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**Liquidity Requirements and the
Interbank Loan Market:
An Experimental Investigation**

Douglas Davis, Oleg Korenok, John Lightle,
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We develop a stylized interbank market environment and use it to evaluate with experimental methods the effects of liquidity requirements. Baseline and liquidity-regulated regimes are analyzed in a simple shock environment, which features a single idiosyncratic shock, and in a compound shock environment, in which the idiosyncratic shock is followed by a randomly occurring second-stage shock. Interbank trading of the illiquid asset follows each shock. In the simple shock environment, we find that liquidity regulations reduce the incidence of bankruptcies, but at a large loss of investment efficiency. In the compound shock environment, liquidity regulations not only impose a loss of investment efficiency but also fail to reduce bankruptcies.

1. Introduction

This paper reports a prototype experiment designed to study how an interbank market reallocates liquidity among banks. The experiment studies a multistage game in which banks are subject to random withdrawal shocks. Each bank initially decides how much of its deposits to invest in cash and how much to invest in a high-return, illiquid asset, under the condition that it may subsequently be subject to random withdrawal demands. The bank can meet those demands by distributing cash that it holds and/or by obtaining more cash from selling its illiquid assets in the interbank market. In half the treatments, liquidity requirements – minimum amounts of cash that banks must hold – are imposed on each bank. Investment decisions and the performance of the interbank market with and without the liquidity requirements are compared.

Interbank markets are an important form of financial intermediation in developed economies. Through these markets, banks with excess liquidity lend to banks that need liquidity, a process that reallocates funds and expands the lending capacity of the banking system. During the financial crisis of 2007-2009, these markets became "stressed" in that interest rates on what were usually considered safe, riskless, short-term loans greatly increased and volumes did not increase to meet increases in demand.[1] Furthermore, several large financial institutions, such as Bear Stearns, Lehman Brothers, Northern Rock, and other banks, experienced liquidity problems.

As part of the regulatory response to the crisis, the Basel Committee on Banking Supervision recommended that bank regulators mandate that banks hold a sizable buffer of liquid assets, with the hope that this would prevent the liquidity problems experienced during the financial crisis.[2] Economic arguments for liquidity requirements are based on the belief that banks will underprovide liquidity. Bhattacharya and Gale (1987), for example, suggest that

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[1] Afonso, Kovner, and Schoar (2011) analyze the U.S. federal funds market for overnight loans following the Lehman Brothers bankruptcy in September 2008 and find that the daily federal funds rate spiked by a weighted average of 60 basis points. Although they further report that overnight loan volumes remained fairly constant, loans for longer maturities did dry up, as reported, for example, by Ivashina and Scharfstein (2010), who find that, at the peak of the crisis, new loans to large borrowers fell by 47 percent relative to pre-crisis levels. Heider, Hoerova, and Holthausen (2015) and Acharya and Merrouche (2013) report similar responses to the crisis in the unsecured euro interbank market and in the U.K. interbank market, respectively.

[2] Formally, the Basel committee recommended two separate liquidity requirements. The first one is the Liquidity Coverage Ratio (LCR), which requires a bank to hold enough liquid assets to meet expected net cash outflows over a 30-day period. For details on how this ratio is calculated, see Kowalik (2013). The second one is the Net Stable Funding Ratio (NSFR), which is intended to ensure that banks adequately balance the sources and uses of funds over a longer term (one year). In the United States, the LCR has been implemented and applies only to the largest banks, while the NSFR rule has not yet been finalized.

banks might free ride off each other's holdings of liquid assets because maintaining these assets is costly, thus creating liquidity shortages in times of aggregate shocks.

Potentially compounding the effects of insufficient liquidity is a propensity for banks to hoard available liquid assets in times of systemic stress. A variety of factors may motivate such hoarding, including precautionary considerations (Gale and Yorulmazer, 2013), as well as strategic efforts to force rivals to sell assets at fire-sale prices (Diamond and Rajan, 2011; Acharya, Gromb and Yorulmazer, 2012). Presumably, by reducing instances of stress, liquidity requirements may ease the negative effects of these incentives.[3]

Basel's liquidity requirements, however, are not without costs. First, required liquidity buffers limit bank lending activity, since banks must hold proportionally more cash and other liquid assets such as Treasury securities.[4] Second, it is possible that liquidity requirements will make a liquidity crisis worse by giving banks an even stronger incentive to hoard liquidity when times are bad. In Gale and Yorulmazer (2013), for example, while liquidity requirements do reduce the probability of a panic, when a crisis does happen the liquidity requirements make the situation worse by increasing banks' incentives to hold liquid assets.

