Financial Contagion in the Laboratory:

Does Network Structure Matter?*

John Duffy
Professor of Economics, University of California, Irvine
duffy@uci.edu

Aikaterini Karadimitropoulou
Research Fellow, Bank of Greece and Senior Lecturer in Macroeconomics University of East Anglia
AKaradimitropoulou@bankofgreece.gr

Melanie Parravano
Lecturer in Economics, Newcastle University
Melanie.Parravano@ncl.ac.uk

We explore the role of interbank network structure and premature liquidation costs for the likelihood of financial contagions in a laboratory experiment. We consider complete versus incomplete networks of banks linked together by interbank deposits, and we further vary premature liquidation costs. Subjects play the role of depositors deciding whether or not to withdraw funds from their interconnected bank. We find that when liquidation costs are high, a complete network structure is significantly less vulnerable to financial contagions than an incomplete network structure. However, when liquidation costs are low, network structure is less important for the frequency of financial contagions.

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The financial crisis of 2007-08 has reinforced the view that interbank network linkages are crucial to understanding the financial fragility of a country's banking system. Unlike earlier financial crises, the crisis of 2007-08 did not simply involve depositors running to withdraw money from their own banks. Rather, it also involved banks (and some large non-banks) with interbank deposits running on other banks holding those deposits. For example, in the U.S., the collapse of Lehman Brothers was associated with a $423 billion dollar contraction in the U.S. dollar *interbank* lending market (Gorton 2010), and this in turn pushed other banks to the brink, requiring government bailouts (e.g., Morgan Stanley) or led them to be sold off (e.g., Merrill Lynch).

The traditional view of financial crises as involving a run by bank depositors on their *own* bank has been modeled as a self-fulfilling equilibrium coordination game by Diamond and Dybvig (1983) where depositor's beliefs play a pivotal role. The more modern view of *financial contagion* as an equilibrium phenomena arising from the interbank *network structure* was first proposed by Allen and Gale (2000). While the Diamond and Dybvig model involves the behavior of depositors in a single bank, Allen and Gale's model considers the behavior of depositors across many interconnected banks. In this paper, we explore the key implication of Allen and Gale's interbank model of financial crises, namely that the network structure *matters* for the fragility of the banking system. We address the importance of network structure for financial fragility using the methodology of experimental economics, which provides us with precise control over the network structure of interbank connections as well as over the information that is available to depositors in that network. This control enables us to gather data that can be used to directly test the role played by network structure in the spread of a financial crisis. While there are many experimental studies of the Diamond and Dybvig model of bank runs, our paper provides the first experimental test of whether the *interbank network structure* matters for the likelihood of financial contagion. In addition, we also consider the role played by premature liquidation costs for the susceptibility of the financial system to a contagion and the interaction of liquidation costs with network structure. As the size of the liquidation costs affects the rate of return that bank depositors get in the event that their bank goes bankrupt, higher liquidation costs (a low liquidation rate) can make the interbank system more fragile and susceptible to panic. Network structure might play a role in mitigating such risks and that is why we consider the interaction between different liquidation rates and different interbank network structures in our experiment.

In the experiment, subjects are depositors in their local regional bank. As in the Allen and Gale model, this regional bank is one of four interconnected banks in the economy. Each bank holds deposits with other banks as a means of insuring against the uncertain liquidity demands of their depositors. Following Allen and Gale (2000), we focus on two different interbank market structures, namely, an "incomplete" market structure where the banks are partially connected (i.e., each bank holds deposits in one adjacent bank) and a "complete" market structure, where the four banks are fully connected (i.e., each bank invests a fraction of their deposits in each one of the other three banks). According to the model, as detailed in Section 2, the introduction of interbank linkages (i.e., exchange of deposits) implies that, in the absence of exogenous liquidity shocks, both market structures can implement the first-best (i.e, no bank run equilibrium). However, if there are liquidity shocks, then the interbank market structure can matter for whether the first-best equilibrium is attainable. Specifically, when there are liquidity shocks, if banks' liquidation rate on long-term investments is sufficiently high, both market structures can continue to implement the first-best equilibrium. However, when there are liquidity shocks and a sufficiently low liquidation rate, the first-best can only be attained under the complete market structure; under the incomplete market structure there is a unique "contagion equilibrium" involving runs on all banks in the network.

Our experiment was designed to test the implications of such fragility and for this reason, in every round we introduce a liquidity shock to one of the four banks in the economy. Depositors' payoffs are carefully calibrated to capture the model assumptions. The result is a risk-sharing coordination game where there is a unique Nash equilibrium involving full contagion when the interbank network is incomplete and the liquidation rate is sufficiently low. By contrast, when the interbank network structure is complete or when the liquidation rate is sufficiently high, both the inefficient and efficient equilibrium coexist allowing for the possibility of either the full contagion or no-contagion equilibria, respectively. We implement a 2x2 between-subjects experimental design, combining each 'network structure' and two levels of liquidation rate (low and high). Participants played 30 rounds of a game in which they were repeatedly confronted with the choice of withdrawing or keeping their deposits with their local regional bank. Our main research objective is to understand whether a more integrated banking system leads to smaller self-fulfilling spillover effects, as predicted by the model.

To preview our findings, our main experimental result is that, when liquidation costs are high so that the return in prematurely liquidated assets --"the liquidation rate"-- is *low*, and the interbank network structure is *incomplete*, we find that all of the economies converge to an outcome approximating the full-contagion equilibrium, which is the unique equilibrium outcome in that setting. By contrast, if the network structure is complete and if the liquidation rate remains low, then there are multiple pure strategy equilibria: full contagion and the more efficient equilibrium where the bank run is limited to the adversely affected bank only. In that setting we find that about one-half of our experimental economies achieve the full contagion equilibrium while the other half achieve the efficient risk-sharing equilibrium outcome where the crisis is limited to the bank facing the adverse shock. Econometric analysis confirms that the probability of a participant withdrawing her deposit in the low liquidation rate treatment is significantly larger under the incomplete network structure than under the complete one, even after controlling for the past behaviour of co-players and own past behaviour. Moreover, in the incomplete network structure, we also observe the expected pattern of contagion, where there is a spillover from the shocked bank to the bank directly connected with that bank and then on to the next connected bank until finally the full banking network is affected. Therefore, our results provide support for the model's prediction that in an incomplete interbank network structure, an initial financial shock spreads to all banks and the crisis becomes global.

When the liquidation rate is high (that is, when liquidation costs are low), both the full-contagion and no contagion (local-only crisis) outcomes are equilibria under both the complete and incomplete network structures. In this case, we find that our experimental economies generally coordinate on the efficient equilibrium where the crisis is limited to the adversely affected bank. That is, when liquidation rates are high, network structure does not play a role in reducing the frequency of contagions. We conclude from these findings that high liquidation rates (low premature liquidation costs) or more complete interbank network structures may be substitutes for one another in reducing the likelihood of financial contagions.

The rest of the paper is organized as follows. The next section situates our paper in the relevant literature. Section 2 presents the model and the main hypotheses concerning the consequences of network structure for financial contagion. Section 3 describes our experimental design and Section 4 presents our experimental results as a number of different findings. Section 5 provides a summary and suggestions for future research.

1. LITERATURE

To date, the experimental literature on bank runs has primarily focused on the behavior of depositors in a *single* bank following the set-up of Diamond and Dybvig (1983).[1] These experimental papers have typically focused on the coordination game aspect of that model, asking subjects whether they wish to keep their deposits in the single bank or to withdraw those funds. As in Diamond and Dybvig's model, early withdrawal can be a (self-fulfilling) best response if depositors believe that a sufficient number of other depositors will withdraw early. In particular, Madiès (2006) investigates the possibility and the degree of persistence of self-fulfilling banking panics and shows that those phenomena are both persistent and difficult to prevent. When looking at alternative ways to prevent those type of crises, Madiès's results suggest that a suspension of payment (i.e., more time to think before making a withdrawal decision) is more efficient than partial deposit insurance. Garratt and Keister (2009) show that the frequency of bank runs increases with (1) uncertainty about the aggregate liquidity demand, and (2) the number of opportunities subjects have to withdraw. Schotter and Yorulmazer (2009) demonstrate that bank runs can be mitigated by the presence of insiders (i.e., depositors who have no uncertainty about the quality of the bank). Arifovic et al. (2013) show that the occurrence of bank runs depends on a coordination parameter, which measures the fraction of depositors that are required to wait so that they can earn a higher payoff than those who withdraw. Their results point towards the existence of three different zones, where bank runs are (i) rare when the parameter is low; (ii) frequent when the parameter is high; (iii) indeterminate and dependent on the history of the game for intermediate values of the coordination parameter. Finally, Kiss et al. (2012, 2014) study how the observability of the withdrawal decisions of other depositors (simultaneous or sequential) interacted with the amount of deposit insurance affects the incidence of bank runs. They find that greater deposit insurance and observability of withdrawal decisions in a sequential (as opposed to simultaneous) order both work to reduce the likelihood of a bank run and that certain sequential information structures can even prevent bank runs from occurring if depositors are sufficiently patient.

Two papers have used a 2-bank model to explore contagion issues, Brown et al. (2017) and Chakravarty et al. (2015). In both studies, depositors in one bank make their decisions first and the depositors in the second bank observe the decisions of depositors in the first bank before acting. Moreover, the banks' liquidity needs are either linked or independent and this is common knowledge to all depositors in Brown et al. (2017), whereas it is only known to the depositors of the first bank in Chakravarty et al. (2015).[2] While in Brown et al. (2017) contagion occurs only when the banks have economic linkages, in Chakravarty et al. (2015) the depositors' actions in the first bank significantly affect the behavior of depositors in the second bank even when the banks' liquidities are independent. While these papers study interbank linkages, with just two banks, the network structure cannot play much of a role. None of these papers consider variations in the interbank network structure for efficient risk sharing and the susceptibility of the banking system to financial crises which is the main contribution of this paper.[3] Indeed, Chakravarty et al. (2015, p. 50) conclude by suggesting that for future experimental research on financial crises "there is value not only in reinforcing banking inter-linkages for their value in diversifying risk (as in Allen and Gale, 2000) but also in making those linkages common knowledge". This is precisely the approach that we take in this paper.

2. MODEL

2.1 The Environment

The model we adopt is based on the intertemporal model of Allen and Gale (2000). There are three dates, $t=0,1,2$ and four regions. Each of the four regions is served by a local regional bank labeled A, B, C and D. Each region/bank has a continuum of ex-ante identical depositors who have an endowment of one unit of the consumption good at date 0 and nothing for the other two dates. These depositors have preferences as in Diamond and Dybvig (1983); they get utility from consumption only in date 1 (2) with probability w $(1-w)$.

$$U(c_1, c_2) = \begin{cases} u(c_1) \text{ with probability } & w \\ u(c_2) \text{ with probability } & 1-w \end{cases}$$

Each bank can invest the deposits of its customers in one of two assets. The liquid (or short) asset acts as storage technology. For each unit of deposits invested in the liquid asset at date t, this short-term asset yields a return of 1 at date $t+1$. The second, illiquid (or long) asset takes two periods to mature, but yields a higher payoff of $R>1$ per unit invested; if investments made in this long asset have to be liquidated early, i.e., at date 1 rather than at date 2, the liquidation return per unit of the asset is given by r, where $0<r<1$. We associate high (low) liquidation costs with low (high) liquidation rates, where the latter are the values for r.

The regions differ in the likelihood that consumers are impatient (early) withdrawers or patient (late) withdrawers. Let w_i denote the probability of early withdrawers in region *i*, and assume that there are just two possible values for $w_i(low \vee high)$: $0<w_L<w_H<1$. Assume further that there are two equally likely states of the world, S_1 and S_2, and that the realizations of the liquidity shocks across the four regions and two states are common knowledge and as given in Table 1:

[Insert Table 1 here.]

The timing of moves is as follows. At date 0, all depositors deposit their endowment in their regional bank and these banks invest these deposits in the two assets. At date 1, state and depositor uncertainty is resolved; the state of the world is revealed and each depositor's liquidity type is made known according to the probabilities given in Table 1. However, the banks are not able to observe a depositor's type, so it is possible that late (patient) depositors mimic early (impatient) depositors by also withdrawing their deposits early.

