaches together, it seems that the “No info” heuristic is able to explain the data pretty well, certainly better than the “Call back” heuristic. Subjects thus seem to concentrate on collecting all available data, not on establishing a connection per se. However, the actual results from the first rounds are still better than the results simulated with the heuristics, especially concerning the steps needed. One explanation is that the subjects find some kind of coordination device not covered in the heuristic. As mentioned before, the distribution of connection attempts between the different nodes in the Full network is no different ($p > 0.1$) from an equal distribution. Refining this analysis, however, reveals that subjects try to connect with one of their geographic neighbors²⁵ significantly more often ($p < 0.05$) than with the other two subjects. Therefore, the geographic location might serve as an additional coordination device, improving the heuristic and making fewer steps possible²⁶.

As a short summary, the coordination problem plays a big role (as expected) for the individual decisions. In the network structures without a coordination problem, the subjects are able to play close to the optimal outcome, especially in later rounds. For the Minimal network with its small coordination problem, it gets harder for the participants to play this way. The large coordination problem in the Full

²³For this heuristic, an additional rule has to be followed: If you have not established a connection in the preceding step and somebody tried to connect with you, choose randomly between calling him back and calling somebody else. If this rule is not added, the possibility exists that no connections are established, resulting in a zero profit.

²⁴The first two rounds are used as the results from later rounds are very path-dependent and therefore not suited to evaluate heuristics.

²⁵By geographic neighbor, the two nodes closest on the screen - i.e. along a virtual circle - are denoted.

²⁶In the data, this rationale can unfortunately not be distinguished from the heuristic without it, as one still has to assume that every participant is chosen with a positive likelihood.

network makes it necessary for the participants to rely on heuristics to achieve some coordination. They mainly use their own information status as a guide who to contact next.

6 Conclusion

The experimental results suggest that the network structure strongly influences the speed and efficiency of information exchange. As expected, increasing the number of possible links in a network has positive (due to more possibilities of information exchange) and negative effects (due to coordination problems). In our experiment, the most efficient network structures are those that find a compromise between these two conflicting aspects, namely the Minimal and the Y network.

Consequently, the results of this paper suggest that cluster and network policies should not pursue the goal to maximize the number of links between the actors involved. In cluster and network structures with only a few links, impulses for additional cooperations will probably increase the efficiency of information sharing. Additional network links in networks that feature a lot of links from the beginning, however, might result in making information sharing and coordination less efficient. Instead, behavior of participants in the Full network suggests the usage of a simple heuristic: participants try to connect with group members whose information they are missing. On the one hand, this helps to achieve relatively favorable outcomes; on the other hand, it prevents the group from reaching efficiency. Furthermore, participants' satisfaction is positively correlated with the number of connections they establish. This could be one reason for superfluous connections and thus limit learning in the way observed. Besides, policies which use a competition to reward promising R&D clusters might use the structure of information exchange as an additional evaluation criterion. Turning to the organizations themselves, our results suggest that the management of the information flow should be an important aspect of the work of a cluster management, especially if cooperation is planned for a longer term. While such measures may incur costs, clusters should accept that coordination problems are real and harmful.

Learning takes place in all network structures, as groups are able to decrease the steps needed over the course of the ten rounds. However, only groups in the Y treatment manage to improve profit and decrease connections significantly. It is furthermore interesting that the differences between the networks only come to light in the second half of the experiment. One must therefore distinguish between experienced and inexperienced networks. In the former, the network structure is a decisive factor in the efficiency of information exchange. Thus, the analysis conducted here is more relevant to longer existing networks and older cluster initiatives.

Despite the prevalence of learning, a consistent pattern of convergence is not observed. This result may be driven by the restricted and ex ante known number of rounds. It might be interesting for future

research to relax this restriction. Generally, the experimental design simplifies the real life situation. For the analysis of R&D networks, situations with imperfect or tacit information diffusion, as well as variations of incentives, information distribution, and group size are natural extensions that should be analyzed.

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Appendix

Derivation of the optimal values in the Minimal network

In the Minimal network the coordination problem is a small one. As a starting point, one optimal path in the Minimal network is depicted in Figure D. Red numbers indicate the step, black lines the allowed links and red lines the established connections. From this, the following reasoning shows the optimal behavior for all participants: In step 1 the decision of everyone but lotu is clear: Laga and lira both try to connect with lotu; lotu however can choose to either call laga or lira. A rational lotu would select randomly as there is no way to predict lelo's behavior in step 2. Lelo in step 2 does not know which of the two connections was established in step 1: lotu with laga or lotu with lira. Consequently lelo selects randomly. The decisions of the others are straight forward. Laga or lira (depending on step 1) respond to lelo, the others are off or do not matter at all. Now two scenarios can take place:

1. In step 2 a connection was established. In this case steps 3 and 4 are clear. The optimum is reached.
2. In step 2 no connection was established. In this case, lelo knows that the decision was unlucky and successfully tries the other option. Everything is thus postponed by one step as all the other players learn about the history during the run (e.g. by failed communication). The group reaches full information in 5 steps and with 6 connections.