Empirically, some evidence suggests that liquidity requirements can make panics worse. In the United States during the National Banking Era (1863-1913), liquidity requirements were one of the main prudential regulatory tools.[5] Despite these requirements, the National Banking Era was characterized by multiple panics, and experts from the era, for example,, Sprague (1910), believed that reserve requirements were partly responsible. The ineffective performance of reserve requirements in the late 19th and early 20th centuries was a primary motivation for the Federal Reserve Act of 1913, which was designed to furnish an elastic supply of currency.[6]

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[3] Other market frictions discussed in the literature that may impair interbank market performance in times of stress include counterparty risk (Heider, Hoerova, and Holthausen 2015).

[4] Several commentators argue that the LCR may limit bank lending activity. See, for example, Kowalik (2013, p. 76). Relatedly, Diamond and Kashyap (2016) analyze a banking model for an institution subject to an LCR requirement and show that the regulated bank must always hold some assets in reserve, even during a crisis, to protect itself from a run, even though doing so inefficiently restricts lending. See De Nicolo, Gamba, and Lucchetta (2012) as well as Hartley (1998) for an analysis in a general equilibrium, cash-in-advance model.

[5] The reserve requirement took the form of requiring a bank to hold assets in the form of specie, Treasury notes, or reserves at other banks of at least 25 percent of its notes and deposits. The precise requirement depended on whether a bank was a Central Reserve City Bank, a Reserve City Bank, or a Country Bank.

[6] Carlson (2013) provides a concise discussion of reserve requirements before, during, and after the National Banking Era. Notably, following the establishment of the Federal Reserve in 1913, the use of reserve requirements remained in use as a tool for promoting bank liquidity. However, the central bank's role as a lender of last resort soon usurped the role of reserve requirements as a provider of liquidity. By the 1930s, reserve requirements, along

Our experiment examines an interbank market in a *simple shock* environment where interbank trade follows an idiosyncratic shock and in a *compound shock* environment where, after the initial shock, a second shock probabilistically impacts the banking system. The simple shock environment isolates the effects of a liquidity requirement on the coordination problem associated with interbank trade. The more complex compound shock environment allows insight into banks' propensities to hold liquid assets given a possible second shock. In both environments, we examine the capacity of liquidity regulations to improve the stability of an interbank market in terms of reducing the number of bankruptcies, as well as the costs of the regulation in terms of aggregate investment.

Experimental results indicate that in the unregulated simple shock environment, banks tend to hold sufficient liquid assets on average. Nevertheless, individual market outcomes are highly variable, resulting in frequent bankruptcies caused by instances where banks collectively hold too little cash. In this environment, liquidity requirements modestly reduce the incidence of bankruptcies, primarily by truncating the asset investment strategy space for individual banks. This truncation reduces portfolio variability and thus the frequency of periods where banks collectively hold too little cash. The incidence of bankruptcies is also affected, to some degree, by strategic hoarding behavior. This hoarding behavior is also marginally lower with a liquidity requirement, perhaps because of reduced uncertainty about the relation of the supply of cash relative to demand. Differences in strategic withholding, however, are not significant across treatments, and in any case, such hoarding activity is not a primary driver of treatment effects.

The amelioratory effects of liquidity requirements do not carry over to the compound shock environment. Although the incidence of bankruptcies in response to the first-stage shock is again lower in the treatment with a liquidity requirement, liquidity-regulated banks hold too little cash for a second-stage shock and, consequently, suffer bankruptcies at much higher rates than their unregulated counterparts following the realization of a second-stage shock.

Finally, in both environments, the reduction in bankruptcies comes at a very high cost in terms of forgone investment. Liquidity requirements reduce by about half the potential gains from investment that interbank trade allows compared with autarky.

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with open market operations, were seen as tools for implementing credit and monetary policy. See Goodfriend and Hargraves (1983) for a discussion.

2. Related Literature

This paper contributes to a small but growing literature that uses experiments to analyze banking and bank regulation. The largest branch of this literature pertains to experiments examining financial fragility in variations of the Diamond and Dybvig (1983) banking model.[7] These papers focus on institutional and environmental factors that affect the tendency of depositors in a single bank to run or coordinate on a degenerate equilibrium and, for that reason, are not tied to the current investigation. Most closely related is Davis, Korenok, and Lightle (2018a), who examine interactions between the level of required liquid assets and the effects of a history of bank stability on bank runs. They find that only very restrictive liquidity requirements effectively insure against bank runs.

