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Abstract

We develop, both theoretically and experimentally, a stereotypical environment that allows for coordination breakdown, leading to a bank run. Three depositors are located at the nodes of a network and have to decide whether to keep their funds deposited or to withdraw. One of the depositors has immediate liquidity needs, whereas the other two depositors do not. Depositors act sequentially and observe others actions only if connected by the network. Theoretically, a link connecting the first two depositors to decide is sufficient to avoid a bank run. However, our experimental evidence shows that subjects' choice is not affected by the existence of the link *per se*. Instead, being observed and the particular action that is observed determine subjects' choice. Our results highlight the importance of initial decisions in the emergence of a bank run. In particular, Bayesian analysis reveals that subjects clearly depart from predicted behavior when observing a withdrawal.

Keywords: bank runs, coordination failures, experimental evidence, networks.

JEL Classification: C70, C90; D85; G21

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1 Introduction

Much of the Great Depression's economic damage was caused directly by bank runs (Bernanke 1983). In 2007, the run on Northern Rock in the United Kingdom heralded the oncoming economic crisis. After that, several banks have been run in developed countries such as the Bank of East Asia in Hong Kong or the Washington Mutual in the United States of America. Non-bank institutions, like investment funds, have also experienced massive withdrawals very similar to a bank run. The collapse of Bear Stearns, or the temporary suspension of redemptions in the real estate investment fund Banif Inmobiliario in Spain are just two recent examples.

The two polar explanations for the occurrence of bank runs are the worsening of fundamental variables (e.g., macroeconomic shocks) and coordination failure among depositors.¹ Empirical evidence suggests that bank runs may not be explained merely by changes in the fundamentals affecting the bank (Calomiris and Mason, 2003), so coordination problems are an important issue at stake too. The workhorse model of coordination problem among depositors is that of Diamond and Dybvig (1983). They show, by the way of a simultaneous-move game, the possibility of multiple equilibria, one of which involves depositors running the bank. The literature that grew out of Diamond and Dybvig (1983) maintains the simultaneous-move framework to study the coordination problem. However, description of bank runs (Sprague 1910, Wicker 2001) and statistical data (Starr and Yilmaz 2007) suggest that decisions are not entirely simultaneous, but are partially sequential. Thus, many depositors have information about what other depositors have done and use it when making their decisions (Kelly and O Grada 2000, Iyer and Puri 2008).

In game theory, two actions are said to be simultaneous if players are not informed about other players' actions. Even though the decisions may be made at different points in time, the game is simultaneous because players make decisions without knowing the actions that are being chosen by others. By contrast, sequentiality requires information flow and knowledge of predecessors' actions.

We build a theoretical model displaying both simultaneity and sequentiality by using networks. Depositors are the nodes of a network, so that a link connecting two nodes implies that one of the depositors can observe the others' actions. As a result, the connected depositors play a sequential game while the depositors who are not linked play a simultaneous game. We consider two different types of depositors and study a three-player network, which is the smallest network where coordination problems may arise.² We assume that there is one impatient depositor who has an immediate need for funds. The other two depositors, who are called

¹Gorton and Winton (2003) is a comprehensive survey on financial intermediation dealing in depth with banking panics.

²Our setup is akin to the existing literature. Green and Lin (2000) analyze the coordination problem with three depositors, whereas one of the main results in Peck and Shell (2003) involves two depositors.

patient, do not need their money urgently. Everybody has to decide whether to withdraw her funds from the bank or keep them deposited. If both of the patient depositors decide to keep the money in the bank, they will receive a payoff which is higher than the payoff associated with withdrawal. If only one of them waits, her payoff will be lower than that of withdrawal.³ Depositors decide in sequence as if they were in the line of a bank. They know their position in the sequence and their type, which is private information. A depositor observes previous actions depending on whether she has a link to those who have acted before. Depositors also know if they will be observed by subsequent depositors. We define a bank run as a situation in which at least one of the patient depositors withdraws. In this respect, we show that if the first and the second depositors are connected, then no bank run is the unique equilibrium. This result is independent of the types of depositors who are linked. Hence, when the link between the first two depositors (henceforth, link 12) is not in place, bank runs may occur in equilibrium. The link 12 represents therefore a sufficient condition to avoid bank runs as it eliminates coordination failure in the network.⁴

Next, we aim at testing our theoretical prediction in the lab. We match subjects in pairs and let the computer acting as the impatient depositor. Subjects are aware of this and know that coordination with the other subject in the lab yields higher payoffs. Statistical tests confirm partially the theoretical prediction. The link 12 decreases significantly the first depositor's withdrawal rate. Nevertheless, we also see that the first depositor's behavior is mainly driven by the fact of being observed, rather than by the link 12. It is the case because the link 13 has also a considerable effect in reducing the first depositor's withdrawal rate. Regarding the second depositor, it turns out that the link 12 is not important in the sense the theory predicts. We find that the second depositor cares about what she observes and not about the existence of the link 12. Thereby, observing a withdrawal increases the probability of withdrawal, while the opposite is true when she observes a waiting. We undertake a Bayesian analysis to complete our experimental study. The result confirms that the second depositor deviates from equilibrium behavior after observing a withdrawal. Indeed, her choice can be better explained by random behavior that induces withdrawal with probability one half.

To our best knowledge, our analysis is the first to approach the classic bank-run problem using a network that channels information among depositors. This modeling choice has various advantages. On the one hand,

³We will use to keep the money in the bank and to wait in an interchangeable manner.

