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Bank of Canada

“Experimental Evidence of Bank Runs as Coordination Failures: Do Sunspots Matter?”

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Experimental Evidence of Sunspot Bank Runs*

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Abstract

We investigate sunspot behavior in the context of a bank-run game in controlled laboratory environments. The sunspot variable takes the form of a sequence of randomly generated announcements that forecasts the number of withdrawals. The main treatment variable is the coordination parameter, defined as the amount of coordination required to generate enough complementarity among depositors who wait so that they earn a higher payoff than those who choose to withdraw. We conduct three treatments with three different values – high, low and intermediate – of the coordination parameter. Our results show that subjects do not react to the sunspot announcement for the high and low values of the coordination parameter: the experimental economies always converge to non-run (run) equilibrium when the coordination parameter is low (high). However, for the intermediate value of the coordination parameter, sunspot behaviors are observed as the experimental economies switch between the run and non-run equilibria in phase with the sunspot announcement.

JEL Categories: D83, G20
Keywords: Bank Runs, Sunspots, Experimental Studies

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1 Introduction

A bank run describes the situation in which a large number of depositors, fearing that their bank will be unable to repay their deposits, simultaneously request to withdraw their funds even in the absence of liquidity needs. Just before the recent financial crisis, bank runs were viewed by many as an extinct historical phenomenon. In the United States, the introduction of federal deposit insurance – in response to widespread bank failures during the Great Depression – almost eradicated bank runs. However, during the recent financial crisis, prominent bank runs reappeared both in the US and other developed economies. Examples are the runs on Countrywide Financial (US), Northern Rock Bank (UK), Bear Stears (US), IndyMac Bank (US) and Washington Mutual (US). The new wave of bank runs has renewed interest on this topic among both academics and policy makers.

Banks are susceptible to runs due to their special asset liability structure. On the asset side, banks pool depositors’ resources to invest in profitable illiquid long-term projects. On the liability side, banks issue short-term demand deposits to meet depositors’ liquidity need. The term mismatch between assets and liabilities opens the gate to bank runs. There are, broadly speaking, two competing views about what induces bank runs. According to the first view, banks runs are caused by adverse information about the bank’s fundamental condition (see, for examples, Chari and Jagannathan, 1988; Jacklin and Bhattacharya, 1988; Alonso, 1996; Champ et al., 1996; Loewy, 1998; Allen and Gale, 1998; Chen, 1999; Morris and Shin, 2001; Goldstein and Pauzner, 2005; Gu, 2011a).

The second view, represented by Diamond and Dybvig (1983) (hereafter DD), explains bank runs as a result of coordination failures. The DD model has two self-fulfilling symmetric pure-strategy Nash equilibria. In one equilibrium, depositors choose to withdraw only when they need liquidity. In the other equilibrium, in fear that the bank will not be able to repay them, all depositors run to the bank to withdraw money irrespective of their liquidity needs. The run forces the bank to liquidate its long-term investment at fire-sale prices and makes the initial fear a self-fulfilling prophecy. As a result, even banks with healthy assets may be subject to runs. DD point out that the selection between the bank run equilibrium and the good equilibrium could depend on realizations of a sunspot variable, i.e., some commonly observed random variable unrelated to the bank’s fundamental condition. Formal modelling of the sunspot theory of bank runs is provided by Waldo (1985), Freeman (1988), Loewy (1991), Cooper and Ross (1998), Peck and Shell (2003), Ennis and Keister (2003) and Gu (2011b).

The empirical work to identify the source of bank runs has produced mixed results. For example, Gorton (1988), Allen and Gale (1998) and Schumacher (2000) show that bank runs have historically been strongly correlated with deteriorating economic conditions, which erode away the value of the bank’s assets. In contrast, Boyd et al. (2001) conclude that
bank runs may often be the outcome of coordination failures.

In this paper we investigate whether sunspot bank runs can arise in controlled laboratory environments, where it is easier to control the different factors that may cause bank runs. To study sunspot-based bank runs, we fix the fundamental condition of the bank and keep it as public information in each session of our experiment. In addition, we introduce a random sunspot variable unrelated to the bank’s fundamental to see whether subjects would condition their choices on the realization of the sunspot variable.

The specific design follows the recent work by Arifovic et al. (forthcoming), who investigate whether bank runs can occur as a result of pure coordination failures in the absence of sunspot variables. Each session of their experiment consists of a series of 10-period repeated games. Each game is characterized by a different value of the coordination parameter, defined as the amount of coordination among depositors choosing to wait that is required for them to receive a higher payoff than depositors who choose to withdraw. Theory predicts that both the run and the non-run equilibria exist for all levels of coordination requirement considered in Arifovic et al.. Their experimental result, however, suggests that the occurrence of miscoordination-based bank runs depends on the value of the coordination parameter. In particular, the values of the coordination parameter can be divided into three regions: the "run" region characterized by high values of the parameter, the "non-run" region characterized by low values of the parameter, and the indeterminacy region characterized by intermediate values of the parameter. When the coordination parameter lies in the run (non-run) region, strategic uncertainty seems to be very low, subjects are almost unanimous about their choices, and all experimental economies stay close or converge to the run (non-run) equilibrium. In games with the coordination parameter located in the indeterminacy region, subjects are much less certain about what the "right" choice is; as a result, the outcomes of the experimental economies vary widely and become difficult to predict.

Following up on the result in Arifovic et al. (forthcoming), we conjecture that if a sunspot variable is introduced to the bank run game, its power as a coordination device is likely to be weak if the coordination parameter lies in the run or non-run region, but strong if the parameter is in the indeterminacy region. We conduct three treatments of experiment to test the hypothesis. Each treatment is characterized by a different value of the coordination parameter that corresponds to the non-run region, the indeterminacy region and the run region of the coordination parameter, respectively. All three games have a sunspot equilibrium where agents coordination their actions on realizations of a sunspot variable. In our experiment, the sunspot variable takes the form of a sequence of randomly generated announcements (which is fixed in all three treatments) that forecast how many people will choose to withdraw. The content of an announcement is either: (1) the forecast is that $x$ or more people will choose to withdraw; or (2) the forecast is that $x$ or less people
will choose to withdraw. The value of $x$ is such that it is optimal to withdraw if and only if the number of withdrawals is $\geq x$.