2.2 The Optimal Risk Sharing Contract

The contract that banks in each region offer their depositors at date 0 can be characterized as the solution to a planner's problem that implements the efficient (first-best) solution without the need to verify depositors' types. This solution is achievable only if the planner is able to transfer resources across banks in different states of the world. Allen and Gale (2000) further demonstrate that this optimal solution can also be decentralized by the banks themselves through their use of the interbank deposit market to insure against uncertain liquidity needs in their own bank/region.

Specifically, in this decentralized setting (which is the environment we study in the laboratory), the optimal contract that each bank offers to its depositors pays $c_1=1$ units of consumption to those withdrawing at date 1 and $c_2=R$ units of consumption to those withdrawing at date 2. Each bank knows that the aggregate demand for liquidity is the same in each state and they also know the average fraction of impatient depositors across all four banks, $\gamma=\frac{w_H+w_L}{2}$. Thus, each bank invests a fraction γ of deposits in the short asset and a fraction $1-\gamma$ of deposits in the long asset at date 0, as it is efficient to pay early withdrawers with the short asset and late withdrawers with the long asset.

The optimal risk sharing arrangement is implemented by transfers of resources that banks hold at other banks. For example, if the state of the world S_1 occurs, then each bank has γc_1 units of the short asset and needs to pay c_1 to each impatient depositor at $t=1$. Banks A and C have excess demand for the short asset in the amount $(w_H-\gamma)c_1$, while Banks B and D have an excess supply of the short asset in the amount $(\gamma-w_L)c_1=(w_H-\gamma)c_1$. Thus at date 1, it is possible to satisfy the excess demand of banks A and C if banks B and D transfer their excess supply of the short asset while at date 2, the opposite transfer flow has to take place from banks A and C to banks B and D to satisfy the excess demand in that period. These transfers can be implemented by an appropriate allocation of interbank deposits across the four regions. However, the precise amount of these interbank deposits will depend on the network structure of the banking system.

2.3 The Importance of Network Structure

With four banks, there are several possible symmetric network structures for interbank linkages, but we choose to focus on the two that are illustrated in Figure 1, as they capture the essential insights about the importance of network structure for financial contagion and they involve network connections among all four banks/regions in the economy. While there are also *asymmetric*, (e.g., "star") network structures, we focus here on *symmetric* network configurations for the banking system as these are easier to explain to experimental subjects and such networks do not involve payoff asymmetries that may trigger inequity (fairness) concerns.

[Insert Figure 1 here.]

In the incomplete network illustrated in Figure 1, bank A places deposits with bank B; bank B places deposits with bank C; bank C places deposits with bank D; and bank D places deposits with Bank A. In line with our experimental instructions, a bank is said to be connected to another bank when it has placed a deposit in that bank. In this incomplete network configuration, Allen and Gale (2000) show that the first-best can be achieved if, at date 0, each bank places $(w_H - \gamma)$ of its deposits in the other bank with which it connected. By contrast, under the complete network structure depicted in Figure 1, each bank can place deposits with any of the other three banks. In this case, given the liquidity shock structure of Table 1, each bank's liquidity needs are negatively correlated with two of the other three banks (i.e., a bank with low liquidity needs is connected with two high liquidity need banks and one other low liquidity need bank, while a high liquidity need bank is connected with two low liquidity need banks and the other high liquidity bank). It follows that the first-best solution can be implemented by having each bank, at date 0, place $(w_H - \gamma)/2$ of its deposits in each of the other three banks [4].

The main difference between these two network structures is their susceptibility to what Allen and Gale term a "zero probability at date 0" perturbation. Specifically, suppose there is a state $\acute{S}$ such that the fraction of impatient depositors in (say) bank/region A is $\gamma + \varepsilon$, while it remains equal to γ in the other 3 regions as summarized in Table 2. Thus, in a perturbed state, the average liquidity demands across the four regions are higher than in the normal states S_1 or S_2. As this perturbed state is not known in advance, the continuation equilibrium is different from the normal state and depends on the network structure. The occurrence of this state leads the aggregate demand for liquidity to be greater than the system's ability to supply liquidity, and therefore to the possibility of a global crisis. Importantly, given the zero probability attributed to that state, banks don't change their investment portfolio.

[Insert Table 2 here.]

In essence, in this state, there are three possible outcomes for Bank A. In the first case, it can meet its excess liquidity demands by drawing upon its deposits with other banks and remain solvent. In a second case it can become insolvent, if after withdrawing its deposits from other banks, it must also liquidate some of its position in the long-term asset. Finally, a third possibility is that Bank A cannot meet its liquidity needs even by fully liquidating all of its long-term asset position and must declare bankruptcy. In the theory of Allen and Gale, the complete network structure is the one that is least susceptible to the last two outcomes, insolvency or bankruptcy, while less connected network structures are more susceptible to these outcomes. Our experiment is designed to test this implication of the theory. Specifically, we have the following two testable hypotheses (which depend on the parameterization of the model).

First, if the interbank market is *incomplete*, the bank facing the liquidity shock (Bank A) will go bankrupt and the crisis can spread to the other interconnected banks. Specifically, these interconnected banks can also become bankrupt if the liquidation rate, r, is small enough, a parameter we vary in our experiment. In a similar manner, the crisis then spreads to the whole system. So, if the interbank market is incomplete, and r is sufficiently low, a run on one bank spreads via a contagion to all other banks and leads to an economy wide financial crisis. On the other hand, if r is sufficiently large, then even under an incomplete network structure it is possible to sustain the first-best outcome where the crisis is limited to the one bank facing the liquidity shock (Bank A); in this case both the first-best and the full contagion outcome are equilibrium possibilities.

Second, if the interbank market is *complete*, the initial impact of a financial shock in one bank may be mitigated if every bank takes a small hit (that is, if every bank liquidates some of the long asset). This possibility exists *regardless* of the value of the liquidation rate, $0<r<1$. Of course it is also possible that depositors refuse to accept such losses (and choose to withdraw early) igniting a contagious wave of bankruptcies in the complete network setting as well. However, the possibility that the crisis is localized to the shocked bank (A) is always an equilibrium scenario (for any r) under the complete network structure and that is the main difference with the incomplete network structure that we wish to test with our experimental design.

2.4 Payoffs

Following Allen and Gale (2000), impatient depositors withdrawing at date 1 do not earn any interest on their deposits and are therefore promised a return exactly equal to the amount initially deposited at their bank. On the other hand, patient depositors are promised a return of R at date 2. However, due to the financial perturbation and possible contagion, some or all banks will need to liquidate part or all of their long-term asset. Given that this is done at a liquidation rate of $0<r<1$, those banks will be unable to pay back, either patient, impatient, or both type of depositors, their promised returns. In those situations, the payoffs are equal to the ratio of the total asset value of the bank divided by the number of withdrawers (including both depositors and connected banks).

Let q^i represent the value of a deposit in bank i at $t=1$. If q^i is less than the promised return in date 1 (i.e., c_1), then, regardless of whether the withdrawer is another bank or a consumer, they will each get q^i from the bank for each unit invested at $t=0$. Given the nature of the interbank network structures, this requires all q^i values to be determined simultaneously.

Consider for instance the *Incomplete Network Structure*. Assume that all depositors of Bank A withdraw at $t=1$, so that the total demand is $n+z$, where n is the number of withdrawers and each deposited one unit at $t=0$ and z is the deposit that Bank D holds in Bank A. The liabilities of Bank A are then valued at:

$$(n+z)q^A \tag{1}$$

The assets of Bank A are the y units it invested in the short asset, the x units it invested in the long asset that will be prematurely liquidated at rate, r, and the amount z of deposits that Bank A has with Bank B. Therefore, Bank A’s assets value is given by:

$$y + rx + z\,q^B \quad (2)$$

The equilibrium values of q^A require the values of assets and liabilities to be equal, so that:

$$q^A = \frac{y + rx + z\,q^B}{n + z} \quad (3)$$

A similar equation will hold for any Bank *i* in which q^i is less than the promised return in period 1.

This equation can be used so long as q^B is equal to the promised return, c_1. If $q^B < c_1$, then the equivalent equation is needed to estimate q^B, which will depend on the value of q^C; and so on.

Similarly, for the *Complete Market Structure*, assume that all depositors of Bank A withdraw at $t = 1$, so that the total demand is $n + 3z$, where n is the number of Bank A customers who each deposited one unit at $t = 0$ and z is the amount deposited in Bank A by each of Banks B, C, and D. The liabilities of Bank A are then valued at:

$$(n + 3\,z)\,q^A \quad (4)$$

The assets of Bank A are again the y units it invested in the short asset, the *x* units invested in the long asset that will be prematurely liquidated at rate, *r*, and the amount z that Bank A deposited in each of Bank B, C, and D. Therefore, the assets value is given by:

$$y + rx + z\left(q^B + q^C + q^D\right) \quad (5)$$

The equilibrium values of q^A require the values of assets and liabilities to be equal, so that:

$$q^A = \frac{y + rx + z\left(q^B + q^C + q^D\right)}{n + 3\,z} \quad (6)$$

A similar equation will hold for any Bank *i* in which q^i is less than the promised return in period 1.

This equation can be used as long as q^B, q^C, and q^D are equal to the promised return, c_1. If $q^B < c_1$, and/or $q^C < c_1$, and/or $q^D < c_1$, then the equivalent equation is needed to estimate $q^B$and/or q^C

and/or q^D, which will depend on the value of all deposits at $t=1$ in the banks with whom they are connected.

As detailed in the next section, we present these different payoff calculations to depositors in the three banks as payoff tables that depend on the liquidation rate, r, and the network structure.

3. EXPERIMENTAL DESIGN AND PROCEDURES

3.1 Design and Hypotheses

In our experimental setting, as in the theory, there are four banks labelled A, B, C and D. Each participant in our experiment is assigned the role of a depositor in one of the four banks. The experimental setting and payoffs is set up based on 4 depositors in each bank.

We set the probability that a depositor is impatient in a bank that faces a low or high liquidity shock to $w_L=1/4$ and $w_H=3/4$, respectively. Thus, the average fraction of impatient depositors in the economy is $\gamma=\frac{\frac{1}{4}+\frac{1}{4}+\frac{3}{4}+\frac{3}{4}}{4}=\frac{1}{2}=0.5$. Therefore, from Table 2 it follows that, in the perturbed state $\acute{S}$, among the banks that do not face the liquidity shock, the number of impatient depositors is equal to $4*\gamma=2$, while in the bank that faces the liquidity shock this number is equal to $4*(\gamma+\varepsilon)=3$.

The banks' use deposits to make investment choices that are pre-determined according to the network structure and the parameterization of the model. Since the average fraction of impatient withdrawers in the economy is 0.5, the banks invest a fraction $\gamma=0.5$ of deposits in the short asset and a fraction $1-\gamma=0.5$ in the long asset. As previously mentioned, Allen and Gale (2000) demonstrated that the first-best outcome is achieved if each bank places fraction $(w_H-\gamma)=\frac{3}{4}-\frac{1}{2}=\frac{1}{4}$ and $(w_H-\gamma)/2=\frac{1}{8}$ of its deposits in each of the bank(s) with which they are connected in the incomplete and complete market structures, respectively, and so the payoff incentives of our experiment take these investment choices as given. That is, the interbank deposits are made according to the first-best risk sharing outcome.

As for the other parameters of the model, we set $R=2$ and we chose two different values for r: $r=0.2$, a low liquidation rate (associated with high liquidation costs) and $r=0.4$, a high liquidation rate (associated with low liquidation costs). Given these parameter choices, we can simultaneously solve for q^i, (as detailed in the previous section) which is the value of all deposits in bank i at $t=1$, and determine the payoffs offered to depositors when banks are illiquid (i.e., they are unable to pay the promised return) or bankrupt. The parameter choices are such that when $r=0.2$, the first-best, contagion free outcome is an equilibrium in the complete network setting, but not in the incomplete network setting where a full contagion is the unique equilibrium outcome. By contrast, when $r=0.4$ the first-best, contagion-free outcome is also an equilibrium under the incomplete network structure. Of course, the full contagion outcome is always an equilibrium for any value of r or for either network structure.