⁴More specifically, the link 12 rules out the possibility of multiple equilibria in Diamond and Dybvig (1983). Uniqueness or multiplicity of equilibria is an important issue in the bank run literature. For instance, contrary to Diamond and Dybvig (1983), Goldstein and Pauzner (2005) show in a global games setup that both run and no run are possible equilibria, but the fundamentals determine unambiguously which one occurs. Green and Lin (2003) show that a bank can offer a contract that implements uniquely the efficient outcome.

it fits the empirical evidence and allows for simultaneity and sequentiality in a natural way. This represents a novelty in the bank run literature. On the other hand, the use of networks helps to disentangle issues involving uniqueness or multiplicity of equilibria. More concretely, our theoretical result contributes to this debate by showing that there are information structures that imply a unique equilibrium without run.

The rest of the paper is organized as follows. Next we review the experimental literature on bank runs. Section 2 provides the theoretical framework we will test, as well as the notation and the main theoretical result. In section 3, we first describe our experiment and then we analyze and discuss the empirical results. Section 4 concludes.

Literature Review

There is a rich literature on coordination games and experimental testing, but only three of the papers involve a bank run scenario.⁵ Schotter and Yorulmazer (2008) focus on the dynamic analysis of bank runs and how different factors (e.g., asymmetric information or deposit insurance) influence the dynamics of withdrawals. They show the importance of the available information on depositors' behavior, and more concretely they find that predictions of the theory are consistent with observed behavior when players have a high level of information. Madies (2006) studies the possibility of self-fulfilling bank runs and the efficiency of policy instruments (suspension of convertibility and deposit insurance) to prevent them. He finds that self-fulfilling banking panics are recurrent and persistent phenomena, but banks with sufficient liquidity or a full deposit insurance may curb them. Our paper departs from these studies as their foci are withdrawal dynamics when a bank run is already underway while our question is how bank runs emerge and what affects the prevalence of runs.

The closest paper to ours is Garratt and Keister (2009). They study how two factors (multiple possibilities to withdraw and forced withdrawals) affect the existence of bank runs. They find that in the absence of forced withdrawals players effectively coordinate on the good outcome and withdrawals are rare. Nevertheless, adding forced withdrawals results in high withdrawal rates. They identify the multiple withdrawal possibility as the culprit of this negative outcome. They claim that more information about other depositors' decision may be harmful for coordination when there are still opportunities to withdraw. In this respect, our analysis

⁵Our analysis relates also to the emerging literature on coordination problems in network. A recent paper in this literature is Choi et al. (2008) that studies a public good game. Despite differences in the model there is a striking similarity in the results. They call strategic commitment the tendency to make contributions early in the game to encourage others to contribute. This commitment is of strategic value only if it is observed by others. Our finding that the first depositor is more likely to wait when observed by any of the subsequent depositors can be seen as case of strategic commitment. Our paper can also be related to coordination problems in organization. Brandts and Cooper (2006) stress the importance of observability in this context.

suggests that having more information through more links may enhance the possibility of bank runs if the impatient depositor is the first to decide. Otherwise, the link 12 enforces coordination and helps to avoid bank runs in equilibrium. Garratt and Keister (2009) also show how simple cutoff rules involving Bayesian updating perform well in explaining observed behavior. Bank runs can then be due to negative beliefs about how other players will play. We can also derive a similar explanation relying on our Bayesian analysis, which suggests that depositors may overweigh the probability of observing withdrawal from patient depositors. In any case, our approach differs from Garratt and Keister (2009) as we introduce an impatient depositor (the computer) that withdraws with certainty. Besides, we use networks to channel information and account for simultaneous and sequential decisions.

2 The Model

Consider three depositors, each of them endowed with $e > 0$ of monetary units. There is a bank which pools the endowments at $t = 0$ and offers a contract $\gamma = (c_{00}, c_1, c_{01}, c_{run}) > 0$ which specifies the depositors' payoffs depending on two factors: (i) depositors' choice at $t = 1$, and (ii) the available funds of the bank.

At the beginning of $t = 1$ depositors learn their liquidity types and their position in the sequence of decision ($i = 1, 2, 3$). One of the depositors has liquidity needs (impatient depositor), so she cares only about immediate consumption at $t = 1$. The other two depositors derive utility from consumption at any period (patient depositors). Liquidity type and position in the line are assumed to be independent (e.g., the impatient depositor is not more probable to be at the beginning of the line).

As usual in the literature, depositors are isolated from each other (they cannot trade directly), but have the opportunity to contact the bank to withdraw their deposit. Since the impatient depositor always withdraws, we focus our attention on the patient ones. Let c_1^i denote depositor i 's payoff upon withdrawal at $t = 1$ and c_0^i the payoff if she waits at $t = 1$ for $i = 1, 2, 3$. The utility function ($u(c^i)$, where $c^i \in \{c_0^i, c_1^i\}$) is strictly increasing and strictly concave. Types are publicly unobservable, but it is common knowledge that there are two patient and an impatient depositors.

Depositors decide once, according to their position in the line (i). As depositors are called to decide in $t = 1$, they may either keep the money in the bank or withdraw it. Notationally, $y_i \in \{0, 1\}$ for $i = 1, 2, 3$ stands for the decision of depositor i , where 0 denotes keeping the money, whereas 1 indicates withdrawal. We define $y_{-i} \in Y_{-i}$ as the unordered decisions of the other depositors, where $Y_{-i} = (\{1, 1\}, \{1, 0\})$.