We have run 6 sessions of experiment for each treatment. The experimental results confirm the hypothesis. Subjects do not react to the sunspot announcement for the non-run (run) values of the coordination parameter, with all 6 experimental economies quickly converging to non-run (run) equilibria despite the sunspot announcement. For the treatment with the value of the coordination parameter in the indeterminacy region, subjects follow the sunspot announcement throughout the whole session in 4 out of 6 the experimental economies. In the other 2 sessions, subjects follow the sunspot variable initially, but coordination on the variable is not strong enough in early periods, and the economies converge to the run equilibrium in the end. The results show that subjects tend to follow sunspots when there is great strategic uncertainty.

In terms of policy implications, our study suggests that people are more susceptible to mood swings when they face great strategic uncertainty. In those situations, a publicly observable announcement made by the government, an influential public figure, or a newspaper, may serve as a coordination device and have a huge impact on people’s choices. In the recent financial crisis, depositors of Northern Rock might have taken the announcement by Bank of England that it would provide emergency liquidity support to the institution as a cue to run on the bank. A publicly released letter by Senator Charles Schumer that questioned the viability of IndyMac was also blamed for inducing panic among the bank’s depositors. During the 911 terrorist attack, the Federal Reserve announced reassuring messages over Fedwire that the fund transfer system was “fully operational” and would remain open until “an orderly closing can be achieved.” Such messages helped to maintain public confidence and reduce disruption to the financial system.

Besides Arifovic et al. (forthcoming) mentioned above, Madiès (2006), Garrat and Keister (2009), Schotter and Yorulmazer (2009), Kiss et al. (2012), Chakravarty et al. (2012), Brown et al. (2012) and Klos and Sträter (2013) also study bank runs in controlled laboratory environments (see Dufwenberg, 2012, for a review of experimental literature on bank runs). Madiès (2006) provides the first experimental study of miscoordination-based bank runs within the framework of the DD model. The paper’s emphasis is on the effectiveness of alternative ways to prevent bank runs, including suspension of payments and deposit insurance. Garrat and Keister (2009) study how depositors’ decisions are affected by uncertainty about the aggregate liquidity demand and by the number of opportunities subjects have to withdraw. They find that uncertainty about the liquidity demand and more withdrawing opportunities tend to increase the frequency of bank runs. Schotter and Yorulmazer (2009) examine the factors that affect the speed of withdrawals, including the number of opportunities to withdraw and the existence of insiders, in a dynamic bank-run game. They find that (i) the more information subjects expect to learn about the crisis as
it develops, the more willing they are to restrain from withdrawing their funds once a crisis occurs; and (ii) the presence of insiders, who know the quality of the bank, significantly mitigates the severity of bank runs. Klos and Sträter (2013) test the prediction of the global game theory of bank runs developed by Morris and Shin (2001) and Goldstein and Pauzner (2005). In the model, depositors receive noisy private signals about the changing quality of the bank’s long-term assets. The theory predicts that depositors employ a threshold strategy choosing to withdraw if and only if the signal is below a cut-off point. Klos and Sträter (2013) find that subjects do follow threshold strategies, and the thresholds increase with the short-term rate promised to withdrawers as predicted by the theory. However, compared to the theoretical predictions of the global games’ approach, the reaction to a change in the repayment rate is less pronounced. Kiss et al. (2012) study the effects of deposit insurance and observability of previous actions on the emergence of bank runs. They find that when decisions are not observable, higher levels of deposit insurance are required to decrease the probability of bank runs, which suggests observability as a partial substitute for deposit insurance.

Chakravarty et al. (2012) and Brown et al. (2012) investigate how runs spread across two different banks through contagion. While Brown et al. (2012) find contagious bank runs only when the fundamentals of the two banks are correlated, Chakravarty et al. (2012) suggest that contagion is a robust phenomenon even in the case of independent fundamentals. When the two banks have independent fundamentals, the coordination result of the leading bank, whose depositors act before the follower bank’s depositors, does not convey any information about the fundamental of the follower bank. From the perspective of the depositors of the follower bank, the choices of the leading bank’s depositors can be viewed as a sunspot variable. In some sense, Chakravarty et al. (2012) show some experimental evidence for sunspot bank runs.

Our paper is also related to experimental studies of sunspot behaviors in different contexts, including Marimon et al. (1993), Duffy and Fisher (2005), Fehr et al. (2012) and Arifovic et al. (2013). The first three papers consider models with multiple steady states that are Pareto equivalent or cannot be Pareto ranked. Arifovic et al. (2013) provide evidence of sunspot behavior in the context of a model with multiple equilibria that can be Pareto ranked. As in Arifovic et al. (2013), the bank run game in our study features multiple equilibria that can be Pareto ranked. Our main focus is to identify the economic situation under which sunspot behaviors are likely to arise. In particular, we investigate how the power of the sunspot variable as a coordination device is affected by the coordination parameter. We find that subjects tend to react (ignore) to sunspot variables when the coordination parameter takes an intermediate (extreme) value and the strategic uncertainty is high (low).