In either case a rational group does not need more than 6 connections. For every subsequent run, however, it is important to distinguish whether the group reached the commonly known optimum in the run before. If they did, it is assumed that they are able to repeat it until the end of the experiment. If not, lotu in step 1 and lelo in step 2 again select randomly (as there is no better rationale). As a result, the group needs 6 connections in every round. How many steps are needed depends on the random decision described beforehand. Assuming that groups are able to stick to an optimal path if they have played it once, one can conclude that rational participants would need a total of 40.999 steps for 10 rounds in expectation. In the first round, one would expect 4.5 steps on average, in the last round 4.00098.

Instructions²⁷

Welcome to the experiment!

You are participating in a study of decision-making behavior in the context of experimental economics. During the study you and the other participants will be asked to make decisions. You can earn money with this study. How much money you earn is dependent on the course of the experiment. You will receive detailed instructions about this in the following. All participants are paid in cash directly after the experiment one by one. To assure this, please remain seated after the experiment until your cabin number is called.

During the course of the experiment, no participant will receive information about the other participants' identities. All decisions are therefore made anonymously.

Should you have questions, please give a sign to alert one of the laboratory's employees. He will come to you and help you. **No communication with the other participants is allowed during the experiment; breaking this rule will lead to an immediate exclusion from the experiment.**

²⁷These instructions are translated from the original, German instructions.

Instructions

The experiment consists of **10 rounds**. Before these rounds start, we would like to ask you to answer some comprehension questions. The experiment can only start when all participants have answered these questions correctly.

Initial situation

In the experiment, 5 randomly chosen participants form one group. This group stays the same for all 10 rounds. **Every group member** possesses **one piece of private information** at the beginning of each round. There are thus 5 different available pieces of information in each group. The group members form a network. During the course of a round the group members can establish connections with each other and exchange their information in that way. In the experiment, the possible connections which can be established in the network are shown on the screen. **Each circle represents a group member and each line represents a possible connection.** The names “lotu”, “laga”, “leje”, “lira”, and “lelo” identify the different positions in the network. Your own position in the network is marked red during the experiment.

Course of the experiment

Each round consists of several periods. At the beginning of each period every group member decides with which other group member he wants to establish a connection. It is also possible to establish no connection in a period. You choose the group member you want to establish a connection with by **clicking the corresponding circle** on the screen. The circle will then be colored blue. As soon as you confirm your choice, the connection attempt is started. If you do not want to establish a connection in this period, please click the corresponding button on the screen.

Only if **two group members choose each other** in one period, a **connection is actually established** and **all pieces of information** which both group members possess **are exchanged**. You are therefore not only passing along your own piece of private information but also - if present - the pieces of information of other participants if you have received them beforehand. In one period, each group member can only establish one connection at most. It is therefore also possible that no connection is established in a period.

A period ends when all participants have made their decision. It follows that all participants start each period at the same time. Starting with the second period, a table summarizing the earlier periods is displayed for every group member. This table also shows which pieces of information you currently possess and which group members have tried to establish a connection with you in the last periods.

A round ends when **all group members possess all 5 available pieces of information** or the deposit (see below) is depleted. A round does not yet end when one group member possesses all

information. The number of periods per round is therefore not predetermined. At the end of each round, the table summarizing the periods is shown again, this time including, in addition, the payoff of the current round.

Participants' payoff

The **group's payoff** per round is calculated as follows: At the beginning of each round, every group has a **deposit of EUR 20**. In the course of a round, the following costs are subtracted:

- Each period costs EUR 0.30.
- Each established connection in the group costs EUR 0.8.

Trying to establish a connection without succeeding is costless. Periods however always cost EUR 0.30, even when no connections are established in them. The group's earnings are calculated by **subtracting all costs from the deposit** for one round. If the total costs from periods and established connections exceed the deposit, the round is aborted and the group's earnings for this round are 0.

The group's payoff is divided equally among the group members. The payoff of one group member for a round is therefore **one fifth of the group's payoff in this round**.

The total payoff for each participant is the sum of the payoffs in all 10 rounds. All members of a group therefore have the same payoff.