The payoffs are determined as follows. If an depositor decides to withdraw, then she receives immediately her money from the bank. The payoff upon withdrawal is $c_1^i = c_1$ for $i \in \{1, 2\}$, and for $i = 3$ it is

$$c_1^i = \begin{cases} c_1 & \text{if } y_{-i} = \{1, 0\} \\ c_{run} & \text{if } y_{-i} = \{1, 1\} \end{cases},$$

where $0 < c_{run} < e < c_1$. In words, the bank commits to pay c_1 to the first two withdrawing depositors. Note that the depositor in the third position may be the second withdrawing depositor and in this case she receives c_1 . After two withdrawals, if the third depositor also decides to withdraw, then she gets the remaining funds in the bank ($c_{run} = 3e - 2c_1$) which is less than the initial endowment e .

If a patient depositor decides to keep the money in the bank, then she receives her payoff at $t = 2$. The amount of funds the bank has at the end of period 1 will be $3e - c_1$ or $3e - 2c_1$, depending on the other patient depositor's decision. This amount earns a return and then it is split up equally among the depositors who have waited yielding the following payoffs:

$$c_0^i = \begin{cases} c_{00} & \text{if } y_{-i} = \{1, 0\} \\ c_{01} & \text{if } y_{-i} = \{1, 1\} \end{cases},$$

where $c_{01} < c_{00}$ and in the subscript the first symbol (0) shows that depositor i waits, while the second symbol denotes the other patient depositor's decision.

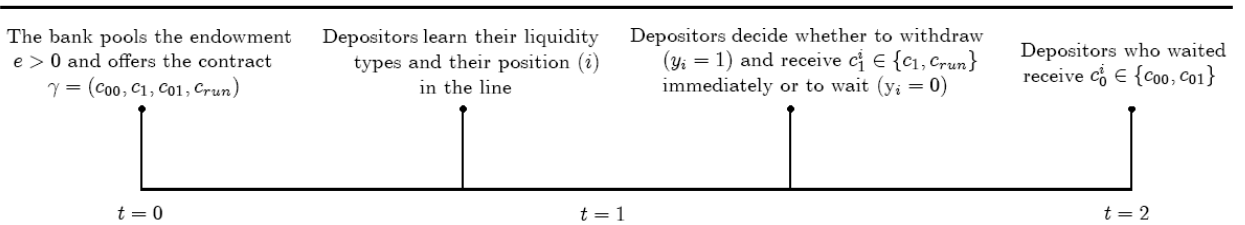
We assume that

$$c_{00} > c_1 > e > c_{01} > c_{run} \tag{1}$$

which allows for coordination problems.

The following graph summarizes the events of our model:

Figure 1. Timing of the model



Network, Information and Bank Runs

We use the network to determine the information flow among depositors. Depositors are set in a social network. Linked depositors are called neighbors and links are undirected so that information flows in both directions. Although types cannot be observed, links allow for observability of neighbors' actions.

Links are independent of liquidity types, so depositors of the same liquidity type are not more likely to be linked. Neither is there any relationship between liquidity type and the number of links. A link is represented by a pair of numbers which shows the depositors who are connected. Hence, ij (for $i, j \in \{1, 2, 3\}$, $i < j$) denotes a link which connects depositors i and j . For instance, 12 denotes a link between the first and the second depositor. A network (Γ) is the set of existing links among the depositors. The possible networks are: (12, 23, 13), (12, 23), (12, 13), (13, 23), (12), (13), (23), (\emptyset), where (\emptyset) stands for the empty network which has no links at all while the structure (12, 23, 13) contains all the possible links and is called the complete network.

Whenever two depositors are connected, the second one to act observes the action of the first one, who knows that her action is observed. Hence, when it is depositor i 's turn to decide, she knows her own type, her position in the line, the actions of those neighbors who preceded her (y_j for $j \neq i$ if $j < i$ and $ij \in \Gamma$) and whether she will be observed by subsequent neighbors. Notice that the depositors' information is local, therefore the network structure is not common knowledge. As a consequence, no depositor knows if the other two depositors are connected or not.⁶

A key element of the model is that when the depositors decide, they may not be sure of the payoff they will receive. For instance, if a patient depositor at the first position waits, then her payoff depends on what the other patient depositor does (i.e., $c_0^1 \in \{c_{00}, c_{01}\}$). Similarly, if a depositor at the third position without links to preceding depositors decides to withdraw, then she does not know whether she will receive c_1 or c_{run} .

We define a bank run in the following way.

Definition 1 *A bank run occurs if at least one patient depositor withdraws.*

We present in the following proposition a full characterization of the possible networks under study. We use iterated deletion of dominated strategies to show that a link connecting the first and the second depositor is sufficient to avoid bank runs, while they may occur in any other network.

Proposition 1 *If the link 12 exists, no bank run is the unique equilibrium. In any network in which the link 12 does not exist, bank runs may occur.*

Proof. Recall that the impatient depositor always withdraws.

First we show that waiting is a dominant strategy for a patient depositor in the third position. Her decision may follow either two withdrawals ($Y_{-3} = \{1, 1\}$) or a waiting and a withdrawal ($Y_{-3} = \{1, 0\}$). In

⁶Given the nature of bank runs it seems reasonable to assume that depositors do not know exactly what other depositors know. However, the theoretical result also holds when network structure is common knowledge.

the first (second) case, by waiting she receives c_{01} (c_{00}), while withdrawal yields c_{run} (c_1). Since $c_{01} > c_{run}$ ($c_{00} > c_1$) waiting is a dominant strategy.