Marimon et al. (1993) find that subjects can "learn" to follow sunspots in the context
of an overlapping generations monetary model that has a unique monetary steady-state equilibrium, 2-period cyclic equilibria and 2-state Markovian sunspot equilibria. In the learning/training stage, the number of subjects in each generation, which is a real variable, cyclically vary between a high and a low number in phase with a sunspot variable in the form of a blinking square on subjects’ computer screens. After the training stage, the real variable is fixed, but subjects continue to react to the sunspot variable. In Duffy and Fisher (2005), subjects act as buyers and sellers to trade a single good. The marginal valuations of buyers and the marginal costs of sellers are determined by the actual price realized in the market. The model has two equilibria featuring different equilibrium prices. The two equilibria cannot be Pareto ranked: some subjects are better off in one equilibrium, whereas others are better off in the other equilibrium. Duffy and Fisher (2005) find that subjects can coordinate on a sunspot equilibrium based on a public announcement that forecasts the level of the market price. Fehr et al. (2012) study a two-player coordination game: players pick a number between 0 and 100, and the payoffs are determined as the squared deviations from the other player’s choice. The game has a continuum of Nash equilibria, all of which have the same payoff. Fehr et al. (2012) find that sunspot equilibria emerge if there are salient public signals.

Arifovic et al. (2013) study coordination in a productive economy with a positive externality such that the productivity of each firm is a nondecreasing function of the average level of employment of other firms. The model has three steady states with different levels of employment, with higher employment levels being associated with higher welfare. There is also a sunspot equilibrium in which the economy switches between the high and low steady states. Arifovic et al. (2013) observe coordination on extrinsic announcements about the level of productivity. Cases of apparent convergence to the low and high steady states are also observed.

The rest of the paper is organized as follows. Section 2 describes the theoretical framework that underlies the experiment. Section 3 introduces the hypothesis and discusses the experimental design. Section 4 presents and analyzes the experimental results. Section 5 concludes.

2 Theoretical Framework

The theoretical framework that underlies our study is the DD model of bank runs. There are three dates indexed by 0, 1 and 2. There are \( D \) ex ante identical agents in the economy. At date 0, the planning period, each agent is endowed with 1 unit of good and faces a liquidity shock that determines her preferences over goods at date 1 and date 2. The liquidity shock is realized at the beginning of date 1. Among the \( D \) agents, \( N \) of them become patient agents, who are indifferent between consumption at date 1 and date 2, and the rest become
impatient agents, who care only about consumption at date 1. Realization of the liquidity shock is private information. Preferences are described by

\[ U(c_1, c_2) = \begin{cases} 
  u(c_1) & \text{for impatient consumers,} \\
  u(c_1 + c_2) & \text{for patient consumers,} 
\end{cases} \]

where \( c_1 \) and \( c_2 \) denote the consumption at date 1 and date 2, respectively. The function \( u(\cdot) \) satisfies \( u'' < 0 < u', \lim_{c \to -\infty} u'(c) = 0 \) and \( \lim_{c \to 0} u'(c) = \infty \). The relative risk aversion coefficient, \(-cu''(c)/u'(c)\), is \( > 1 \) everywhere. There is a productive technology that transforms 1 unit of date 0 output into 1 unit of date 1 output or \( R > 1 \) units of date 2 output.

At the socially optimal allocation, impatient agents consume only at date 1, and patient agents consume only at date 2. Let \( c_i \) and \( c_p \) denote the consumption by impatient consumers and patient consumers, respectively. The optimal allocation, \((c_i^*, c_p^*)\), is characterized by \( 1 < c_i^* < c_p^* < R \). A bank, by offering demand deposit contracts, can provide liquidity insurance to agents. The contract requires agents deposit their endowment with the bank at date 0. In return, agents receive a bank security which can be used to demand consumption at either date 1 or 2. The bank promises to pay \( r > 1 \) to depositors who choose to withdraw at date 1. Resources left after paying withdrawers generate a rate of return \( R > r \), and the proceeds are shared by all who choose to roll over their deposits and wait until date 2 to consume. If the number of withdrawing requests at date 1, \( e \), exceeds \( \hat{e} = D/r \), the bank will not have enough money to pay every withdrawer the promised rate \( r \). In this case, the bank divides its resources evenly among those who request to withdraw, while those who choose to wait receive nothing. Let \( \pi_1 \) and \( \pi_2 \) be the payoffs to those who choose to withdraw and roll over, respectively. The deposit contract can be formulated as

\[
\pi_1 = \min \left\{ r, \frac{D}{e} \right\}; \\
\pi_2 = \max \left\{ 0, \frac{D - er}{D - e} R \right\}.
\]

The optimal risk-sharing allocation can be achieved by setting \( r \) to \( r^* = c_i^* \).

Note that for simplification, we deviate from the original setup in DD to abstract from the sequential service constraint. The sequential service constraint is not essential for the existence of multiple equilibria; the fact that \( r > 1 \) is sufficient to generate a payoff externality and panic-based runs. We follow Madiès (2006) to make a second deviation from the original DD model. In DD, there are both patient and impatient agents. Impatient agents always withdraw, and only patient agents are "strategic" players. In this study we focus on strategic players, so we let \( D = N \). To rule out the possibility that bank runs are
caused by weak performance of the bank's long-term portfolio, we fix the rate of return of the long-term investment, $R$, throughout the experiment. For the short-term interest rate $r$, we do not use the optimal rate $r^*$. Instead, we set $r$ to be values greater than 1. As will become clear shortly, there is a one-on-one correspondence between $r$ and our main treatment variable, the coordination parameter.\footnote{For optimal contracting in the DD framework, please refer to Green and Lin (2000, 2003), Andolfatto, Nosal and Wallace (2007), Andolfatto and Nosal (2008) and Ennis and Keister (2009a, 2009b, 2010). The first three papers show that the multiple-equilibria result goes away if more complicated contingent contracts – as compared with the simple demand deposit contracts in DD – are used. The three papers by Ennis and Keister show that the multiple-equilibria result is restored if the banking authority cannot commit not to intervene in the event of a crisis, or the consumption needs of agents are correlated.} The resulting payoff functions used in the experiment can be represented as

\[
\pi_1 = \min \left\{ r, \frac{N}{e} \right\}, \quad (1)
\]

\[
\pi_2 = \max \left\{ 0, \frac{N - er}{N - e} R \right\}. \quad (2)
\]

The coordination parameter, denoted as $\eta$, measures the level of coordination that is required for agents who choose to wait to receive a higher payoff than those who choose to withdraw. It is calculated as the fraction of depositors who choose to wait that equalizes the payoffs to the two strategy choices. We can calculate $\eta$ in two steps. First, solve for the value of $e$, the number of depositors who choose to withdraw, that equalizes the payoffs associated with withdrawing and waiting,

\[
r = \frac{N - er}{N - e} R,
\]

and denote it by $e^*$. Thus, $e^*$ is given by

\[
e^* = \frac{R - r}{r(R - 1)} N.
\]

Second, $\eta$ can be calculated from the equation,

\[
\eta = 1 - \frac{e^*}{N} = \frac{R(r - 1)}{r(R - 1)}.
\]

Note that there is an one-on-one correspondence among $\eta$, $e^*$ and $r$.