Tables and Figures

TABLE A: Questionnaire variables

Variable name	Question asked
Sex	Are you male or female?
Age	How old are you?
Study field	Which subject are you currently studying?
Length of study	How many semesters have you been studying your current subject?
Abi	What was your final grade point average in high school?
German	What was your last grade in high school in German?
Math	What was your last grade in high school in math?
Open start	Please think back to the beginning of the experiment. How did you decide to which group member you wanted to establish a connection in the very first period?
Closed diff	Did you proceed differently concerning establishing connections in the first one or two rounds than in the later rounds?
Open last	Please comment briefly on your decisions in the last round.
Closed happy	In how many rounds have you been content with the result?
Closed minperiods	In your opinion, how many periods are at least necessary until every group member has all information?
Closed minconnections	In your opinion, how many connections are at least necessary until every group member has all information?
Closed important1	Are all group members equally important for the exchange of information in your opinion?
Closed important2	If not: Which group member(s) is (are) the most important? (You can choose more than one)
Closed coop	Do you think that all group members worked together to exchange information?
Closed aspects 1 to 10	Which of the following aspects were important for your decisions with whom to establish a connection:
Closed aspects 1	Chance
Closed aspects 2	Experience from earlier rounds
Closed aspects 3	Connection attempts / order of connections from earlier periods
Closed aspects 4	Establish a connection with a group member whose information I am still missing
Closed aspects 5	Names (laga, leje, lotu, lira, lelo) of the other group members
Closed aspects 6	Geometrical position ("to the left of me", "to the right of me", etc.) of the other group members
Closed aspects 7	More / less important position of the other group members in the network
Closed aspects 8	Improving the result from the previous round
Closed aspects 9	Few alternatives to choose from
Closed aspects 10	Spread information, even without receiving new information myself

FIGURE A: Example of an optimal path in the Full network

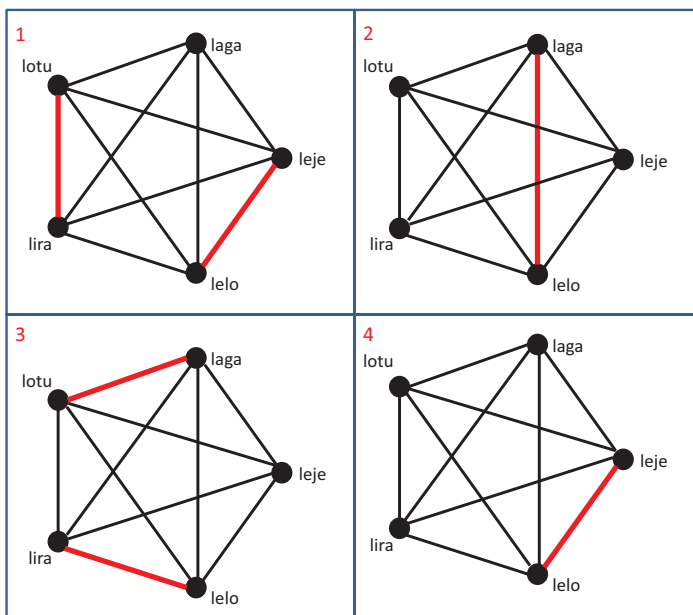


FIGURE B: Example of an optimal path in the Star network

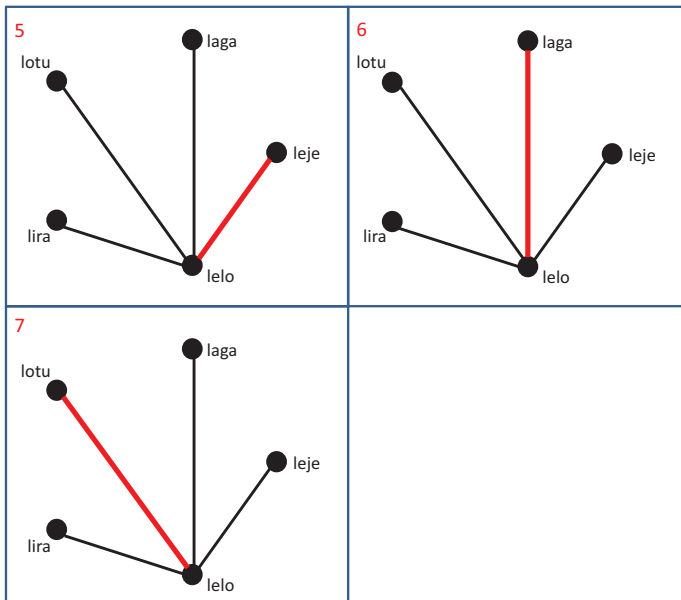
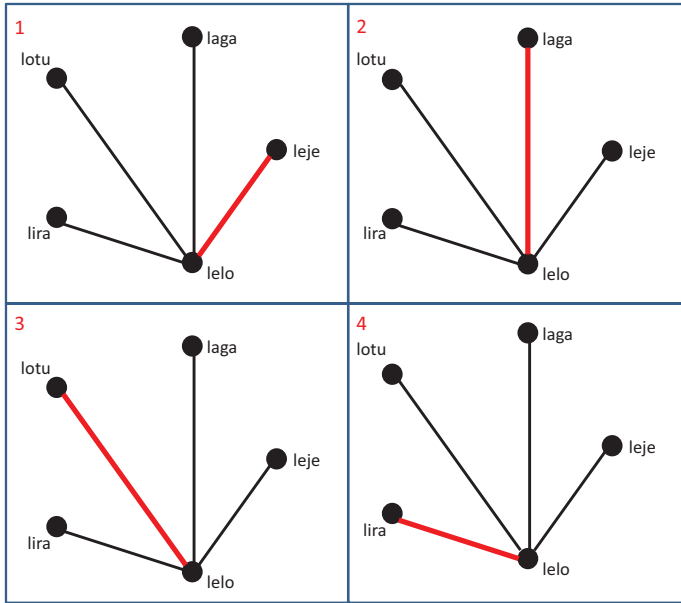