Now, suppose that the link 12 is in place. If a patient depositor in the second position observes a waiting, her dominant strategy is to wait ($c_{00} > c_{01}$). Given the previous results, a patient depositor in the first position, waits. This follows after noting that this depositor gets the highest payoff by waiting ($c_{00} > c_1$). Optimality requires that the second depositor should believe that withdrawals are due to the impatient depositor with probability 1. As a consequence, if the second depositor observes a withdrawal it is optimal to wait ($c_{00} > c_1$). Therefore, the second depositor waits regardless of what she observes. This proves the first part of the proposition.

The second part of the proposition assumes that link 12 does not exist. We show multiplicity by constructing a non bank run and a bank run equilibrium.

A profile of strategies where patient depositors wait always in any position is a no bank run equilibrium. Recall that a patient in the third position waits. If the strategy of the second (first) depositor when patient is to wait, then the best response of the first (second) depositor is also to wait ($c_{00} > c_{01}$). Therefore for the patient depositors "waiting at any position" defines an equilibrium.

In the bank run equilibrium, consider the profile of strategies where depositors 1 and 2 withdraw if patient. Note that if depositor 1 (depositor 2) withdraws if patient, the best response of depositor 2 (depositor 1) is also to withdraw if $u(c_1) > \frac{1}{2} [u(c_{00}) + u(c_{01})]$ is satisfied, since Bayesian updating requires that depositor 2 (depositor 1) believes that depositor 1 (depositor 2) is patient or impatient with probability $\frac{1}{2}$. Thus if link 12 is absent, for c_1 high enough, there exist a bank run equilibrium. As a result, there are multiple equilibria. ■

Discussion of the Result

Our theoretical result is based on the fact that depositors know their position in the line.⁷ The proposition then uses iterated deletion of dominated strategies to show that the existence of the link 12 is important to avoid bank runs in equilibrium. The result also implies that once the link 12 exists, the links 13 and 23 are irrelevant. It does not imply, however, that in the absence of the link 12 bank runs always occur. In that case, depositors 1 and 2 may withdraw or wait in equilibrium.

The proof of the proposition relies on depositors' optimal beliefs. Specifically, it uses that in the presence

⁷Kiss and Rosa-García (2008) show that if agents do not know their position in the line of the bank, then bank run is a possible equilibrium outcome in any network, except in the complete network and in the network {12,13} when the first agent is patient.

of the link 12, after observing a waiting (withdraw) a patient depositor in the second position believes that the first one is patient (impatient) with probability 1. On the other hand, if depositors 1 and 2 are not linked, optimality requires that a depositor in the second (first) position believes that the first (second) depositor is patient with probability $\frac{1}{2}$, given that each possible liquidity type vector describing positions in the line is equiprobable. This result allows for a full characterization of the eight possible networks regarding the possibility of bank runs. In the set of networks comprised by $\{(12, 23, 13), (12, 23), (12, 13), (12)\}$ bank runs should not occur according to our theoretical prediction. In the rest of the networks, both run and no run are possible equilibria.

3 Experimental Design and Evidence

Experimental Environment

Two experimental sessions were conducted at the Laboratory of Theoretical and Experimental Economics (LaTeX) of the Universidad de Alicante. A total of 48 students (24 per session) were recruited among the undergraduate population of the University using *Campus Virtual* (students' virtual access to their scholar information). Through the different sessions, students were received and invited to take a numbered ball to determine their place in the lab. The laboratory consists of 24 computers in separate cubicles. When subjects were in front of their computers, instructions were read aloud. As usual, any communication during the experiment was strictly forbidden.

The computerized experiment used z-Tree (Fischbacher, 2007). Subjects played a one-shot coordination problem during 18 rounds, with variation of information and matching across rounds. The first three rounds in each session were used for subjects to get familiar with the software and the experimental procedure. Participants knew that the first 3 rounds were not going to be paid at the end of the experiments but the remaining 15 were. We let subjects ask about any doubt after the first three rounds. The average duration of each session was 45 minutes.

Subjects were divided into two matching groups of 12 people so subjects from different matching groups never interacted with each other. We randomly and anonymously matched in pairs subjects in the same matching group. We formed 12 different banks at the beginning of each round (each of them with 2 subjects in the room). The initial endowment of the depositors ($e = 40$ pesetas) was deposited in a common bank. In addition, 40 pesetas were invested by a third depositor simulated by the computer.⁸ Then, each participant

⁸It is standard practice for all experiments run in Alicante to use Spanish pesetas as experimental currency. The reason for this design choice is twofold. First, it mitigates integer problems, compared with other currencies (USD or euros, for example).

had to choose between withdrawing her money or to wait. At the end of each round, subjects were informed about their payoffs but not about other depositor's action. In addition, participants were always presented a different situation to avoid learning (i.e., in each round, subjects were placed in a different network or in a different position of the same network). In each possible network, the computer-depositor was intended to embody the impatient depositor so it was programmed to withdraw always her money regardless of the situation. Subjects knew about the computer as the third depositor in their bank that always withdraws. They were also informed about the independence of liquidity types and positions in the line. Therefore, the coordination problem arises in the spirit of our theoretical model above so if depositors in the lab coordinate on waiting, they get higher payoffs than if they do not.