Summarizing, we employ a 2×2 between-subjects experimental design where the two treatment variables are (1) the network structure, complete or incomplete as illustrated in Figure 1, and (2) the liquidation rate, $r=0.2$ (low) or $r=0.4$(high). The design and the equilibria that are possible in each of the four treatment cells of our experiment are summarized in Table 3.

[Insert Table 3 here]

While the experimental setting and payoffs are established on the basis of 4 depositors in each bank or 16 depositors for the total economy, our primary focus is the behaviour of the 'strategic' players, namely, the patient depositors who can choose whether or not to withdraw early, that is, in period 1; the impatient depositors just mechanically withdraw early and so are of little behavioural interest. Therefore, we parameterized our experiment in such a way that human subjects are only needed to play the role of the patient depositors in all four banks. That is, in our experiment, each economy consists of just 8 (rather than 16) human subject depositors, 2 subjects for each bank. Effectively, the actions that would be taken by the early withdrawers are built into the payoff tables that the two strategic players at each bank have to consider.

In addition, one of the "patient" human subject depositors was randomly subjected to the perturbed shock and forced to withdraw early at date 1 in each repetition of the game. To further simplify the experimental setting, the financial fragility shock always originates with bank A; that is, one of the two "patient" depositors in Bank A is randomly forced to withdraw early at date 1, in each repetition (round) of the three period game, while the other human subject at Bank A was free to withdraw at date 1 or at date 2 (as was also the case for the 6 other human subject players at Banks, B, C and D.

An experimental observation consists of the play of 30 rounds by the *same* 8 subjects representing a single economy under one of the four treatment conditions. At the beginning of each round, pairs of subjects are randomly assigned to 1 of the 4 banks. We chose to keep subjects in the same cohort of 8 players to better allow for learning behavior. The random assignment of players to banks at the start of each round was chosen to avoid having the same subjects be repeatedly exposed to the liquidity shock in Bank A.

Specifically, at date $t=0$, each randomly formed pair or "group" is assigned to a bank and learns which bank it is, A, B, C or D. We used the terminology "group" to refer to the 2 subjects assigned to each of the 4 banks. Next, subjects deposit their endowment of 100 experimental pounds (EP) in their bank.[5] Then, at date $t=1$, depositors in bank A learn whether or not they are the impatient depositor, and thus the one who is forced to withdraw their deposit at date 1. All other 7 patient depositors have to make a single decision: whether to withdraw their deposit in $t=1$or wait until $t=2$ (not withdraw). Participants have full information about the perturbation shock, that is, that the shocked bank is always bank A and to which bank they are assigned in each round. After all decisions are made (i.e., withdraw or not withdraw), each participant learns the outcome of their decision (round earnings), the decision of the group-mate and the aggregated decisions of the depositors in the connected banks. A history table summarizing this information for previous rounds is also presented. Round earnings are in EP. At the end of the experiment, one round is randomly selected for payment.

Round earnings depend on the network structure. We implement each network structure and liquidation rate r as a separate between-subjects treatment. In each treatment, subjects are informed of the network linkages and the payoff consequences from choices by their own bank members and others via the interbank network connections. In our setup, there are 54 possible combinations of withdrawal requests. To ease presentation, the payoff tables were created by grouping the combinations according to the choice of the person in the same bank (group-mate) and the number of withdrawal requests in the connected banks and taking the median of the payoffs for each grouping, as shown on Tables 4-7 below.[6] For the incomplete network structure, the payoff tables for patient depositors are shown in Tables 4 and 5.

[Insert Tables 4 and 5 here]

In both Tables 4-5, the player's own choice, to Not Withdraw (N) or to Withdraw (W) is indicated in the left column and the choice of the group-mate (in the same bank) is indicated in the top row of the two right columns. The two right columns are further sub-divided up according to the choices made by the two depositors in the *connected* bank - the other bank holding deposits of the bank the two players are in. Here, N means no (0) Withdraw choices by depositors in the connected bank, while 1W and 2W mean 1 or 2 withdrawals, respectively by the depositors in the connected bank. Recall that initially all subjects deposit 100 EP in the bank, so the payoff numbers indicate the *additional* EP from the various actions. Thus, for both incomplete network treatments, if the group-mate does not withdraw, choosing N, and there are not any withdrawals in the connected bank, N (a possibility so long as the connected bank is not Bank A), then, the players would gain 100 EP from choosing N (not withdraw) reflecting our choice of $R=2$ (i.e., their initial deposit of 100 EP is doubled). In this same scenario, in the low liquidation rate treatment, the player would lose 15 EP if she instead chose to withdraw W for a net payoff of 85 EP, while in the high liquidation rate treatment she would lose only 5 EP if she instead chose to withdraw W for a net payoff of 95 EP; these differences reflect the two different values for the liquidation rate, r. Notice that losses are always capped at -100, resulting in a net payoff of 0 (given the initial endowment of 100 EP). Notice further that if a player's group-mate withdraws, it is always a dominant strategy for the player to withdraw as well under both incomplete network treatments. Finally, consider the case of Bank A, where one depositor is forced to withdraw. His patient-type group mate, knowing that he is in Bank A and facing the payoff table above should play a best response of withdrawing as well in both treatments. Since there will (rationally) be two withdrawals (2W) in Bank A, members of the bank connected to (with deposits in) Bank A, i.e., Bank D depositors, in the incomplete network structure, should rationally anticipate that they will face 2W in the connected bank, in which case the dominant strategy for both players in Bank D depends on the value of r. If$r=0.2$, Table 4 reveals that the two depositors in Bank D facing 2W from Bank A have a dominant strategy of choosing W. Then, recognizing that the two players in Bank D will play 2W, the two players in Bank C should also play W, and, recognizing this outcome, the two players in Bank B will also play W, making the financial contagion complete. Thus, for the incomplete market structure with $r=0.2$, we find, via backward induction, that the unique equilibrium involves a full contagion (FC) outcome where all 8 depositors choose W. By contrast, if $r=0.4$, Table 5 reveals that the two depositors in Bank D facing 2W from Bank A do not have a dominant strategy; if each believes the other will play N, then N is a best response, while W remains a best response to the belief that the group-mate will play W. Applying a generalization of risk dominance to our n-player, binary choice game (a flat prior assumption about outcomes in connected banks) it can be shown that when $r=0.2$, the financial contagion equilibrium is both risk and payoff dominant. When $r=0.4$, the full contagion equilibrium remains risk dominant but the payoff dominant (first-best) equilibrium is the outcome where bankruptcy is limited to Bank A.

In making predictions as to how subjects will behave, we shall assume that payoff efficiency is the relevant equilibrium selection criterion. This assumption enables us to make *unique* predictions for all of our treatments. In addition, there is experimental evidence from a variety of two-player, Pareto-ranked coordination games that payoff efficiency is the most commonly used equilibrium selection principle (as opposed to, say, risk dominance)-see Rankin et al. (2000). Under this maintained assumption, we have the following hypothesis:

Hypothesis 1: *In the INCOMPLETE network structure with a low liquidation rate* $(r=0.2)$*, the original financial shock spreads to all banks as one after the other faces bankruptcy. With a high liquidation rate* $(r=0.4)$*, players recognize that the contagion can be avoided and coordinate on the first-best equilibrium with bankruptcy limited to Bank A.*

For the complete network structure, the payoff tables for patient depositors are shown in Tables 6 and 7. These payoff tables are read similarly to the payoff tables for the incomplete network treatments, but now the possible actions of players in the connected banks is greater, as there are three connected banks in the complete network as opposed to just one in the incomplete network and so anywhere from 0 to 6 players can choose to withdraw among these three connected banks. Of course, 0W by depositors of other connected banks is only a possible outcome for members of Bank A, and this fact was made clear in the instructions.

[Insert Tables 6 and 7 here]

Consider first the payoffs to depositors in the low liquidation rate $r=0.2$ treatment, as shown in Table 6. In this treatment, conditional on one's group-mate not withdrawing (i.e., choosing N), it is a best response for the player not to withdraw so long as the number of withdrawals by players in connected banks does not exceed 3W. Since for banks B-D, the number of withdrawals in connected banks can rationally be expected to be, at a minimum, 2 - namely the two players in Bank A - the efficient (first-best) equilibrium is for no members of Banks B-D to choose withdraw early (all 6 choose N) and as a result all players in Banks B-D earn 25 EP on top of their 100 EP investment (since the two players in Bank A play 2W). On the other hand, if players believe that all other depositors will choose to withdraw, then it is an equilibrium best response for all players to withdraw as well, so that the inefficient financial contagion equilibrium also exists in this complete network setting. The same multiplicity of equilibria holds in the $r=0.4$treatment as can be seen by the payoffs in Table 7, but the incentives to not withdraw and coordinate on the efficient first-best equilibrium are greater in this case. Specifically, conditional on one's group-mate not withdrawing (i.e., choosing N), it is a best response for the player not to withdraw for any number of withdrawals (0-6W) by members of connected banks. The full contagion equilibrium is obtained only if all players believe that their group-mate will withdraw.

For the complete network under both values for r, the full contagion equilibrium is again risk dominant while the efficient risk sharing equilibrium, where only Bank A goes bankrupt, is payoff dominant. Again, assuming that payoff efficiency is the relevant equilibrium selection criterion, we have the following two hypotheses:

Hypothesis 2: *In the COMPLETE network, depositors coordinate on the efficient, risk sharing outcome where only the bank facing the financial shock goes bankrupt regardless of the value of* r.

Hypothesis 3: *A high liquidation rate r acts as a substitute for completeness of the interbank network structure.*

The latter hypothesis will be tested by comparing withdrawal decisions in the incomplete network treatment when $r=0.2$ and $r=0.4$ and comparing these outcomes with complete network treatment results.

3.2 Procedures

The experiment was computerized using zTree (Fischbacher, 2007). Subjects were students at the University of East Anglia. No subject had any prior experience with our experimental design and subjects were only allowed to participate in a single session/treatment of our experiment. We obtained 11 observations on choices by 8-subject cohorts for each of our four treatment conditions. Thus, our study involved a total of $4\times11\times8=352$ subjects (average age = 21.3 years; 57.7% females).

Each experimental session began with subjects being given written instructions which were then read aloud in an effort to make those instructions common knowledge (copies of these written instructions are included in the Appendix). After the instructions were read, subjects had to answer a number of questions designed to check their comprehension of those instructions. Subjects who made mistakes were instructed as to the correct answers prior to the first round of the game.

After completing 30 rounds, subjects were informed as to which round was randomly selected for payment and their payoff for that round. Earnings in EP were converted into British Pounds at the known exchange rate of 1 EP = 0.1 British Pounds. In addition, subjects received a 3 British pounds show-up payment. Between the end of the experiment and the payment phase, a demographics and feedback questionnaire was administered. Participants received their payment in cash at the end of the session.

Each session was completed within 1 hour (50 minutes on average) and 2 or 3 eight-player cohorts (16 – 24 subjects) participated in a single session. The average payment was 8.96 British

Pounds (SD 2.96 British Pounds) in the incomplete network with low liquidation rate treatment; 9.65 British Pounds (SD 4.47 British Pounds) in the complete network with low liquidation rate treatment; 15.36 British Pounds (SD 6.89 British Pounds) in the incomplete network with high liquidation rate treatment and 15.32 British Pounds (SD 6.33 British Pounds) in the complete network with high liquidation rate treatment.

4. FINDINGS

4.1 Bankruptcies and Withdrawals

We report the results of our experiment as a number of different findings. We begin with an aggregate analysis of the main differences across the four treatments before moving on to the more micro-level differences.

Finding 1: *Consistent with Hypothesis 1, under the INCOMPLETE network with a low liquidation rate* $r=0.2$*, the original financial shock frequently spreads to the other three banks, which then face bankruptcy. With a high liquidation rate,* $r=0.4$*, players frequently learn to avoid the contagion and coordinate on the first-best equilibrium where bankruptcy is limited to Bank A.*

[Insert Figure 2 here]

Support for Finding 1 comes from Figure 2 which shows the average number of banks other than Bank A experiencing bankruptcy in each of the 30 rounds for all four of our treatments. Here bankruptcy is defined as an inability to meet the payment promises made to depositors choosing to withdraw at $t=1$. The average number of bankrupted banks over time in the incomplete network treatments is shown by the two dashed lines, labelled I-0.2 and I-0.4, for the incomplete network, $r=0.2$ and $r=0.4$ treatments, respectively. As Figure 2 clearly reveals, over time, the number of bankrupted banks other than bank A averages around 2.5 in the Incomplete,

$r=0.2$ treatment and this same average approaches 0.5 over time in the Incomplete$r=0.4$ treatment.