FIGURE C: Example of an optimal path in the Y network

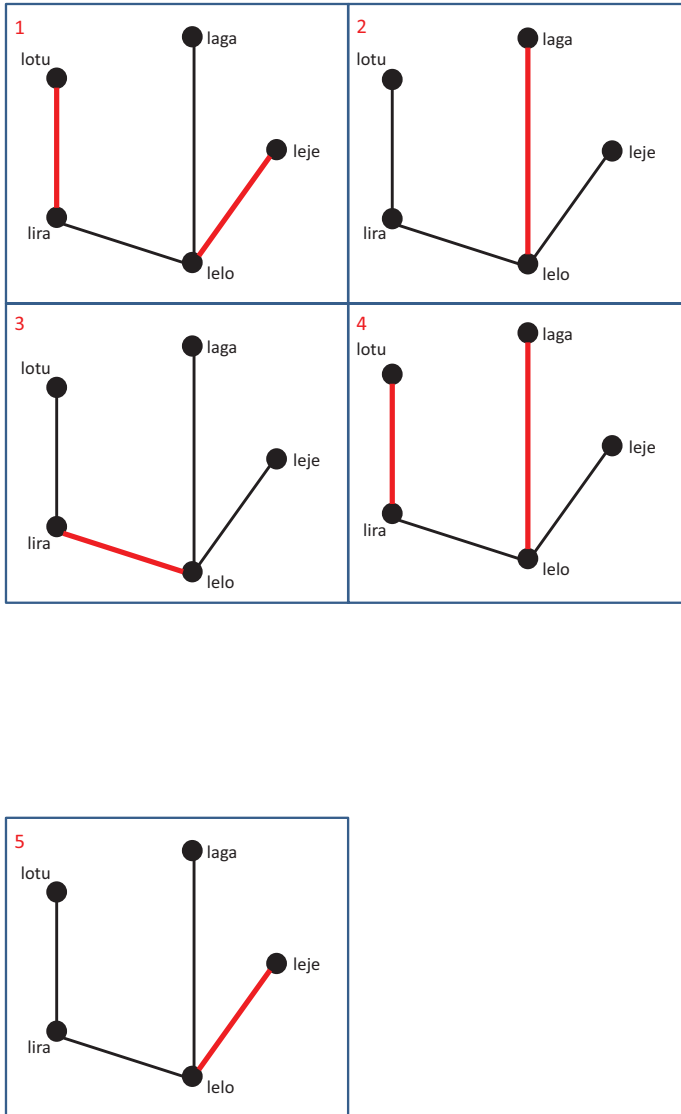


FIGURE D: Example of an optimal path in the Minimal network

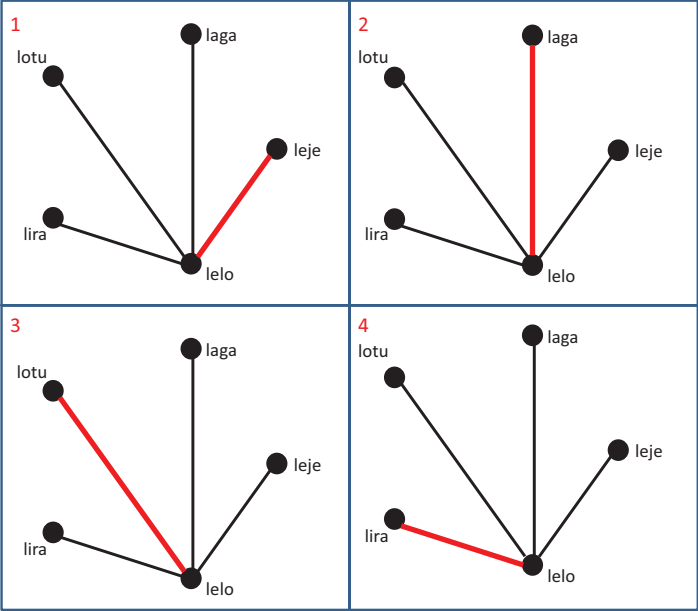


FIGURE E: Share of identically coded decisions