Subjects were provided a payoff table which specified their payoff in each possible history. To introduce the network structure in an easy-handle way, participants were told that they were in a given position in the line of a three-depositor bank and might have information concerning predecessors' choice and if their action is going to be observed by someone else in the line. Thus, the problem was sequential and, at the time of making their decision, experimental subjects were presented local information about the network structure in the round. This information was summarized in a picture and a short text message that specified the available information and the possible payoff consequences of both actions, waiting and withdrawing. Within rounds, subjects in the same bank decided one after the other, so, for instance, the third player in the line had to wait until the other two depositors (the other player and the computer) have decided. Subjects knew that the graph and the information changed at every round so it was important for them to consider the cases carefully.

Payoffs

The bank was provided a total of 120 pesetas per round and the contract was given by $\gamma = (c_{00}, c_1, c_{01}, c_{run}) = (70, 50, 30, 20)$. We justified these payoffs as follows.⁹

The initial endowment $e = 40$ pesetas was invested at $t = 0$ in a project that yielded a high long-term return. The computer was an impatient depositor that needed her funds so she was programmed to withdraw her money at $t = 1$, taking $c_1^i \in \{c_1, c_{run}\}$ where $c_1 = 50$ pesetas and $c_{run} = 20$ pesetas. The first amount ($c_1 = 50$ pesetas) was received unless there had been already two withdrawals and corresponds to the initial

On the other hand, although Spanish pesetas are no longer in use (replaced by the euro in 2002), Spanish people still use pesetas to express monetary values in their everyday life. In this respect, by using a "real" (as opposed to an artificial) currency, we avoid the problem of framing the incentive structure of the experiment using a scale (e.g., "experimental currency") with no cognitive content. Exchange rate: 1 euro = 166,386 pesetas.

⁹The payoffs resemble the ex ante optimal contract in Diamond and Dybvig (1983), satisfying the relation in (1).

deposit ($e = 40$) plus the interest rate (10 pesetas). If the computer was the third withdrawing depositor, then its payoff was $c_1^3 = c_{run} = 20$ pesetas which corresponds to the initial endowment minus twice the amount paid to withdrawing depositors (i.e., $c_{run} = 3e - 2c_1$).

If both subjects in the lab coordinated on waiting, the project was carried out by the bank and each of the subjects who waited received $c_0^i = c_{00} = 70$ pesetas. This amount was received after doubling the available funds at $t = 1$ ($3e - c_1$) and then dividing it equally among patient subjects. Withdrawal, however, was also possible for subjects in the lab. Actually, if only one of the subjects in the lab decided to withdraw, she would face exactly the same situation as the impatient depositor (computer) taking $c_0^i = c_1 = 50$ pesetas, regardless of her position. If only one patient subject decides to wait, then the available money after the two withdrawals (20 pesetas) was incremented by 10 pesetas, and then given to the patient subject that is $c_{01} = 30$ pesetas.

Finally, the position in the line is important when both subjects in the lab withdraw. Since the initial investment is 120 pesetas and withdrawal would imply 50 pesetas for each subject, the last subject in the line cannot receive 50 pesetas and will get $c_{run} = 20$.

The payoff table in Figure 2 replicates the one that subjects had in the instructions and summarizes our payoff scheme:

Figure 2. *Payoff table for the experiment*

Number of previous withdrawals	If you withdraw	If you wait, then...	
		If the other depositor in the room waits and only the computer withdraws	If the other depositor in the room and the computer withdraw
0	50	70	30
1	50	70	30
2	20	Not applicable	30




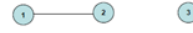


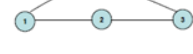

During the first three rounds, subjects were informed about how to read the table. For instance, the payoff 30 in the first row and the last column tells that although there have not been any withdrawal yet, the first subject in the line may end up obtaining 30 pesetas. As commented above, this occurs if she is the only subject who waits regardless of her position in the line.

Experimental Results

We report the descriptive statistics in Table 1. We specify in each cell the number of observations (in brackets) and the observed probability of subject i 's withdrawal. The results are presented for each possible

network structure and for each possible position $i \in \{1, 2, 3\}$ in the line of the bank. We have 720 observations in total (12 banks x 2 patient subjects x 15 rounds x 2 sessions).

Table 1. Descriptive statistics for each possible network

	Network	Agent 1	Agent 2	Agent 3
1		(25) 0.16	(24) 0.2083	(25) 0.16
2		(25) 0.2	(24) 0.3333	(25) 0.24
3		(24) 0.2917	(25) 0.32	(24) 0.0417
4		(24) 0.1667	(24) 0.375	(24) 0.1667
5		(22) 0.5908	(23) 0.3478	(24) 0.0833
6		(22) 0.1818	(24) 0.3333	(24) 0.25
7		(48) 0.0416	(49) 0.18367	(47) 0.14285
8		(48) 0.2917	(48) 0.375	(48) 0.3333

We observe in Table 1 that the existence of the link 12 is important for the first depositor. In fact, when the link 12 exists, the probability of depositor 1's withdrawal is at most 20% (Network 2). Contrariwise, if such a link is not present, the highest probability of withdrawal occurs in the network 5, in which the first depositor's action is unobservable by any other depositor. The probability of withdrawal in that case increases up to nearly 60% of the times. To carry out a t-test, we group the networks into two categories depending on the existence of the link 12. We reject the hypothesis that depositor 1 withdraws with the same probability when the link 12 exists and when it does not ($t = -3.8964$, $p - value = 0.0001$).

The evidence, however, is not so clear for depositor 2 who seems to withdraw around one third of the times regardless of the existence of the link 12. Indeed, we cannot reject the hypothesis that depositor 2's probability of withdrawal is the same when the link 12 is present and when it is not ($t = -1.5862$, $p - value = 0.1140$). Thereby, we can conclude that the link 12 affects differently the first and the second

depositor. Whereas the first depositor seems to act in line with the theoretical predictions, it is not the case for the second depositor.