The coordination game characterized by the above payoff structure has two symmetric pure-strategy Nash equilibria.\footnote{There is also a symmetric mixed-strategy equilibrium where each depositor chooses to wait with a probability between 0 and 1 and the expected payoff from the two strategies are equalized.} In the run equilibrium, every depositor chooses to withdraw and run on the bank expecting others to do the same. As a result, $e = N$, and everybody receives a payoff of 1. In the non-run equilibrium, every depositor chooses to wait expecting
others to make the same choice. In this equilibrium, $e = 0$, and everybody receives a payoff of $R$. There also exist stationary sunspot equilibria where the economy switches between the run equilibrium or the non-run equilibrium contingent on the realization of a sunspot variable.

3 Hypothesis and Experimental Design

Arifovic et al. (forthcoming) investigate how the level of coordination requirement affects the occurrence of bank runs as a result of pure coordination failures in controlled laboratory environments. They find that miscoordination-based bank runs can be observed when the coordination parameter, $\eta$, is high enough. In particular, they divide the values of the coordination parameter into three regions: the run region ($\eta \leq 0.5$), characterized by high values of the parameter; the non-run region ($\eta \geq 0.8$), characterized by low values of the parameter; and the indeterminacy region ($0.6 \leq \eta \leq 0.7$), characterized by intermediate values of the parameter. In the run (non-run) region, all experimental economies stay close or converge to the run (non-run) equilibrium. When the coordination parameter lies in the indeterminacy region, the outcomes of the experimental economies vary widely and are hard to predict.

In this paper, we follow up on these results to introduce a sunspot variable into the bank-run game and study whether sunspots matter for the occurrence of bank runs. Our main focus is to identify the economic situation under which sunspot behaviors are likely to be observed. In particular, we investigate how the power of the sunspot variable as a coordination device is affected by the coordination parameter.\(^3\) Given the results in Arifovic et al. (forthcoming) that there is great (little) strategic uncertainty when the coordination parameter lies in the indeterminacy (run and non-run) region, our hypothesis is that the power of the sunspot variable is likely to be high when $\eta$ lies in the indeterminacy region, but low when $\eta$ is in the run or non-run region.

The design of our experiment incorporates some of the nice features in existing experimental studies of sunspot behaviors (refer to the Appendix for the experimental instructions). All the studies show that the occurrence of sunspot equilibria requires a common understanding of the semantics of the sunspot variable. As summarized in Duffy and Fisher (2005), semantics has three ingredients. First, a sunspot variable can be a coordinating device only if its meaning is transparent. Second, a sunspot variable must have realizations that are public. Third, there must be some “training periods” during which subjects believe that the sunspot variable is actually correlated with market outcomes.

In our experiment, the sunspot variable is phrased as a forecast about how many people

\(^3\)Note that in the bank run model, sunspot equilibria can be constructed for any $\eta$ between 0 and 1.
will choose to withdraw. The sequence of announcements is randomly generated. The value of the sunspot variable is shown to all subjects. More specifically, the following explanation is included in the instructions:^4

"In each period, an announcement will show up in the lower right section of the screen to forecast the number of withdrawing requests for this period. The announcement will be either ‘The forecast is that \( e^* \) or more people will choose to withdraw,’ or that ‘The forecast is that \( e^* \) or less people will choose to withdraw.’ Everybody receives the same message. The announcements are randomly generated. There is a possibility of seeing either announcement, but the chance of seeing the same message that you saw in the previous period is higher than the chance of seeing a different announcement. These announcements are forecasts, which can be right or wrong. The experimenter does not know better than you how many people will choose to withdraw (or wait) in each period. The number of withdrawals is determined by the decisions of all participants. Your actual payoff depends only on your own choice and the choices of other participants."

The value of \( e^* \) is the number of subjects requesting to withdraw that equalizes the payoff to both strategies. Note that it is optimal to withdraw if and only if the number of withdrawals, \( e \), is \( \geq e^* \). In the following, we use \( A \) to denote the sunspot announcement, with \( A = 0 \) corresponding to the announcement of low number of withdrawals, or \( e \leq e^* \), and \( A = 1 \) corresponding to the announcement of high number of withdrawals, or \( e \geq e^* \). The announcement \( A = 0 \) is equivalent to "waiting is a better strategy," and the announcement \( A = 1 \) is equivalent to "withdrawing is a better strategy."

In each session of experiment, subjects play a repeated one-period game for 56 periods. Each subject starts a new period with 1 unit of experimental money in the bank. Upon observing the realization of the sunspot variable, the subjects decide simultaneously whether to withdraw their money from the bank or to wait. Each session consists of 6 practice periods and 50 formal periods. During the practice periods, subjects familiarize themselves with the task that they are requested to perform. Given that all existing experimental studies of sunspot behaviors emphasize the importance of "training" in inducing reaction to sunspots, we also use the practice periods to build the correlation between the coordination outcome and the realization of the sunspot variable. The forecast is that \( e \leq e^* \) in the first 3 practice periods, and \( e \geq e^* \) in the second 3 practice periods. The numbers of withdrawals in those periods are predetermined to make the announcements self-fulfilling.