Further support for Finding 1 comes from Figures 3-4. In particular, Figures 3-4 shows the number of bankrupt banks over time disaggregated by each of the eleven 8-player cohorts in the Incomplete $r=0.2$ and Incomplete, $r=0.4$ treatments, respectively. As Figure 3 reveals, the number of bankrupted banks in the Incomplete$r=0.2$ treatment was typically between 2 and 3, so that the financial contagion was not always perfectly complete (to all 3 banks) in that treatment. On the other hand, Figure 4 displays what appears to be a mirror image of Figure 3, with the number of bankrupted banks being typically between 0 and 1 for the Incomplete,$r=0.4$ treatment. As such, the efficient first-best equilibrium (where 0 banks other than bank A go bankrupt) was not always reached in this treatment. Nevertheless, the evidence clearly suggests that the full contagion equilibrium is the more likely outcome in the Incomplete, $r=0.2$ treatment, while the efficient first-best equilibrium is the more likely outcome in the Incomplete, $r=0.4$ treatment.

[Insert Figures 3-4 here]

Finding 2: *Consistent with Hypothesis 2, under the COMPLETE network with a high liquidation rate ¿0.4 , the efficient, first-best equilibrium outcome where 0 banks other than Bank A are bankrupt is more likely to be observed. However, in consistent with Hypothesis 2, when the liquidation rate is low,* $r=0.2$*, the financial crisis sometimes becomes global, spreading to all 3 banks.*

Support for Finding 2 can be seen again in Figure 2, in which the average number of bankruptcies in the Compete, $r=0.2$treatment is further disaggregated according to whether the cohorts coordinated near the efficient ("Good" equilibrium) or the inefficient full contagion ("Bad" Equilibrium). Further support for Figure 2 comes from Figures 5-6 which show the number of bankrupted banks over time, disaggregated by each of the eleven 8-player cohorts of the Complete $r=0.2$ and Complete $r=0.4$ treatments, respectively.

[Insert Figures 5-6 here]

Figure 5 clearly reveals a bifurcated outcome for the Complete $r=0.2$ treatment, with 5 out of 11 cohorts repeatedly experiencing 0 or 1 bankruptcies among banks other than Bank A—a "contained" financial crisis—while the other 6 cohorts often experience a complete, or nearly complete global financial contagion where all or nearly all banks (other than Bank A) immediately become bankrupt. While both pure equilibria are possibilities under the complete network structure, our results indicate that complete interbank connectedness and the more efficient risk sharing that it allows for, provides *no guarantee* that agents will coordinate on the efficient (first-best) outcome when the liquidation rate, r is low.

By contrast Figure 6 suggests that when the network is Complete and $r=0.4$, the full contagion outcome is almost always avoided; the more likely outcome is that 0 or 1 banks other than Bank A go bankrupt, so that, consistent with Hypothesis 2, depositors' behavior is closer to the first-best equilibrium outcome in this treatment.

In addition to considering the aggregate number of bankrupt banks it is also of interest to consider the number of withdrawal requests by depositors at *individual* banks over time to examine in further detail how contagions unfold or are contained. Figure 7 shows the mean *withdrawal* decisions by depositors at banks, A, B, C, and D over the 30 rounds of each treatment using 5-round moving averages of the number of withdrawals made at each of the four banks. The top two panels compare the Incomplete and Complete Networks settings with $r=0.2$ while the bottom two panels do the same for the $r=0.4$ case. The middle two panels again separate the Complete, $r=0.2$ treatment into the 5 cohorts that coordinated on the "Good" i.e., First-best equilibrium and the 6 that coordinated on the "Bad" i.e., the full contagion equilibrium.

[Insert Figure 7 here]

Figure 7 clearly reveals that across all treatments, the number of withdrawal requests in Bank A is the greatest on average, closely approximating the equilibrium prediction of 2 withdrawals (including the one forced withdrawal). The distinction between the number of withdrawal requests in Bank A versus Banks B, C, and D is least pronounced in the Incomplete Network $r=0.2$ treatment by comparison with the other three treatments, reflecting the fact that the full contagion equilibrium was common in that treatment. Indeed, under the Incomplete Network $r=0.4$ treatment and the two Complete network treatments, there is a much clearer separation between the number of mean withdrawal requests for Bank A versus the other three banks; the two withdrawal outcome, associated with bankruptcy, is clearly greater for Bank A than for the other three banks suggesting that under the complete network structure, and under the incomplete network structure with $r=0.4$, the contagion is contained to some extent. However, as the middle two panels make clear, this distinction is less pronounced in the Complete network $r=0.2$ treatment. The separation in the mean withdrawal requests between Bank A and Banks B, C, and D is clearly evident in the middle left panel among the 5 cohorts of that treatment for which the financial contagion was contained to Bank A. For the other 6 cohorts of the Complete $r=0.2$ treatment, as seen in the middle right panel, there is little difference in the mean number of withdrawal requests, which are all close to 2 by the final, 30^{th} period (indicating perfect bankruptcy). These figures provide additional support for both Findings 1 and 2.

The 5-round moving averages help to smooth out the effect of the withdrawal requests for each round and reveal some differences in the ordering of the number of withdrawals especially in the Incomplete $r=0.2$ treatment relative to the other treatments. In this treatment, a spillover effect is observed: the financial shock of Bank A is transmitted to Bank D (which has invested its deposit into Bank A). This shock then spreads to Bank C, who has invested in Bank D; and finally, to Bank B which has invested in Bank C. There is a clear contagion in the form of spillovers in the incomplete market structure, before the crisis becomes global. For the complete network treatments, the withdrawal decisions of the other three banks are more coordinated, reflecting the completeness and the risk-sharing nature of the network structure in those treatments.

4.2 Average Efficiency across Treatments

In accordance with Findings 1-2, we have the following result regarding efficiency comparisons across treatments.

Finding 3*: Average Efficiency is greatest in the two treatments where* $r=0.4$*. For the two* $r=0.2$ *treatments, average efficiency is greater in the Complete network as compared with the Incomplete Network.*

Support for Finding 3 comes from Figure 8, which shows average efficiency over the 30 rounds of the experiment using data from all 11 cohorts of each of the four treatments. Average efficiency is estimated by averaging the ratio of all depositors' payoffs to the "bad" equilibrium (i.e., full contagion) payoff. For the Complete, $r=0.2$ treatment, we also report average efficiency separately for the 5 cohorts that were able to contain the financial contagion and the 6 cohorts of the complete network structure for which the contagion was global.

[Insert Figure 8 here]

Figure 8 clearly reveals that average efficiency is greatest in the two $r=0.4$ treatments, regardless of the network structure. The Complete, $r=0.2$ treatment provides the next highest average efficiency, followed by the Incomplete, $r=0.2$ treatment, which has the lowest average efficiency of the four treatments. Focusing on the two $r=0.2$treatments, statistically significant efficiency differences between the two network structures are only found when comparing average efficiency for the 5 cohorts of the Complete Network $r=0.2$ treatment that avoided the full contagion with all eleven cohorts of the Incomplete, $r=0.2$treatments[7].

4.3 Regression Analysis of Withdrawal Decisions

We next turn to a regression analysis of withdrawal decisions using a mixed effects panel logit regression estimator where decisions are analyzed at 3 different levels: Individual, Group and Cohort. For this exercise we consider all individual withdrawal decisions, where the subject could *choose* whether or not to withdraw. Thus we exclude the withdrawal decisions of those subjects who were assigned to Bank A and who were *forced* to withdraw; there is 1 such subject in each 8-subject cohort who fits this description in each round. Thus, we have data on the voluntary withdrawal decisions of 7 subjects per cohort over 30 rounds and we have 44 cohorts in total (11 of each treatment). This provides us with $7 \times 30 \times 44 = 9{,}240$ observations on individual withdrawal decisions from our experiment.

The results of our regression exercise are reported in Table 8, where the dependent variable is the individual withdrawal decision in each round, with 1 = withdraw early (in period 1), and 0 = no withdrawal. We used a mixed effects logit estimator and we report the odds ratios from the estimation. We make use of the following explanatory variables: (1) Network Structure Incomplete is a dummy variable for choices made under the incomplete network treatment; (2) Liquidation Rate High (0.4) is a dummy variable indicating that $r = 0.4$; (3) Incomplete x Liquidation Rate High is an interaction term that multiplies the two previous dummy variables; (4) Withdraw (if not forced) in $t-1$ is the lagged withdrawal decision if the player is not the one in Bank A who was forced to withdraw in the previous round; (5) Partner withdraw in $t-1$ is the lagged withdrawal decision of the player's partner if the partner is not the one in Bank A who was forced to withdraw in the previous round; (6) Number of withdraws in connected banks in $t-1$ is the normalized number of withdrawals in connected banks in the lagged round.[8] In addition to these economic choice variables, we include a number of control variables making use of the demographic data we collected on individual subject characteristics in the survey questionnaire administered following the 30th round of play of the main task. These variables include sex, age, English language skills and prior experience in economic decision-making (DM) experiments. We find that the latter demographic factors have no significant explanatory power on withdrawal decisions.

[Insert Table 8 here]

Table 8 reveals several interesting results. First, we observe in our simplest regression model, specification 1, that (i) the odds of a withdrawal in the incomplete network treatment with $r = 0.2$ are significantly larger, specifically 3.5 times greater than in the baseline $r = 0.2$ complete network treatment. This provides evidence that network structure matters in this environment. (ii) The odds of a withdrawal in the $r = 0.4$ complete network treatment are 4.978 times lower (1/0.201), again relative to the baseline $r = 0.2$ complete network treatment, confirming that the liquidation rate, r, is also a significant factor in withdrawal decisions. These findings continue to hold across all of the other specifications reported in Table 8. These results provide further evidence in support of Findings 1 and 2 that the interbank network structure and the liquidation rate both matter for the incidence of contagion.

Second, Table 8 reveals that there is an interaction effect between the network structure and the liquidation rate as evidenced by the significant odds ratio for the Incomplete x Liquidation Rate High dummy variable. The coefficient from the first specification suggests that the difference in the odds of withdrawal when comparing Incomplete versus Complete network structures is about 3.4 times (1/0.293) larger when the liquidation rate is low than when it is high. While the coefficient estimate on this interactive dummy variable is only marginally significant, it is consistently so across all specifications reported in Table 8.

We summarize the last findings as follows.

Finding 4: *There is some weak support for Hypothesis 3 that a high liquidation rate reduces the effects of network structure on withdrawal decisions.*

Third, Table 8 further reveals that *history* also matters, as the lagged withdrawal choices by the subject, his partner or by depositors in the connected banks all increase the odds that the subject chooses to withdraw in the current round. This finding suggests that there is some path dependence of withdrawal outcomes that accounts for the withdrawal decisions of cohort members in the current round. These results are in line with Garratt and Keister (2009) who find that an individual's history of experience with runs at a single bank matters for their subsequent likelihood of withdrawing early. Our results extend the notion that history matters since withdrawal decisions depend not only on the depositors' history within their own bank, but also on the history of outcomes at connected banks. Nevertheless, even after accounting for this path dependence as is done in specifications (3), (5) and (7), the evidence continues to suggest that the network structure and the liquidation rate still matter for the frequency of current withdrawal choices.