We estimate a probit and a logit model to study in detail the depositors' behavior. Recall that $y_i \in \{0, 1\}$ for $i = 1, 2, 3$ denotes the decision of depositor i , where 0 denotes keeping the money, whereas 1 indicates withdrawal. We propose the following specification that accounts for all possible information that depositor 1 might have when taking her decision:

$$\Pr(y_1 = 1) = F(\alpha_0 + \alpha_1 L12 + \alpha_2 L13 + \alpha_3 L12L13) \quad (2)$$

where $F(z) = e^z/(1 + e^z)$ in the logistic specification, whereas $F(z) = \Phi(z)$ in the probit model in which $\Phi(\cdot)$ is the cumulative distribution for the standard normal. Then, the equation (2) states that the probability of withdrawal for depositor 1, $\Pr(y_1 = 1)$, may depend on the existence of the link 12 and 13. The explanatory variable Lij is then defined as a dummy variable that takes the value 1 (0) when the link ij is (not) present for $i, j \in \{1, 2, 3\}$, $i < j$. As a result, L12L13 is obtained as the product of the two dummy variables L12 and L13. This variable stands for the cases in which both links are present (networks 2 and 7) and introduces flexibility in the model because it allows to determine whether there is some additional effect of having both links, apart from the effect that the links generate separately.

We run the probit and the logit model in (2) over 238 observations. We present the main results in Table 2. The estimated standard errors of the parameters (SE) take into account the matching group clustering.

Table 2. *Probit and logit model for the first depositor*

Regressor	Probit Model				Logit Model			
	Coefficient	SE	p-value	Marginal Effect	Coefficient	SE	p-value	Marginal Effect
Constant	-0.2905	0.1677	0.083		-0.4654	0.2707	0.086	
L12	-0.6906	0.1966	0.000	-0.1961	-1.1688	0.3565	0.001	-0.1890
L13	-0.4186	0.0848	0.000	-0.1185	-0.6921	0.1446	0.000	-0.1109
L12L13	0.0944	0.2894	0.744	0.0272	0.0825	0.5593	0.883	0.0133

The estimated standard errors of the parameters take into account matching group clustering. Number of obs: 238. Pseudo-R2=0.0741

All the coefficients are significantly different from 0 except α_3 . The marginal effects reveal that the probability of withdrawal depends negatively on the existence of the links 12 and 13. In fact, the link 12 significantly decreases the probability of withdrawal for depositor 1 around 20% whereas the link 13 decreases this probability in 10%. This suggests that what is really important for depositor 1 is the fact of being observed rather than the existence of the link 12. Indeed, if we test the hypothesis that the link 12 has the same impact that the link 13 in reducing the probability of depositor 1's withdrawal (i.e., $H_0 : \alpha_1 = \alpha_2$), we cannot reject that hypothesis at any common significance level ($\chi_1^2 = 1.01$, p-value=0.3141).

In order to analyze the second depositor’s behavior, we define the dummy variable $Y11$ ($Y10$) which takes the value 1 when she observes withdrawal (waiting) and is zero otherwise. Thus, if there is no link between the first and the second depositor, we will have $Y11 = Y10 = 0$. The explanatory variable $L23$ stands for the existence of the link 23. The variable $Y11L23$ combines information about what player 2 observes and whether she is observed. It takes the value 1 if she observes a withdrawal and has a link with the last player in the line.¹⁰ Thus, we propose to model the second depositor’s choice as follows:

$$\Pr(y_2 = 1) = F(\alpha_0 + \alpha_1 Y11 + \alpha_2 Y10 + \alpha_3 L23 + \alpha_4 Y11L23) \quad (3)$$

where $F(\cdot)$ is defined as above. In Table 3 we present the main results. We run the regression (3) over 205 observations, taking into account the matching group clustering.

Table 3. *Probit and logit model for the second depositor*

Regressor	Probit Model				Logit Model			
	Coefficient	SE	p-value	Marginal Effect	Coefficient	SE	p-value	Marginal Effect
Constant	-0.3555	0.0451	0.000		-0.5705	0.0733	0.000	
Y11	0.5355	0.2448	0.029	0.2008	0.8582	0.39313	0.029	0.1971
Y10	-1.2894	0.3276	0.000	-0.3283	-2.3739	0.7264	0.001	-0.3299
L23	-0.0752	0.2200	0.732	-0.0274	-0.1226	0.3595	0.733	-0.0271
Y11L23	-0.4145	0.2556	0.105	-0.1414	-0.6615	0.4148	0.111	-0.1347

The estimated standard errors of the parameters take into account matching group clustering. Number of obs: 205. Pseudo-R2=0.0615

Recall that our theoretical model predicts that the link 12 is important. The results in Table 3 provide evidence to support the prediction that the link 12 changes the probability of withdrawal of depositor 2 given that we reject the null hypothesis $H_0 : \alpha_1 = \alpha_2 = 0$ at any common significance level ($\chi_1^2 = 63.00$, p-value=0.0000). The theoretical prediction, however, states that no matter what depositor 2 observes, she must always wait. In particular, she should identify the withdrawal with the impatient depositor’s action. We test $H_0 : \alpha_1 = \alpha_2$ to confirm that observing withdrawal or waiting is equally important for depositor 2. We reject that hypothesis at any common significance level ($\chi_1^2 = 10.30$, p-value=0.0013). One way to interpret the results is that depositor 2 does not take into account the existence of the link 12 but bases her decision on what she observes. The marginal effects in Table 3 show that a withdrawal significantly increases her probability of withdrawal by 20%, while observing waiting significantly decreases this probability by 32%. Moreover, the existence of the link 23 does not seem to be important in affecting depositor 2’s choice.