To test our hypothesis about the power of the sunspot variable, we conduct three treatments of experiment with three values of the coordination parameter. The value of \( \eta \) is equal to 0.2, 0.7 or 0.9, which lies in the non-run region, the indeterminacy region and the run region, respectively.^5 Our hypothesis is that the power of the sunspot variable is likely

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^4 See the Appendix for the experimental instructions.

^5 Note that although we use \( \eta \) as the treatment variable, following the discussion in the previous section
to be high when $\eta = 0.7$, but low when $\eta = 0.2$ or 0.9. More specifically, the economy is likely to switch between the run equilibrium (when high withdrawals are announced) and non-run equilibrium (when low withdrawals are announced) in the treatment with $\eta = 0.7$. When $\eta = 0.2$, the economy is likely to stay at the non-run equilibrium irrespective of the announcement. When $\eta = 0.9$, the economy is likely to stay at the run equilibrium irrespective of the announcements.

We ran 6 sessions of experiment for each of the three treatments, with a total of 18 sessions. To facilitate comparison among different sessions, we follow Arifovic et al. (2013) to generate the random sequence of announcements before the experiment and use the same sequence of announcement in all sessions of experiment. The sunspot announcements follow a Markov process in which the probability of observing the same announcement is the next period is 0.8. We adopt a persistent shock sequence to make the experimental environment more stable. With a low switching probability of 0.2, the environment is more likely to remain the same for an extended period of time instead of switching frequently back and forth between the two announcements. The average number of $A$ in the 50 formal periods is 0.56 with slightly more announcements with high withdrawals. Table 1 lists the parameters used for each treatment of the experiment.

The program used to conduct the experiment is written in z-Tree (Fischbacher, 2007). At the beginning of a session, each subject is assigned a computer terminal. In each period, every subject starts with 1 experimental dollar in the bank and decides whether to withdraw or to wait and roll over their deposits through the decision screen. The computer screen shows the payoff table, which lists the payoff that an individual will receive if he/she chooses to withdraw or wait given that $n = 1 \sim 9$ of the other 9 subjects choose to withdraw. The payoff table helps to reduce the calculation burden for the subjects so that they can focus on playing the coordination game. The screen also contains information about the history of the experiment with a graph of total number of withdrawals in all past periods and a history table that contains the history of the announcements, the actual number of withdrawals, the subject’s decision, the subject’s own payoff in each period, and the subject’s cumulative payoff. The sunspot announcement is located right above the buttons "withdraw" and "wait," which subjects click on to input their withdrawing decisions. Once all the decisions are made, the total number of withdrawals is calculated. Subjects’ payoffs are then determined by equations (1) and (2). Communication among subjects is not allowed during the experiment. The experiment was run at Economic Science Institute, Chapman University, Orange, USA, from fall 2012 to winter 2013.

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6In fact, we use the same sequence of announcements as in Arifovic et al. (2013).

7Since the game in the experiment is fairly straightforward, it is important that the subjects have no prior experience with experiments of coordination games. Subjects should also be from mixed sources to
about 50 minutes. The average earning is about $14.

4 Experimental Results

Figure 1 plots the coordination results for each of the 18 sessions of experiment. The horizontal axis represents the time period running from –5 to 50. Periods –5 to 0 are the practice periods. Periods 1 to 50 are the formal periods. The solid line with dot markers graphed against the left vertical axis depicts the time path of the number of withdrawals. The upper dashed line is $e^*$ used for the announcement. The lower dash line is $\hat{e}$, at which the bank becomes bankrupt or runs out of money to meet withdrawing requests. The announcement ($A$) is represented as circles against the right vertical axis.

Table 2 shows three statistics, the average number of withdrawals, the percentage of bankruptcies, and the percentage of individual subjects’ choices that are consistent with the announcement, i.e., to withdraw (wait) if the announcement is that $e \geq (\leq) e^*$. We provide the statistics for each session and for each treatment (in bold face) derived as the average of the session statistics. For each statistic, we calculate the values for the whole session, periods with $A = 0$ and periods with $A = 1$ (excluding the practice periods).

To further capture the effect the sunspot announcement on the average number of withdrawals, we run a rank-sum test of the average number of withdrawals associated with the two types of sunspot announcements for each of the three treatments. The first group contains the statistics for periods with $A = 0$, and the second group contains statistics for periods with $A = 1$. Each group has 6 observations corresponding to the 6 sessions of experiment run for each treatment. The test results are in table 3.

We first check the results for the treatment with $\eta = 0.2$. In this treatment, the number of withdrawals is hardly affected by the sunspot announcement. All 6 experimental economies quickly converge to the non-run equilibrium. The treatment average number of withdrawals is very small for both types of announcements: 0.21 for $A = 0$ and slightly higher at 0.26 for $A = 1$. A rank-sum test between the average numbers of withdrawals for the two types of announcements shows that the two cases have exactly the same rank sum. The two-sided (one-sided) $p$-value is 100% (50%). In other words, in terms of the average number of withdrawals, the two samples cannot be distinguished from each other. There are no bankruptcies with either announcement. The probability that individual choices are consistent with the announcement is very high at 98% for $A = 0$, but very low at 3% for $A = 1$.

For the treatment with $\eta = 0.9$, the effect of the sunspot variable on the number of withdrawals is also very weak (though stronger than in the treatment with $\eta = 0.2$). All 6 guarantee that they do not have close relationships before participating in the experiment.
experimental economies converge to vicinity of the run equilibrium by period 30 and stay close to the equilibrium afterwards. The average value of withdrawals is very high with both types of announcements at 8.09 for $A = 0$ and slightly larger at 8.78 for $A = 1$. The rank-sum test between the average number of withdrawals for the two announcements suggests that subjects tend to withdraw more often with $A = 1$, generating a $p$ value of 10% (5%) if two-sided (one-sided) test is used. However, the difference between the average numbers of withdrawals is quite small at 0.69. The probability of bankruptcies is very high with both types of announcements: 92% with $A = 0$ and 98% with $A = 1$. The percentage of individual choices that are consistent with the announcement is 89% for $A = 1$, and much lower at 19% for $A = 0$.