4.4 Contemporaneous Crisis or a Slow Contagion Effect?

Finally, we consider whether a financial contagion, if it occurs, unfolds in the manner predicted by the theory under the two different network structures. Recall that, under the complete network structure, Bank A has interbank connections with the other three banks. Thus, a bankruptcy in Bank A has immediate payoff consequences for depositors in all of the other three banks. If depositors in these other banks do not all immediately choose to withdraw, they can achieve the first-best equilibrium wherein the financial shock is localized to Bank A. However, if depositors believe that enough other non-bank-A depositors will withdraw early, the contagion to all depositors withdrawing should occur simultaneously and with the same incidence across all three banks. Since all banks are connected under the complete network setup, the number of withdrawals in the connected banks represents the number of withdrawals in the entire banking system, so that players have complete system-wide information at the end of each round. By contrast, under the incomplete network structure, the bankruptcy of Bank A (if it occurs) has immediate spillover effects only to depositors in Bank D, which by design, holds some of its depositors' deposits in Bank A. If Bank D fails, then depositors in Bank C are adversely affected, and if Bank C fails depositors in Bank B are adversely affected completing the financial contagion around the incomplete network. Because of the incompleteness of the network structure, this financial contagion may take some time to unfold and it may well be that distance from and connectedness to the source of the financial crisis-- namely Bank A-- matters for the timing of withdrawal decisions in repeated play of the game.

To examine whether network structure matters for the speed with which a contagion unfolds we examine the decisions of non-Bank-A depositors to ``wait'' (i.e., to not withdraw=1) for all four treatments. Specifically, we considered the impact of depositors' distance from bank A on their waiting decision. We used the same mixed effects panel logit estimator as in Table 8 to examine the waiting choices of non-Bank-A depositors as a function of dummy variables, B, C, D, representing their bank membership. The results of this estimation are reported in terms of odds ratios in Table 9.

[Insert Table 9 here]

Table 9 reveals that for the incomplete network $r=0.2$ treatment (i.e., Incomplete – Low LR), the odds of waiting are different across the three banks. Indeed, a Wald test of the hypotheses that these odds ratios are equal between banks D and C, banks C and B, and banks D and B is easily rejected (Prob > χ^2 < 0.05 for all three pairwise comparisons) in favour of the alternative that the odds of waiting are *lower* the closer is the connection to Bank A (the baseline). In particular, the order of waiting odds across the three banks is $D<C<B$. This pattern is consistent with a behavioural bias favouring (against) early withdrawal the more (less) directly connected the bank is to the source of the financial crisis, namely Bank A.

Conversely, for the complete network treatments (both Low and High LR) and the Incomplete $r=0.4$ treatment, the odds ratios are *not* significantly different from one another across the three banks; (Wald Test Prob > χ^2 > 0.10 in all three pairwise comparisons) and are *higher* than in the incomplete Low LR treatment. The lack of a difference in the odds ratios across the three banks is consistent with the theoretical prediction that a contagion, if it happens, does so instantaneously across all four banks in the economy. The lower odds of waiting in the incomplete $r=0.2$ treatment relative to the other three treatments simply reflects the finding that financial contagions always occur under the incomplete network $r=0.2$ structure, but occur less frequently under the complete network structure or in the incomplete network structure when $r=0.4$ We summarize the results from Table 9 as follows:

***Finding 5**: While theory predicts that a financial contagion, if it occurs, spreads to all banks immediately in period 1, in the experiment we find that the contagion is slower to unfold in the incomplete network structure where the liquidation cost is high (i.e., LR low) and the timing of depositors' decisions to wait/withdraw depends on the distance of their bank from the source of the financial crisis (Bank A).*

5. CONCLUSIONS AND EXTENSIONS FOR FUTURE RESEARCH

Modern banking systems involve many connections across banks (and non-banks) e.g., for risk management and payment processing reasons. Thus, it is not surprising that modern financial crises will potentially have contagion effects with spillovers from one bank to another. In this paper we report on the first experiment exploring the role of interbank network structure for the incidence of financial contagion. Consistent with the theoretical framework of Allen and Gale (2000) that we implement and test in the laboratory we find that financial contagions are common under incomplete network structures in cases where efficient risk sharing is not possible and liquidation rates are low. We further find that when efficient risk sharing is possible under a complete interbank network structure or if liquidation rates are high in an incomplete network, financial contagions can sometimes be contained. However, we also find that financial contagions continue to be a possibility even under the complete interbank network structure. Thus, an important implication of our results is that while more complete interbank network structures may reduce the incidence of financial contagions by facilitating more efficient risk sharing among banks, such complete network structures are not a *panacea* for preventing such contagions. Indeed, our experiment suggests that a more promising approach to reducing the frequency of contagions is to raise the liquidation rate (equivalently lower the liquidation costs in the event of bankruptcy).

There are several directions for future research on this topic. First, we have considered a setting with the minimal number of banks needed to examine network interaction effects (4). It would be of interest to consider larger networks of banks in combination with further variations in network structures. In particular, it would be of interest to consider more realistic asymmetric interbank network structures where different banks have differing numbers of interbank network connections that could be determined according to existing, real-world interbank network structures. Indeed, this approach has been pursued in a recent paper by Choi et al. (2017).

Second, an implication of our last Finding 5 is that there may be some value to modeling financial contagion among interconnected banks in incomplete network environments using an explicitly *dynamic game* approach as opposed to the static, simultaneous-game approach that is used in our experiment based on the model of Allen and Gale (2000). We leave these extensions to future research.

APPENDIX

A.1 Printed Instructions: Incomplete Network Structure, r=0.2 (Instructions for r=0.4 are Similar)

Instructions

Welcome to this experiment in economic decision-making. Please pay careful attention to these instructions as they explain how you earn money from the decisions that you make. After we read the instructions, please raise your hand if you have any questions. An experimenter will go to your desk and answer your question in private.

During today's session, your payoffs will be in terms of an experimental currency called “experimental pounds”, in short EP. At the end of the experiment, this experimental currency will be converted into British pounds. The amount you earn in this experiment will depend on the decisions that you and other participants make. Your earnings will be paid to you in cash at the end of the experiment. In addition, you will receive £3 for taking part in the experiment.

Please do not talk with others during the session and make sure you have silenced any mobile devices.

Description of the task

In this experiment, you will be part of a cohort of 8 participants. The other 7 participants in your cohort can be anyone in this room. Each participant will take on the role of a depositor who has his or her deposits with an experimental ‘bank’. There are 4 banks, named A, B, C and D. You and the other 7 participants will be divided up into 4 groups (2 participants in each group). You will remain in the same group of two and the same cohort for the entire experiment.

The experiment consists of 30 rounds, and in each round your group will be randomly assigned to one of the four banks. At the beginning of each round you and your group-mate will be informed about the bank to which you have been assigned.

At the beginning of each round you and the 7 other persons automatically deposit 100 EP in the bank to which you have been assigned. You must decide whether to withdraw your funds, or to wait and leave your funds deposited with your bank.

In each round one depositor assigned to bank ‘A’ (and bank ‘A’ only) will be randomly chosen and forced to withdraw. Both depositors in bank ‘A’ have an equal chance of being selected and forced to withdraw. If you have been assigned to bank ‘A’, then you will be informed about whether you have been selected and forced to withdraw. If this is the case, the computer will automatically select the action ‘withdraw’ for you. Every other depositor will need to decide whether to withdraw their funds, or to wait and leave them deposited in their bank.

The banks are partially connected to one another as represented in the figure below:

Specifically, banks ‘A’, ‘B’, ‘C’, and ‘D’ are partially connected. Banks are said to be connected to the bank in which they invest part of their deposits. The arrows in the figure display the direction the investment takes place. Here, bank ‘A’ invests in bank ‘B’, which invests in bank ‘C’, which invests in bank ‘D’ which in turn invests in bank ‘A’. So, bank ‘A’ is connected to bank ‘B’; bank ‘B’ is connected to bank ‘C’; and so on. This means that your payoffs depend on your own decision, the decisions of your group-mate, and the decisions of the people in the bank you are connected with. Specifically, how much you earn or lose if you make a withdrawal request or how much you earn or lose by leaving your money deposited in the bank depends on whether your group-mate places a withdrawal request and on how many people in the other bank you are connected with place withdrawal requests. To facilitate your decision, the payoff table below shows the payoffs, that is, the earnings or losses you incur on your 100 EP deposit. The payoff table lists the payoffs that you can obtain depending on your choice, the choice of the other person in your bank, and the choice of the people in the bank you are connected with. Note in the table below that ‘N’ stands for ‘not withdraw’ and ‘W’ stands for withdraw for your choice and the choice of your group-mate. The number of withdrawals in the other, connected bank can be `0W’, `1W’, or `2W’ which stand for 0, 1, or 2 person(s) withdrawing, respectively. Remember that in bank ‘A’ one person is forced to withdraw, so if you are in that bank and you are not forced to withdraw, the column corresponding to no withdrawal request, `N’, by your group-mate is not relevant to you. Also, if you are a depositor in bank ‘D’, the two columns that correspond to zero withdrawal requests, `0W’, in the connected bank are not relevant to you.

	Choice of your group-mate	N			W		
	Number of withdrawals in the connected bank	0W	1W	2W	0W	1W	2W
Your Choice	N	100	-4	-83	-100	-100	-100
	W	-15	-20	-24	-32	-36	-39

Note that since you cannot communicate with others, you must guess what other people will do – whether your group-mate will withdraw (if you are not in bank ‘A’) and how many of the people in bank you are connected with will withdraw (if any) - and act accordingly.

Procedure

You will perform the task described above 30 times. Each time is called a round. Each round is completely independent, i.e., you start each round with 100 EP in the bank. At the end of each round, the computer screen will show you your decision and your payoffs for that round. Information for earlier rounds is also provided.

Computer instructions

You will see three types of screens: the decision screen, the payoff screen and the waiting screen. Your withdrawal decisions will be made on the decision screen as shown in Figure 1. You can choose to withdraw your funds or leave your funds in the bank by clicking the corresponding option. Note that your decision will be final once you press the ‘Confirm’ button. The header provides information about what round you are in and the time remaining to make a decision. After the time limit is reached, you will be given a flashing reminder “please reach a decision!”

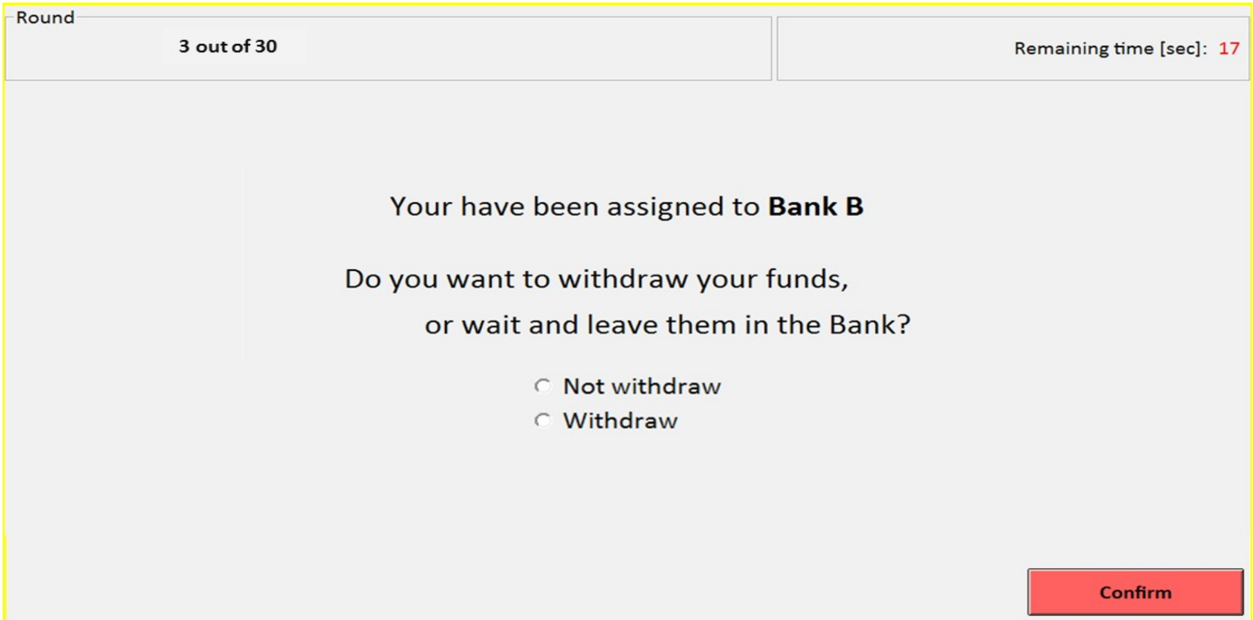

Figure 1: The decision screen

After all participants enter their decisions, a payoff screen will appear as shown in Figure 2. You will see your decision and payoffs for the current round. The history of your decisions, the decisions of your group-mate, the decisions of people in the connected bank and your payoffs is also provided. After you have finished reading this information, click on the "Continue" button to go on to the next round. You will have up to 15 seconds to review the information before a new round begins.