¹⁰The explanatory variable $Y10L23 = Y10 * L23$ predicts failure perfectly. This implies that when agent 2 observes waiting and is linked with agent 3, she always waits. We do not use these 36 observations.

In short, this implies that regardless of whether her decision is being observed or not, the depositor 2 finds optimal to withdraw and ensures 50 pesetas after observing a withdrawal. This finding contradicts the theoretical prediction that states that depositor 2 should deduce that first depositor's withdrawal was due to impatient depositor (computer) and thereby she should wait.

Bayesian Analysis

While the theoretical analysis pinpoints that the existence of the link 12 is sufficient to eliminate bank runs, the experimental findings are not so clear-cut. The first depositor values being connected as both link 12 and 13 are significant and decrease the probability of withdrawal. The fact that the marginal effect of the link 12 is higher suggests the partial validity of the theoretical result. The evidence is not so clear for the second depositor. Her decision is highly influenced by what she observes. Theoretically, it should not be the case: the second depositor should think that a withdrawal in the first position was due to the impatient depositor and therefore she should always wait. If she does not, it is because she attributes some chance to the possibility that the first player was the patient depositor. We undertake a Bayesian approach to elicit the second depositor's beliefs upon observing a withdrawal.

We denote $Y_i = (y_i^1, \dots, y_i^l, \dots, y_i^n)$ the set of depositor i 's action, for $i = 1, 2, 3$. Slightly abusing notation, we define $\hat{Y}_2 = (y_2^l \in Y_2 \mid y_1^l = 1, L12 = 1)$, $\hat{Y}_2 \subseteq Y_2$ as the collection of patient depositors in the second position of the line who have observed a withdrawal. These depositors should decide whether to withdraw ($\hat{y}_2^l = 1$) or to wait ($\hat{y}_2^l = 0$). Since $\hat{Y}_2 = (\hat{y}_2^1, \dots, \hat{y}_2^l, \dots, \hat{y}_2^k)$ can be interpreted as k independent random variables, the probability mass function is given by a binomial distribution, so

$$\Pr(\hat{Y}_2 \mid \theta) = \theta^w (1 - \theta)^{k-w} \quad (4)$$

where w denotes the total number of withdrawals for depositor 2 and $\theta \in [0, 1]$ denotes the probability of withdrawal (both conditional on the fact that depositor 2 has observed a withdrawal).

Theoretically, our model predicts that the second depositor should always wait if linked with the first one (i.e., $\theta = 0$). This follows after reasoning that no withdrawal in the first position can be due to the patient depositor. Suppose, however, that depositor 2 is "naive" upon observing a withdrawal. We interpret *naïveté* as random behavior but we can also consider it as if with probability $\frac{1}{2}$ the second depositor thought that the impatient depositor (i.e., the computer) had withdrawn, while with probability $\frac{1}{2}$ she thought that the withdrawal was due to the patient depositor. Both cases lead to withdrawal with $\theta = \frac{1}{2}$.

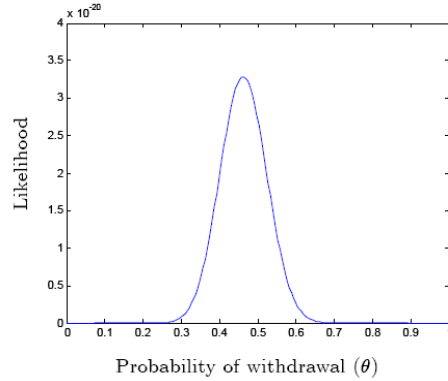
Our objective now is to test whether the second depositor's behavior can be better explained by the theoretical prediction (hereafter, θ_1) or by the naive behavior (hereafter, θ_2). Recall that it follows from

Bayes's theorem that

$$\Pr(\theta_i|\hat{Y}_2) = \frac{\Pr(\hat{Y}_2|\theta_i) \Pr(\theta_i)}{\Pr(\hat{Y}_2)}$$

where the expression above relates the posterior distribution $\Pr(\theta_i|\hat{Y}_2)$ to the likelihood function $\Pr(\hat{Y}_2|\theta_i)$, the prior $\Pr(\theta_i)$ and the marginal distribution of the data $\Pr(\hat{Y}_2)$. In principle, $\Pr(\hat{Y}_2)$ does not involve θ_i and the posterior $\Pr(\theta_i|\hat{Y}_2)$ is proportional to $\Pr(\hat{Y}_2|\theta_i) \Pr(\theta_i)$. Moreover, this posterior density can be interpreted as the probability of θ_i being true after the evidence in the data. The likelihood $\Pr(\hat{Y}_2|\theta_i)$ can be obtained by using the data and evaluating the probability mass function. We therefore replace $k = 65$ and $w = 30$ in equation (4). We plot the likelihood function $\Pr(\hat{Y}_2|\theta_i)$ in Figure 3. The maximum is located at $\theta_{ML} = w/k = 30/65 \simeq 0.46$. This implies that after observing a withdrawal, the second depositor withdraws with probability 0.46 on average.