Compared to the treatments with $\eta = 0.2$ and 0.9, subjects respond strongly to the sunspot variable in the treatment with $\eta = 0.7$. The rank-sum test of the average number of withdrawals under the two types of announcements generates a very small $p$-value of 0.39% (0.20%) if two-sided (one-sided) test is used. The difference between the treatment average numbers of withdrawals when $A = 0$ and $A = 1$ is very high at 5.09. The effect of the sunspot variable is therefore both statistically and economically significant.

The effect of the sunspot announcement is particularly strong in sessions 7, 8, 9 and 12, where the experimental economy switches between the two equilibria in line with the announcement throughout the whole session. When $A = 0$, the experimental economy stays close to the non-run equilibrium with the average number of withdrawals between 0.36 and 2.14. When $A = 1$, the economies stay close to run equilibrium with the average number of withdrawals lying between 7.79 and 8.54. There are no bankruptcies when $A = 0$ but frequent bankruptcies when $A = 1$ (between 71% and 86%). The percentage of individual choices that are consistent with the announcement is high for both $A = 0$ (between 79% and 96%) and $A = 1$ (between 78% and 85%).

In sessions 10 and 11, the power of the sunspot announcement is weaker than in sessions 7, 8, 9 and 12, but is stronger than in the other two treatments. The two experimental economies respond to the sunspot in early periods up until period 26 in session 10 and period 20 in session 11. However, during two earlier episodes of low announcement (periods 12–13 and periods 18–22), the number of withdrawals does not drop enough to confirm the announcement. In later periods, subjects stop responding to the sunspot variable and keep on withdrawing their money from the bank, and the two economies converge to the vicinity of the run equilibrium. The performance of the two economies in the second half mimics the situation where $\eta = 0.9$. The difference between the average numbers of withdrawals under the two types of announcements is 2.41 in session 10 and 1.66 in session 11. The percentage of individual strategies that are consistent with the announcement is high for $A = 1$ (88% in session 10 and 85% in session 11), but much lower for $A = 0$ (40% in session 10 and 29% in session 11). Bankruptcies occur frequently (86% of the time in both sessions) when
$A = 1$. For the announcement $A = 0$, there is still a high incidence of bankruptcies (45% of the time in session 10 and 64% of the time in session 11). The different performance of the experimental economy in treatment 7 (sessions 10 and 11 versus the other 4 sessions) suggests that a strong and persistent correlation between the coordination result and the sunspot variable is required to make the sunspot variable believable.

To summarize, subjects tend to disregard the sunspot announcement when $\eta = 0.2$ and 0.9, but have a strong tendency to follow the sunspot variable when $\eta = 0.7$. In the bank run game (and many other coordination games), there is often a tension between efficiency and security. The non-run equilibrium is more efficient associated with a higher payoff. As hinted in Arifovic et al. (forthcoming), the riskiness of the non-run equilibrium can be captured by the coordination parameter: a higher value of the parameter implies a higher level of risk. As shown in Temzelides (1997) and Ennis (2003), the non-run equilibrium is risk dominant if and only if $\eta < 0.5$. When $\eta = 0.2$, the non-run equilibrium is both payoff dominant and risk dominant, which means there is no tension between efficiency and security. As a result, there is minimal strategic uncertainty, and subjects almost unanimously choose to wait and ignore the sunspot announcement of high level of withdrawals. When $\eta = 0.9$, the non-run equilibrium is payoff dominant but the run equilibrium is risk dominant so there is some tension between efficiency and security. With a high value of $\eta$, security is the dominating concern. The extent of strategic uncertainty is small as most subjects opt for the safe choice to withdraw disregarding the announcement of low withdrawals. When $\eta = 0.7$, the tension exists as well. However, unlike the case with $\eta = 0.9$, where the risk concern dominates the efficiency concern, it is not clear whether efficiency or security is of a greater concern. This creates great strategic uncertainty as subjects hesitate about whether to withdraw or wait. In this situation, an extraneous sunspot variable is more readily accepted as a coordination device.

5 Conclusion

This paper investigates sunspot behaviors in the context of a bank run game. In a related work, Arifovic et al. (forthcoming) find that in the absence of sunspot variables, the occurrence of miscoordination-based bank runs depends critically on the coordination parameter ($\eta$), which measures the amount of coordination required to generate enough complementarity among depositors who wait so that they earn a higher payoff than those who choose to withdraw. In particular, the values of the coordination parameter can be divided into three regions. In the run region where $\eta \geq 0.8$, all experimental economies stay close or converge to the run equilibrium; in the non-run region where $\eta \leq 0.5$, all experimental economies stay close or converge to the non-run equilibrium; in the indeterminacy region

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*Risk dominance is introduced by Harsanyi and Selten (1988) as an equilibrium selection criterion.*
where $\eta = 0.6$ or $0.7$, the outcomes of the experimental economies vary widely and become difficult to predict.

Following the above result, we conjecture that the following would happen if a sunspot variable is introduced to the bank run game. When $\eta$ lies in the indeterminacy region, in which situation there is great strategic uncertainty, the power of the sunspot variable as a coordination device is likely to be strong; the reverse holds if $\eta$ lies in the run or non-run region. To test the hypothesis, we conduct three treatments (with 6 sessions for each treatment) of experiment with $\eta = 0.2$, 0.7 and 0.9 corresponding to the three regions of the coordination parameter. The sunspot variable consists of a sequence of random forecasts about the number of withdrawals.