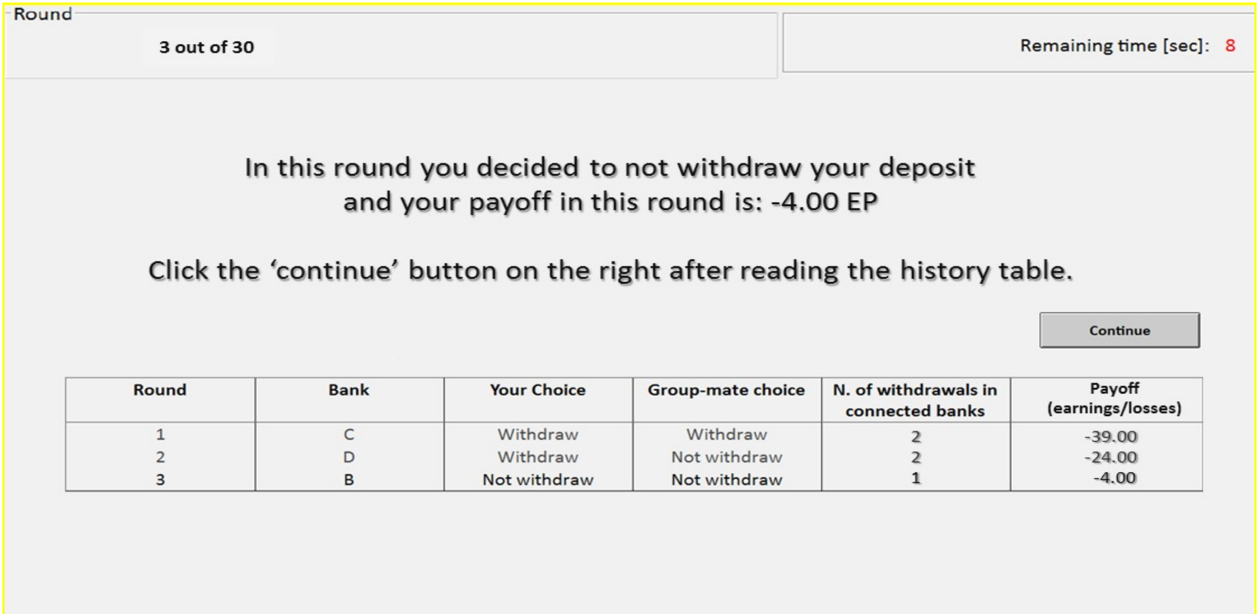

Figure 2: The payoff screen

You might see a waiting screen (as shown in Figure 3) following the decision or payoff screens. This means that other people are still making decisions or reading information on the outcome of a round and you will need to wait until they finish to go on to the next step.

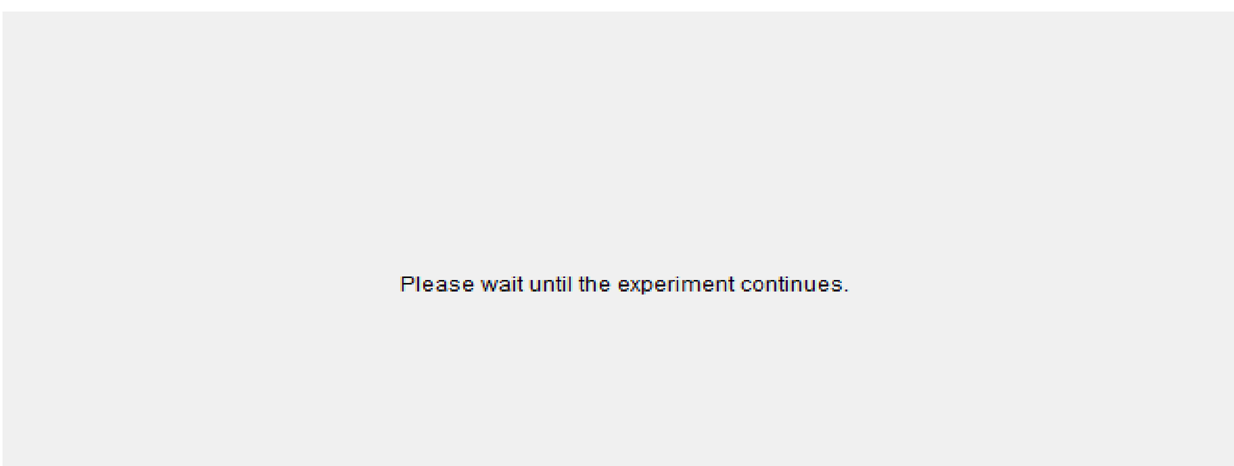

Figure 3: The waiting screen

Payment

Once you have completed the 30 rounds the computer program will randomly select 1 round. The payoff (earnings/losses) in the selected round will be added to your deposit of 100EP and transformed into British pounds using the following formula:

[100 EP + Payoff (in EP)] × 0.1

Also, the participation fee will be added to calculate your final earnings. This information will be summarized in your computer screen. After this, you will be asked to answer a short questionnaire. In the meantime, the experimenter will prepare your payment. After all participants finish the questionnaire, the experimenter will call you one by one to the payment desk where you will receive your payment in cash.

You may now click start. Before starting we will ask you to complete a comprehension quiz in order to make sure that you understood the instructions. After completing the quiz, you will start round 1.

[Are there any questions?]

A.2 Printed Instructions: Complete Network Structure, r=0.2 (Instructions for r=0.4 are Similar)

Instructions

Welcome to this experiment in economic decision-making. Please pay careful attention to these instructions as they explain how you earn money from the decisions that you make. After we read the instructions, please raise your hand if you have any questions. An experimenter will go to your desk and answer your question in private.

During today's session, your payoffs will be in terms of an experimental currency called "experimental pounds", in short EP. At the end of the experiment, this experimental currency will be converted into British pounds. The amount you earn in this experiment will depend on the decisions that you and other participants make. Your earnings will be paid to you in cash at the end of the experiment. In addition, you will receive £3 for taking part in the experiment.

Please do not talk with others during the session and make sure you have silenced any mobile devices.

Description of the task

In this experiment, you will be part of a cohort of 8 participants. The other 7 participants in your cohort can be anyone in this room. Each participant will take on the role of a depositor who has his or her deposit with an experimental 'bank'. There are 4 banks, named A, B, C and D. You and the other 7 participants will be divided up into 4 groups (2 participants in each group). You will remain in the same group of two and the same cohort for the entire experiment.

The experiment consists of 30 rounds, and in each round your group will be randomly assigned to one of the four banks. At the beginning of each round you and your group-mate will be informed about the bank to which you have been assigned.

At the beginning of each round you and the 7 other persons automatically deposit 100 EP in the bank to which you have been assigned. You must decide whether to withdraw your funds, or to wait and leave your funds deposited with your bank.

In each round one depositor assigned to bank 'A' (and bank 'A' only) will be randomly chosen and forced to withdraw. Both depositors in bank 'A' have an equal chance of being selected and forced to withdraw. If you have been assigned to bank 'A', then you will be informed about whether you have been selected and forced to withdraw. If this is the case, the computer will automatically select the action 'withdraw' for you. Every other depositor will need to decide whether to withdraw their funds, or to wait and leave them deposited in their bank.

The banks are fully connected to one another as represented in the figure below:

Specifically, banks 'A', 'B', 'C', and 'D' are fully connected. When banks are connected it implies that they invest part of their deposits in the banks they are connected with. The arrows in the figure display the direction the investment takes place. Here, all banks invest in all other banks. This means that your payoffs depend on your own decision, the decisions of the other people in your group, and the decision of the people in the banks you are connected with. Specifically, how much you earn or lose if you make a withdrawal request or how much you earn or lose by leaving your money deposited in the bank depends on whether your group-mate places a withdrawal request and on how many people in the other three banks you are connected with place withdrawal requests. To facilitate your decision, the payoff table below shows the payoffs that is the earnings or losses you incur on your 100 EP deposit. The payoff table lists the payoffs that you can obtain depending on your choice, the choice of the other person in your bank, and the choice of the people in the banks you are connected with. Note, in the table below 'N' stands for 'not withdraw', 'W' stands for withdraw for your choice and the choice of your group-mate. The number of withdrawals in the other, three connected banks can be `0W' '1W', '2W', '3W, '4W', '5W' and '6W' which stand for 0, 1, 2, 3, 4, 5, or all 6 person(s) withdrawing respectively. Remember that in bank 'A' one person is forced to withdraw, so if you are in that bank and you are not forced to withdraw, the column corresponding to no withdrawal request, `N', by your group-mate is not relevant to you. And if you are a depositor in bank 'B', 'C', or 'D', the columns corresponding to zero withdrawal requests in the connected banks are not relevant.

	Choice of your group-mate	N							W						
	Number of withdrawals in the connected banks	*0W*	*1W*	*2W*	*3W*	4W	5W	6W	0W	1W	2W	3W	4W	5W	6W
Your Choice	N	100	67	25	-18	-77	-100	-100	-100	-100	-100	-100	-100	-100	-100
	W	-13	-15	-17	-19	-22	-24	-26	-29	-31	-33	-34	-37	-38	-40

Note that since you cannot communicate with others, you must guess what other people will do – whether your group-mate will withdraw (if you are not in bank 'A') and how many of the people in banks you are connected with will withdraw (if any) - and act accordingly.

Procedure

You will perform the task described above 30 times. Each time is called a round. Each round is completely independent, i.e., you start each round with 100 EP in the bank. At the end of each round, the computer screen will show you your decision and your payoffs for that round. Information for earlier rounds is also provided.

Computer instructions

You will see three types of screens: the decision screen, the payoff screen and the waiting screen. Your withdrawal decisions will be made on the decision screen as shown in Figure 1. You can choose to withdraw your funds or leave your funds in the bank by clicking the corresponding option. Note that your decision will be final once you press the 'Confirm' button. The header provides information about what round you are in and the time remaining to make a decision. After the time limit is reached, you will be given a flashing reminder "please reach a decision!"

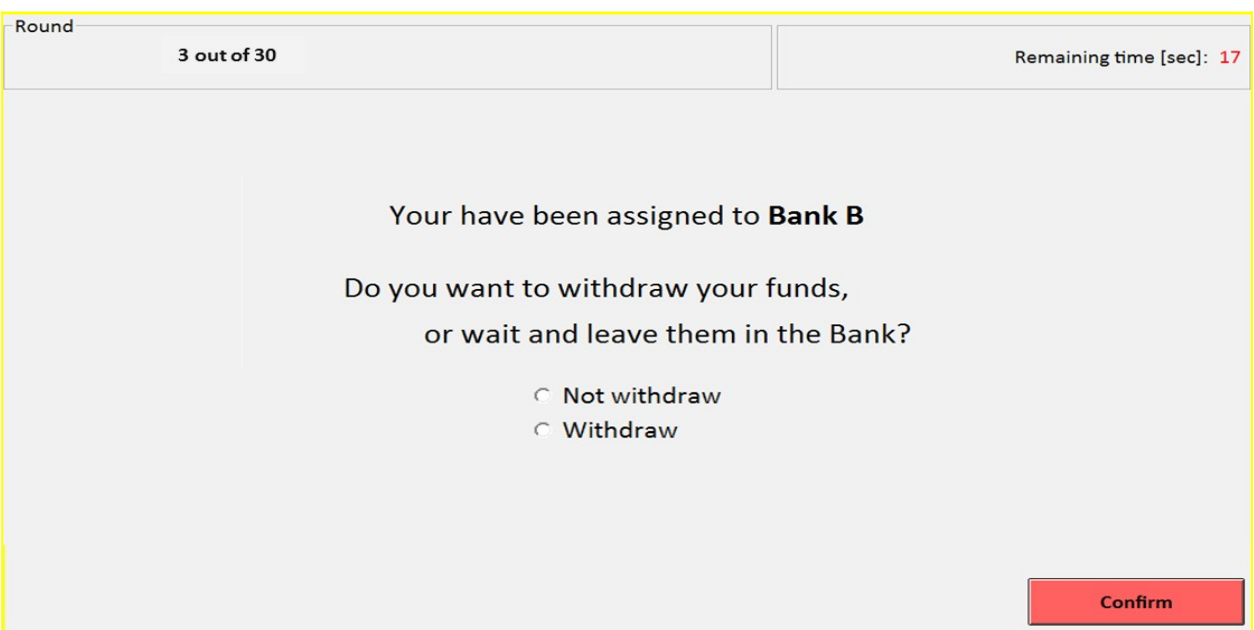

Figure 1: The decision screen

After all participants enter their decisions, a payoff screen will appear as shown in Figure 2. You will see your decision and payoffs for the current round. The history of your decisions, the decisions of your group-mate, the decisions of people in the connected banks and your payoffs is also provided. After you have finished reading this information, click on the “Continue” button to go on to the next round. You will have up to 15 seconds to review the information before a new round begins.