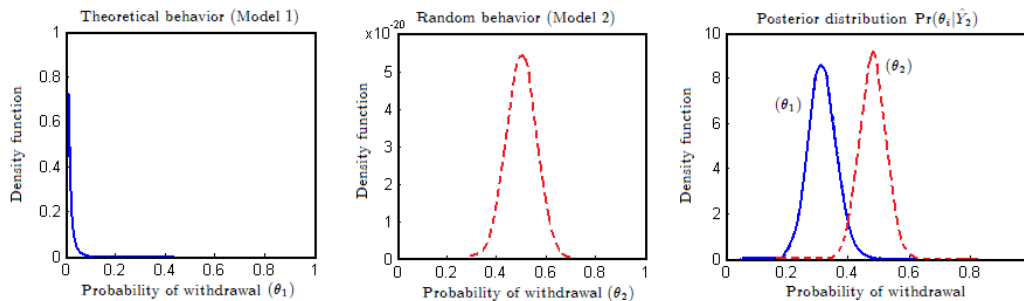
Figure 3. Likelihood function



In principle, we need to account for the prior $\Pr(\theta_i)$ distribution to obtain the posterior $\Pr(\theta_i|\hat{Y}_2)$. We choose a natural conjugate prior which is proportional to $\theta^{\alpha-1}(1-\theta)^{\beta-1}$ and leads to a posterior distribution in the same Beta family.¹¹ We perform our analysis specifying two different priors which correspond to our plausible models described above. Thus, we first consider the case of $\alpha = 1$ and $\beta = k + 1 = 66$. This prior distribution is represented on the left-hand side of Figure 4 and corresponds to the prior $\Pr(\theta) = (1-\theta)^{66}$ and therefore, to the theoretical prediction of no withdrawal (Model 1). On the other hand, the naive distribution considers $\alpha = \beta = \frac{k+1}{2} = 33$ and leads to $\Pr(\theta) = \theta^{33}(1-\theta)^{33}$ so that it centers around $\theta = 1/2$ (Model 2).

¹¹In particular, the posterior distribution $\Pr(\theta_i|\hat{Y}_2)$ is a $Beta(w + \alpha + 1, k + \beta - w + 1)$. Importantly, we do not consider hierarchical priors that allow for different responses (for instance, depending on the existence of the link 23). We do so because the link 23 is not important once the link 12 is in place. This theoretical result is also consistent with our experimental evidence in Table 3.

Figure 4. Bayesian analysis: Priors and posterior distribution



We also plot the posterior distribution $\Pr(\theta_i|\hat{Y}_2)$ on the right-hand-side of Figure 4.¹² We are interested in choosing the more appropriate model to explain the second depositor’s behavior so we use the Bayes Factor. Consider that both models (prior distributions) are equally likely to explain our data, i.e., $\Pr(\theta_1) = \Pr(\theta_2) = \frac{1}{2}$. The Bayes Factor compares how well both hypotheses predict the data. We then test the null hypothesis that the theoretical prediction (Model 1) explains the data \hat{Y}_2 against the alternative of random choices (Model 2). Since $BF_{12} \equiv \frac{\Pr(\hat{Y}_2|\theta_1)}{\Pr(\hat{Y}_2|\theta_2)} = \frac{8.3265}{5.2494 \cdot 10^{-6}} = 1.5862 \cdot 10^6 > 10$, the evidence against the null is decisive (Kass and Raftery, 1995). This reveals that naive behavior is more likely to explain the data than the probabilities provided by the theory.

4 Conclusion

An important issue regarding the emergence of bank runs is what kind of information depositors have about the bank and about other depositors’ decision. Existing theoretical models impose information structures that rely on a simultaneous-move game. We generalize the information structure and suppose that an underlying social network channels the information among depositors. This modeling choice allows for incorporating both simultaneous and sequential decisions in the same framework and conform to the empirical evidence.

We derive a theoretical prediction about depositors’ behavior in a tractable environment that resembles a classic bank-run setup. We find that no bank run emerges as unique equilibrium in any setup in which the first two depositors to decide are connected. This pinpoints the importance of links enabling information

¹²This distribution has not been normalized to report the probability of θ_i being true given our data but we can obtain the result by integrating the probability to be one.

flow among the depositors at the beginning of the sequence and contribute to the debate on the possibility of unique *versus* multiple equilibria in bank runs models.

We design a laboratory experiment to test the theoretical prediction. We find that the first subject's behavior is influenced by the link 12, as predicted by the theory. Nevertheless, the existence of the same link does not really affect the second depositor's choices, who instead focuses on the information transmitted by this link. More specifically, observing a waiting decreases considerably the probability that she withdraws. If a withdrawal is observed, the opposite happens. On average, these results suggest that the same subject who is waiting in the first position, withdraws in the second position if observing a withdrawal. This finding is puzzling both in face of the theoretical result and individual consistency. Indeed, Bayesian analysis shows that when the second depositor is patient and observes a withdrawal, she seems to behave randomly.

Moving beyond our specific setup, our interpretation is twofold. On the one hand, links can be efficiently used for signaling purposes. On the other hand, if the information transmitted by the link is not unambiguous, then being connected may lead to worse outcomes than the absence of a link. Thereby, although our analysis is cast in classic terms of bank runs, it also sheds light on the potential weaknesses of other financial institutions like mutual or hedge funds. Indeed, any institution performing the maturity transformation of investing short-term liabilities in long-term assets faces the problem of being run. Whenever investors are able to withdraw funds with relative ease, a run arises when they do it *en masse*. Some of these institutions have a reduced number of investors (like hedge funds) which renders our simple setup more applicable to them. Our analysis highlights the importance of designing proper mechanisms governing the information flow among investors in these institutions.

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