The experimental results confirm our conjecture: when $\eta = 0.2$, all (6 out of 6) experimental economies quickly reach the non-run equilibrium irrespective of the sunspot announcement; when $\eta = 0.9$, all (6 out of 6) experimental economies converge to the run equilibrium disregarding the sunspot variable; when $\eta = 0.7$, the experimental economies respond strongly to the sunspot variable, with 4 out of 6 sessions switching between the run and non-run equilibria conditional on the sunspot announcement. The results suggest that in economic situations with great strategic uncertainty, agents are susceptible to mood swings and tend to respond strongly to extrinsic public information. In those circumstances, the government should be very careful about the messages it sends to the public as the messages are likely to be used as a coordination device.
References


Figure 1: Experimental Results

session 1, $r = 1.11$, $\eta = 0.2$

session 2, $r = 1.11$, $\eta = 0.2$

session 3, $r = 1.11$, $\eta = 0.2$

session 4, $r = 1.11$, $\eta = 0.2$

session 5, $r = 1.11$, $\eta = 0.2$

session 6, $r = 1.11$, $\eta = 0.2$
Figure 1: Experimental Results

session 7, $r=1.54$, $\eta=0.7$

session 8, $r=1.54$, $\eta=0.7$

session 9, $r=1.54$, $\eta=0.7$

session 10, $r=1.54$, $\eta=0.7$

session 11, $r=1.54$, $\eta=0.7$

session 12, $r=1.54$, $\eta=0.7$
Figure 1: Experimental Results

session 13, $r=1.82$, $\eta=0.9$

session 14, $r=1.82$, $\eta=0.9$

session 15, $r=1.82$, $\eta=0.9$

session 16, $r=1.82$, $\eta=0.9$

session 17, $r=1.82$, $\eta=0.9$

session 18, $r=1.82$, $\eta=0.9$
Table 1: Experimental parameters

<table>
<thead>
<tr>
<th>η</th>
<th>r</th>
<th>e*</th>
<th>A (practice)</th>
<th>e displayed (practice)</th>
<th>Mean A (formal)</th>
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</thead>
<tbody>
<tr>
<td>0.2</td>
<td>1.11</td>
<td>8</td>
<td>000111</td>
<td>121889</td>
<td>0.56</td>
</tr>
<tr>
<td>0.7</td>
<td>1.54</td>
<td>3</td>
<td>000112</td>
<td>121789</td>
<td>0.56</td>
</tr>
<tr>
<td>0.9</td>
<td>1.82</td>
<td>1</td>
<td>000113</td>
<td>111789</td>
<td>0.56</td>
</tr>
</tbody>
</table>
Table 2: Statistics

<table>
<thead>
<tr>
<th>Session</th>
<th>Mean withdrawals</th>
<th>% Bankruptcies</th>
<th>% Actions consistent with announcement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Whole session</td>
<td>( A=0 )</td>
<td>( A=1 )</td>
</tr>
<tr>
<td>1</td>
<td>0.18</td>
<td>0.32</td>
<td>0.07</td>
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<td>2</td>
<td>0.14</td>
<td>0.05</td>
<td>0.21</td>
</tr>
<tr>
<td>3</td>
<td>0.04</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>4</td>
<td>0.04</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>5</td>
<td>0.70</td>
<td>0.68</td>
<td>0.71</td>
</tr>
<tr>
<td>6</td>
<td>0.34</td>
<td>0.14</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>Sessions 1-6 (( \eta=0.2 ))</strong></td>
<td><strong>0.24</strong></td>
<td><strong>0.21</strong></td>
<td><strong>0.26</strong></td>
</tr>
<tr>
<td>7</td>
<td>4.90</td>
<td>0.36</td>
<td>8.46</td>
</tr>
<tr>
<td>8</td>
<td>5.28</td>
<td>2.09</td>
<td>7.79</td>
</tr>
<tr>
<td>9</td>
<td>5.60</td>
<td>2.14</td>
<td>8.32</td>
</tr>
<tr>
<td>10</td>
<td>7.40</td>
<td>6.05</td>
<td>8.46</td>
</tr>
<tr>
<td>11</td>
<td>8.02</td>
<td>7.09</td>
<td>8.75</td>
</tr>
<tr>
<td>12</td>
<td>5.68</td>
<td>2.05</td>
<td>8.54</td>
</tr>
<tr>
<td><strong>Sessions 7-12 (( \eta=0.7 ))</strong></td>
<td><strong>6.15</strong></td>
<td><strong>3.30</strong></td>
<td><strong>8.39</strong></td>
</tr>
<tr>
<td>13</td>
<td>8.40</td>
<td>8.27</td>
<td>8.50</td>
</tr>
<tr>
<td>14</td>
<td>7.16</td>
<td>6.59</td>
<td>7.61</td>
</tr>
<tr>
<td>15</td>
<td>8.18</td>
<td>7.45</td>
<td>8.75</td>
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<td>16</td>
<td>9.20</td>
<td>9.05</td>
<td>9.32</td>
</tr>
<tr>
<td>17</td>
<td>8.72</td>
<td>8.18</td>
<td>9.14</td>
</tr>
<tr>
<td>18</td>
<td>9.20</td>
<td>9.00</td>
<td>9.36</td>
</tr>
<tr>
<td><strong>Sessions 13-18 (( \eta=0.9 ))</strong></td>
<td><strong>8.48</strong></td>
<td><strong>8.09</strong></td>
<td><strong>8.78</strong></td>
</tr>
</tbody>
</table>
Table 3: Rank-sum test of the effect of the sunspot announcement on the average number of withdrawals