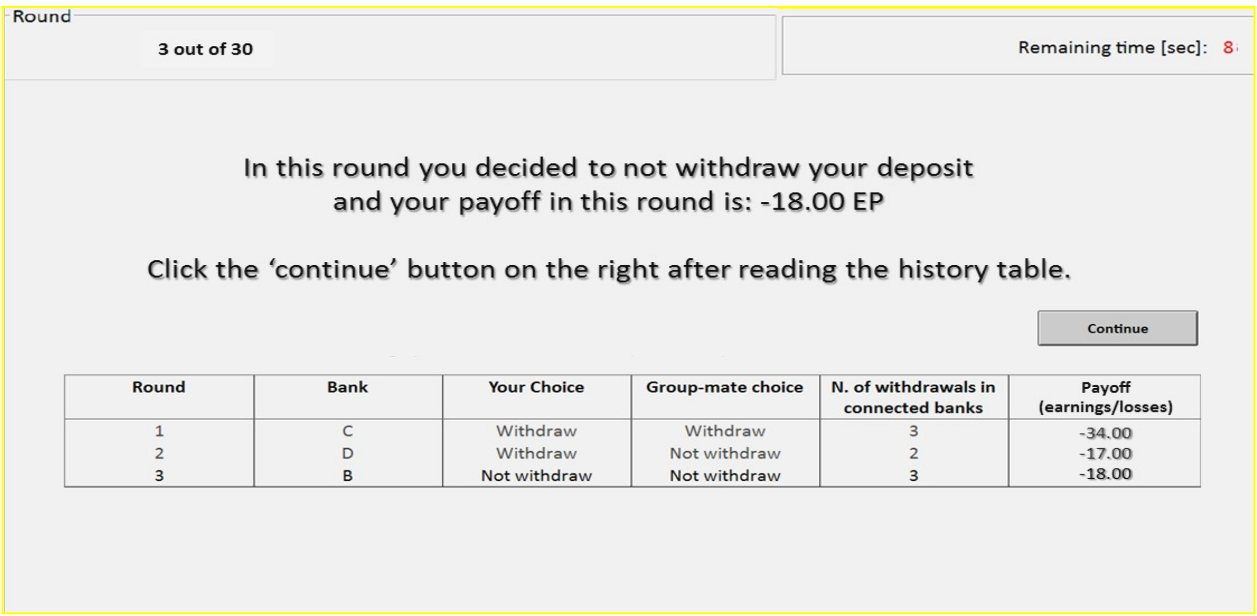

Figure 2: The payoff screen

You might see a waiting screen (as shown in Figure 3) following the decision or payoff screens. This means that other people are still making decisions or reading information on the outcome of a round and you will need to wait until they finish to go on to the next step.

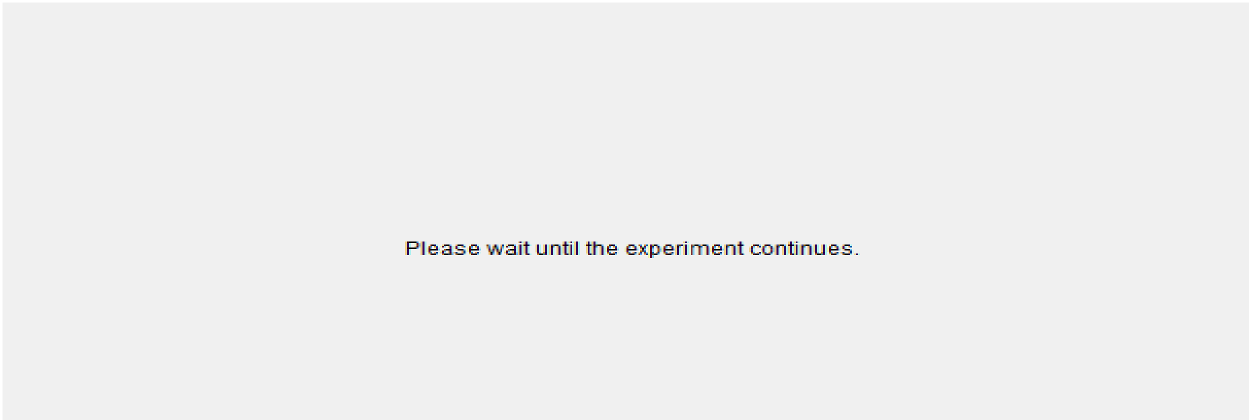

Figure 3: The waiting screen

Payment

Once you have completed the 30 rounds the computer program will randomly select 1 round. The payoff (earnings/losses) in the selected round will be added to your deposit of 100 EP and transformed into British pounds using the following formula:

[100 EP + Payoff (in EP)] × 0.1

Also, the participation fee will be added to calculate your final earnings. This information will be summarized in your computer screen. After this, you will be asked to answer a short questionnaire. In the meantime, the experimenter will prepare your payment. After all participants finish the questionnaire, the experimenter will call you one by one to the payment desk where you will receive your payment in cash.

You may now click start. Before starting we will ask you to complete a comprehension quiz in order to make sure that you understood the instructions. After completing the quiz, you will start round 1.

[Are there any questions?]

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FOOTNOTES

TABLES

	A	**B**	**C**	**D**
S_1	w_H	w_L	w_H	w_L
S_2	w_L	w_H	w_L	w_H

Table 1: Distribution of liquidity shocks across banks and states

	A	**B**	**C**	**D**
$\acute{S}$	$\gamma+\varepsilon$	γ	γ	γ

Table 2: Distribution of liquidity shocks across banks for perturbed state

		Liquidation Rate	
		$r = 0.2$	$r = 0.4$
Network Structure	Complete	FB, FC	FB, FC
	Incomplete	FC	FB, FC

Table 3: Experimental Design and Equilibrium Possibilities: FB=First-best, FC=Full Contagion

	Choice of your group-mate	**N**			**W**		
	Number of Withdrawals in the connected bank	**N**	**1W**	**2W**	**N**	**1W**	**2W**
Your Choice	**N**	100	-4	-83	-100	-100	-100
	W	-15	-20	-24	-32	-36	-39

Table 4: Incomplete Network Payoff Table, Low Liquidation Rate Treatment $(r = 0.2)$

	Choice of your group-mate	**N**			**W**		
	Number of Withdrawals in the connected bank	**N**	**1W**	**2W**	**N**	**1W**	**2W**
Your Choice	**N**	100	81	34	-100	-100	-100
	W	-5	-7	-12	-24	-26	-29

Table 5: Incomplete Network Payoff Table, High Liquidation Rate Treatment ($r = 0.4$)

	Choice of your group-mate	**N**							**W**						
	Number of withdrawals in the connected banks	**0W**	**1W**	**2W**	**3W**	**4W**	**5W**	**6W**	**0W**	**1W**	**2W**	**3W**	**4W**	**5W**	**6W**
Your Choice	**N**	100	67	25	-18	-77	-100	-100	-100	-100	-100	-100	-100	-100	-100
	W	-13	-15	-17	-19	-22	-24	-26	-29	-31	-33	-34	-37	-38	-40

Table 6: Complete Network Payoff Table, Low Liquidation Rate Treatment ($r = 0.2$)

	Choice of your group-mate	**N**							**W**						
	Number of withdrawals in the connected banks	**0W**	**1W**	**2W**	**3W**	**4W**	**5W**	**6W**	**0W**	**1W**	**2W**	**3W**	**4W**	**5W**	**6W**
Your Choice	**N**	100	94	88	63	51	25	0	-100	-100	-100	-100	-100	-100	-100
	W	-4	-5	-6	-8	-9	-12	-14	-22	-22	-23	-25	-26	-28	-30

Table 7: Complete Network Payoff Table, High Liquidation Rate Treatment ($r = 0.4$)

VARIABLES	(1) Odds ratio	(2) Odds ratio	(3) Odds ratio	(4) Odds ratio	(5) Odds ratio	(6) Odds ratio	(7) Odds ratio	(8) Odds ratio
Network Structure Incomplete =1	3.498**	3.462**	3.279**	3.260**	3.137**	3.118**	2.790**	2.773**
	(1.657)	(1.629)	(1.457)	(1.438)	(1.343)	(1.325)	(1.071)	(1.056)
Liquidation Rate High (0.4) =1	0.201**	0.202**	0.224**	0.226**	0.240**	0.241**	0.285**	0.287**
	(0.0950)	(0.0946)	(0.0992)	(0.0991)	(0.102)	(0.102)	(0.109)	(0.109)
Incomplete x Liquidation Rate High	0.293	0.301	0.310	0.312	0.324	0.326	0.356	0.359
	(0.196)	(0.200)	(0.194)	(0.194)	(0.196)	(0.196)	(0.193)	(0.193)
Withdraw (if not forced) in t-1			1.650**	1.650**	1.455**	1.456**	1.447**	1.448**
			(0.119)	(0.119)	(0.110)	(0.110)	(0.110)	(0.110)
Partner withdraw in t-1					1.504**	1.501**	1.569**	1.567**
					(0.113)	(0.112)	(0.118)	(0.118)
Number of withdrawals in connected banks in t-1 (normalized)							1.986**	1.985**
							(0.214)	(0.214)
if sex =Female		1.151		1.172		1.176		1.178
		(0.138)		(0.125)		(0.134)		(0.136)
Age (years)		0.985		0.987		0.986		0.987
		(0.0120)		(0.0107)		(0.0114)		(0.0116)
If native language not English		0.953		1.028		1.020		1.019
		(0.131)		(0.126)		(0.133)		(0.134)
Experience in DM Experiments		1.002		0.997		0.997		0.998
		(0.0154)		(0.0138)		(0.0146)		(0.0148)
Constant		1.504		1.192		1.022		0.660
		(0.638)		(0.464)		(0.400)		(0.249)
Observations	9,240	9,240	7,834	7,834	7,834	7,834	7,834	7,834
Number of groups (cohorts)	44	44	44	44	44	44	44	44

Notes: Dependent variable: "withdraw=1". Mixed-effects panel logistic regression, Three levels: Cohort (N=44)-group (N=176)-individual (N=352). Standard errors in parentheses. ** p<0.01, * p<0.05.

Table 8: Mixed Effects Panel Logit Regression Analysis of Withdrawal Decisions

	Incomplete - $r = 0.2$	Complete - $r = 0.2$	Incomplete - $r = 0.4$	Complete - $r = 0.4$
Bank				
B	10.48**	20.64**	81.98**	81.02**
	(2.011)	(3.958)	(16.91)	(16.34)
C	7.433**	21.90**	87.62**	78.71**
	(1.406)	(4.208)	(18.11)	(15.83)
D	4.581**	20.59**	59.99**	63.29**
	(0.890)	(3.944)	(11.71)	(12.42)
Constant	0.0371**	0.0517**	0.111**	0.115**
	(0.0135)	(0.0254)	(0.0358)	(0.0327)
Observations	2,640	2,640	2,640	2,640
Number of groups (cohorts)	11	11	11	11

Note: Dependent variable "wait=1". Three levels: Cohort (N=44)-group (N=176)-individual (N=352). Standard errors in parentheses. ** p<0.01, * p<0.05.

Table 9: Mixed Effects Panel Logit, Showing Odds Ratios for Banks (Baseline Bank A) by Treatment.