<table>
<thead>
<tr>
<th>Treatment with $\eta = 0.2$</th>
<th>Announcement</th>
<th>Sample size</th>
<th>Average number of withdrawals</th>
</tr>
</thead>
<tbody>
<tr>
<td>A=0</td>
<td>6</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>A=1</td>
<td>6</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>Z-Value</td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>p-value (2-sided)</td>
<td></td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Treatment with $\eta = 0.7$</th>
<th>Announcement</th>
<th>Sample size</th>
<th>Average number of withdrawals</th>
</tr>
</thead>
<tbody>
<tr>
<td>A=0</td>
<td>6</td>
<td>3.30</td>
<td></td>
</tr>
<tr>
<td>A=1</td>
<td>6</td>
<td>8.39</td>
<td></td>
</tr>
<tr>
<td>Z-Value</td>
<td></td>
<td>2.887</td>
<td></td>
</tr>
<tr>
<td>p-value (2-sided)</td>
<td></td>
<td>0.39%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Treatment with $\eta = 0.9$</th>
<th>Announcement</th>
<th>Sample size</th>
<th>Average number of withdrawals</th>
</tr>
</thead>
<tbody>
<tr>
<td>A=0</td>
<td>6</td>
<td>8.09</td>
<td></td>
</tr>
<tr>
<td>A=1</td>
<td>6</td>
<td>8.78</td>
<td></td>
</tr>
<tr>
<td>Z-Value</td>
<td></td>
<td>1.601</td>
<td></td>
</tr>
<tr>
<td>p-value (2-sided)</td>
<td></td>
<td>10.93%</td>
<td></td>
</tr>
</tbody>
</table>
Instructions (for $r=1.54$ or $\eta=0.7$)

Today you will participate in an experiment in economic-decision making. You will be paid for your participation. There is a show-up fee of $7. The additional amount of cash that you earn will depend upon your decisions and the decisions of other participants. You will be earning experimental currency. At the end of the experiment, you will be paid in dollars at the exchange rate of 10 experimental currency units = $1.

As your earnings depend on the decisions that you will make during the experiment, it is important to understand the instructions. Read them carefully. If you have any questions, raise your hand and the experimenter will come to your desk and provide answers.

Your Task

You and 9 other people start with 1 ED deposited in an experimental bank. You must decide whether to withdraw your 1 ED or wait and leave it deposited in the bank. The bank promises to pay $1.54$ EDs to each withdrawer. After the bank pays the withdrawers, the money that remains in the bank will be doubled, and the proceeds will be divided evenly among people who choose to wait. Note that if too many people desire to withdraw, the bank may not be able to fulfill the promise to pay $1.54$ to each withdrawer. In that case, the bank will divide the 10 EDs evenly among all withdrawers and those who choose to wait will get nothing.

Your payoff depends on your own decision and the decisions of the other 9 people in the group. Specifically, how much you receive if you make a withdrawal request or how much you earn by waiting depends on how many people in the group place withdrawing requests.

On the last page, you can find the payoff table that lists the payoffs associated with the two choices – to withdraw or to wait – if $n$ of the 10 subjects request to withdraw. Let’s look at two examples:

**Example 1.**

Suppose 2 subjects choose to withdraw (and 8 choose to wait).

If you choose to withdraw, your payoff is 1.54, and if you choose to wait, your payoff is 1.73.

**Example 2.**

Suppose 8 subjects choose to withdraw (and 2 choose to wait).

If you choose to withdraw, your payoff is 1.25, and if you choose to wait, your payoff is 0.
Note that you are not allowed to ask other participants what they will choose. You must guess what other people will do – how many of the other 9 people will withdraw – and act accordingly.

**Announcement**

In each period, an announcement will show up in lower right section of the screen to forecast the number of withdrawing requests for this period.

The announcement will be either

- “The forecast is that 3 or **more** people will choose to withdraw”, or that
- “The forecast is that 3 or **less** people will choose to withdraw”.

Everybody receives the **same** message. The announcements are randomly generated. There is a possibility of seeing either announcement, but the chance of seeing the same message that you saw in the previous period is higher than the chance of seeing a different announcement. These announcements are forecasts, which can be right or wrong. The experimenter does not know better than you how many people will choose to withdraw (or wait) in each period. The number of withdrawals is determined by the decisions of all participants. Your actual payoff depends only on your own choice and the choices of other participants.

**Number of Periods**

This experimental session consists of **50** periods.

**Computer Instructions**

In each period, you start with 1 ED in the experimental bank and make a withdrawing decision through a computer screen. An example screen is shown below.
The header provides information about what period you are in and the time remaining to make a decision. After the time limit is reached, a flashing reminder, “please reach a decision”, will appear. For your convenience, the same payoff table as the one on the last page of the instructions is shown on the left section of the screen.

You choose to withdraw money or wait by clicking on one of the two red buttons “withdraw” or “wait”.

The screen also contains information about the history of the experiment:

- A graph of total number of withdrawals in all past periods
- History table that contains: the history of the announcements, the actual number of withdrawals, your decision, your payoff in each period, and your cumulative payoff

**Practice Periods**

Before we formally start the experiment, you will have the chance to practice your decision making for 6 periods. This is an opportunity for you to become familiar with the task you will perform during the experiment. Your choice in the practice period does not count toward your total earnings in the experiment.

**Payoff**

At the end of the entire experiment, the experimenter will pay you in cash. Your earnings in Dollars will be:

\[
\text{Total payoff in ED} \times 0.1
\]
Table: payoffs if \( n \) of the 10 subjects **withdraw**

<table>
<thead>
<tr>
<th>( n )</th>
<th>payoff if you withdraw</th>
<th>payoff if you wait</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>n/a</td>
<td>2.00</td>
</tr>
<tr>
<td>1</td>
<td>1.54</td>
<td>1.88</td>
</tr>
<tr>
<td>2</td>
<td>1.54</td>
<td>1.73</td>
</tr>
<tr>
<td>3</td>
<td>1.54</td>
<td>1.54</td>
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<tr>
<td>4</td>
<td>1.54</td>
<td>1.28</td>
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<td>1.54</td>
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<td>6</td>
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<td>7</td>
<td>1.43</td>
<td>0.00</td>
</tr>
<tr>
<td>8</td>
<td>1.25</td>
<td>0.00</td>
</tr>
<tr>
<td>9</td>
<td>1.11</td>
<td>0.00</td>
</tr>
<tr>
<td>10</td>
<td>1.00</td>
<td>n/a</td>
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</table>