FIGURES

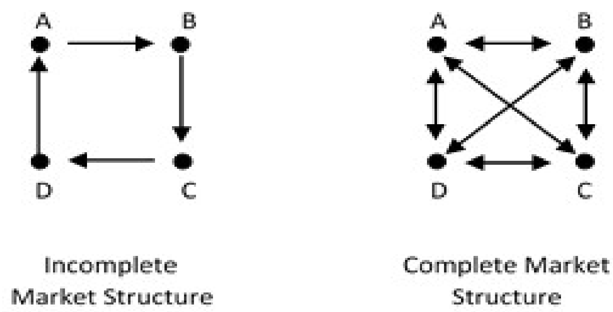


Figure 1: Symmetric Banking System Network Structures.

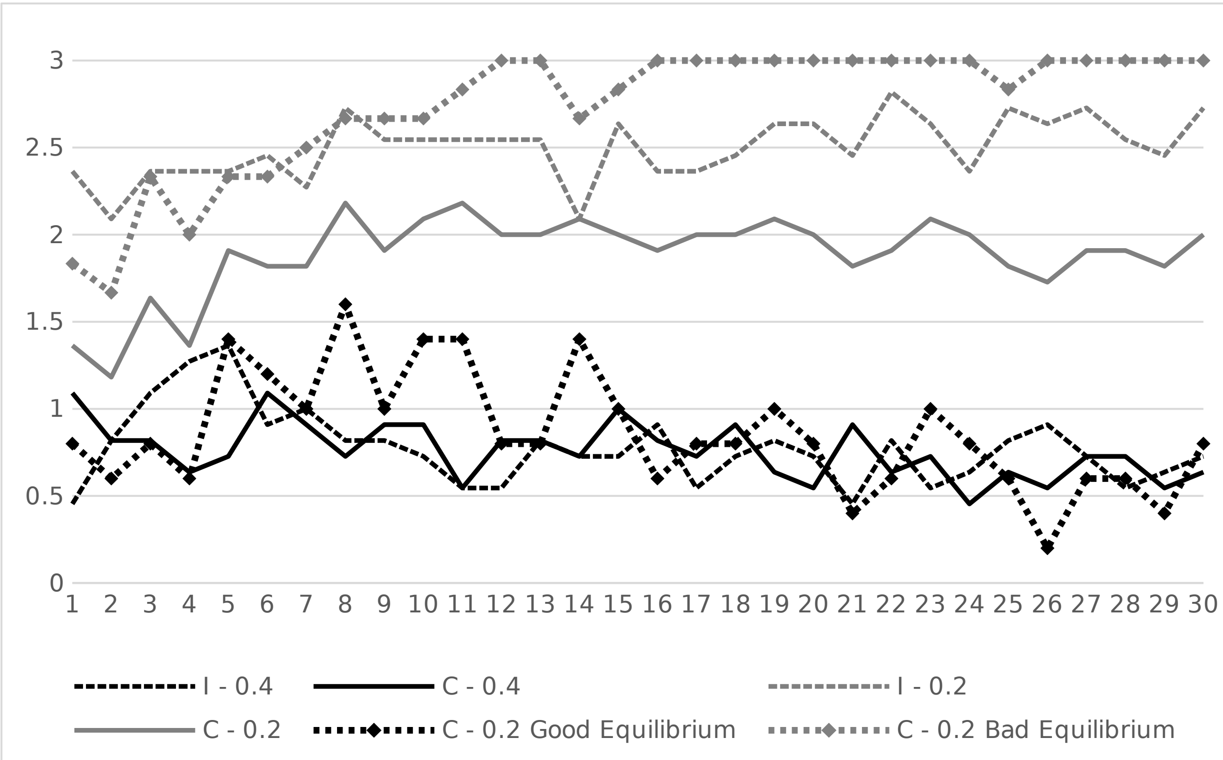


Figure 2: Average Number of Bankrupted Banks (excluding "A") over time, all four treatments.

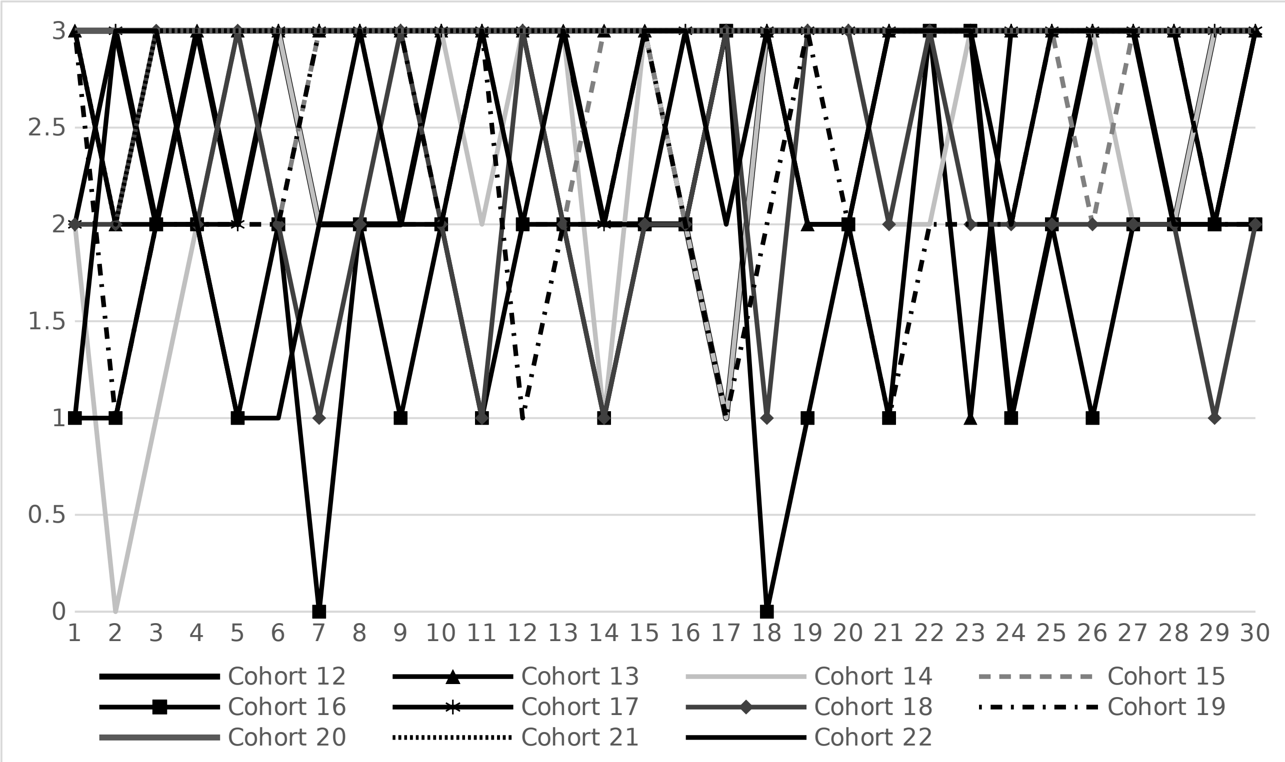


Figure 3: Number of Bankrupted Banks (excluding Bank "A") over time, each cohort of the Incomplete, $r=0.2$ treatment.

Figure 7: Number of Withdrawal decisions by banks in various treatments/cohorts over time (five round moving averages).

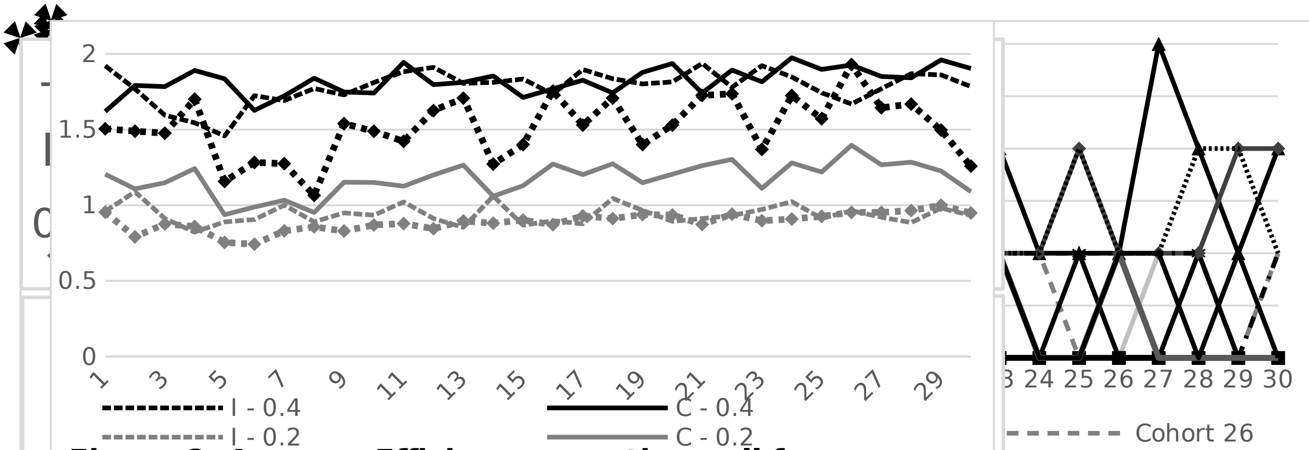
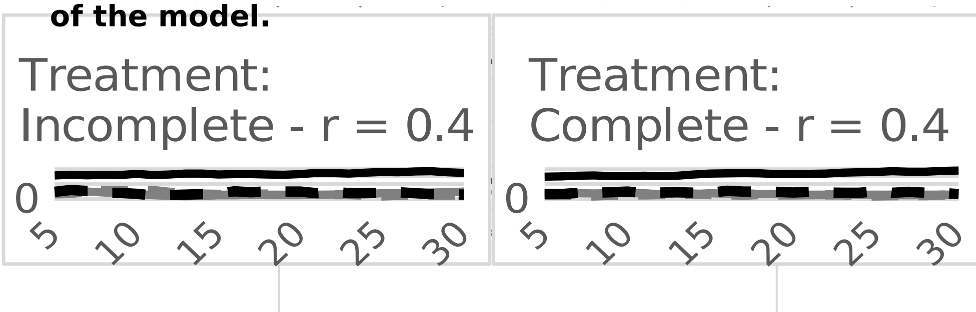


Figure 8: Average Efficiency over time, all four treatments. The Complete, treatment is subdivided into cohorts closer to the good or to the bad equilibria of the model.



[1] See Dufwenberg (2015) for a recent survey of the literature.

[2] Other differences between the papers include the number of withdrawers in each bank, strategic uncertainty regarding types, and the number of repetitions of the game.

[3] Corbae and Duffy (2008) study the role of network structure for equilibrium selection in N-player Stag Hunt games but their main focus is on the endogenous choice of network structure. By contrast, in this paper we impose the network structures exogenously and ask whether those different structures matter for the prevalence of efficient risk sharing.

[4] See Allen and Gale (2000) for a detailed description on how to get these first-best allocations.

[5] This was computerized and the subjects' endowments were automatically deposited in their respective bank. As noted earlier, deposits were invested by the bank so as to achieve the first best outcome; these choices are reflected in the payoff tables that subjects face when considering whether to make withdrawal decisions.

[6] For example, given that there are 4 banks, there can be 4 different combinations where only 1 person withdraws in the entire banking system. The payoffs for each bank if one person withdraws might differ due to the asymmetry in the forced withdrawal request in Bank A. For this reason, we calculate the median value of those 4 payoffs and this is what appears, for instance under the N, 1W column of Table 4. The payoff tables for all possible combinations of withdrawal demands are available upon request.

[7] 95% confidence interval bars were added to the different average efficiency time series to conclude about statistical differences. However, for presentation purposes, we do not present these confidence interval bars in Figure 8.

[8] Recall that in the complete network for any bank, the number of connected banks is three while in the incomplete network it is one, therefore in the complete network the maximum number of withdrawals in the connected banks is six whereas in the incomplete network it is two. To make treatments comparable, we used a unity-based normalization, that is: $x' = \frac{x - min(x)}{max(x) - min(x)}$, where x is the observed number of withdrawals in the connected banks.