In contrast to the Diamond-Dybvig based experiments, this paper investigates the provision of liquidity through an interbank market. Only a handful of other experimental papers examine aspects of regulations or institutional features of interbank markets designed to improve bank stability. Davis, Korenok, and Prescott (2014) and Davis and Prescott (2017) report experiments examining the consequences of alternative triggering mechanisms for Contingent Capital bonds, a new class of hybrid securities intended to boost banks' capital requirements in the event of financial stress. Armentier and Holt (2017) report an experiment conducted to isolate the bank stigma associated with accessing a discount window in times of stress, and then identify ways to alleviate it. Bosch-Rosa (2018) studies the effects of differing credit maturities over the course of the business cycle. He finds that while longer maturities help stabilize markets in periods of economic expansion, these longer maturities have a destabilizing effect in recessionary times. He interprets his results as suggesting that policies designed to reduce security mismatches may have the unintended effect of destabilizing markets in recessionary times.

The most closely related paper is Davis, Korenok, and Lightle (2018b), (DKL), who report an initial experiment examining the efficiency and stability of an interbank loan market. Their experiment design is related to the model by Allen and Gale (2004b), in which banks are impacted by idiosyncratic and system-wide aggregate shocks. DKL find that while the interbank market allows substantial improvements in trading efficiency relative to the autarkic narrow bank solution, investment efficiency remains below maximum sustainable levels in all treatments because of a persistent heterogeneity in portfolio choices by participants within and across

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[7] See, for example, Davis and Reilly (2016) and the references therein.

periods. Consistent with the predictions of Allen and Gale (2004b), they also observe persistently volatile asset prices and frequent instances of bank losses following interbank exchange.

The present paper builds on DKL by examining the effects of a liquidity requirement on interbank market performance. Our experiment design differs from that in DKL in three main respects.[8] First, rather than using a double auction institution to conduct asset trades post-shock, we introduce a homogeneous price trading mechanism whereby, following the realization of a shock, banks with extra cash simultaneously select an amount of cash to make available in light of the aggregate cash deficiency. Following cash supply decisions, the asset transaction price is determined either as the initial asset purchase price (in the case that the supply of cash is less than or equal to the aggregate cash need) or as the value of assets at maturity (in the case that an excess supply of cash is made available). Second, we change the structure of the combination shock treatment. Rather than combining idiosyncratic and probabilistic components into the realization of a single shock in a three-stage game, we use a four-stage structure that adds a period with a probabilistically occurring second shock to a period with the realization of an initial idiosyncratic shock. Finally, rather than examining the effects of asset price restrictions on interbank market stability, we evaluate the effects of a liquidity requirement. The first two of these differences allow for an analytical characterization of predictions and a cleaner identification of participants' motivations for liquidity withholding behavior, respectively. The remaining difference is the motivation for the study.

3. Experiment Design and Procedures

3.1 Experiment Design. The experiment is based on the incomplete markets model of Gale and Yorulmazer (2013), which in turn is a variant of a frequently used model of the interbank market.[9,10] The experiment uses two environments. The first features idiosyncratic shocks to a

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[8] The experiment design for the present study also differs from DKL in the treatment of bankruptcies. In DKL, liquidity-deficient banks suffered losses up to the entire value of their initial deposit endowment. By way of contrast, banks here simply become insolvent any time remaining obligations exceed assets and pay a fixed liquidation fee.

[9] The basic model, which adapts the banking model by Diamond and Dybvig (1983) to a banking system, was first proposed by Battacharya and Gale (1987). Allen and Gale (2004a) provide a welfare analysis of the interbank game. A sampling of related contributions that analyze variations of the same basic model includes Allen and Gale (2004a); Allen, Carletti, and Gale (2009); Ashcraft, McAndrews, and Skeie (2011); Freixas, Martin, and Skeie (2011); and Heider, Hoerova, and Holthausen (2015).

[10] Gale and Yorulmazer (2013) analyze a more complex version of our compound shock regime. Their motivating interest was to identify conditions under which both precautionary and strategic motivations for liquidity withholding arise as subgame perfect equilibrium phenomena, so that they might explore interactions between the

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subset of banks. We call this the simple shock environment and study it to isolate the effects of liquidity restrictions on the provision of liquidity. The second adds to the simple environment a probabilistically occurring second-stage shock. We call this the compound shock environment and we study it because it provides additional reasons to hoard liquidity.

3.1.1. The Simple Shock Regime. Consider a three-stage game played by eight symmetric and risk-neutral banks. In an initial stage 0, each bank i, $i \in \{1, 2,\ldots,8\}$, is exogenously endowed with \$12 in deposits and constructs a portfolio consisting of cash and assets. Assets can be purchased at a unit price P_o=\$1.00 in stage 0 and yield a return R=\$2.00 in terminal stage 2. Assets, however, are illiquid in stage 1 and can be converted to cash only by selling them to banks with excess cash.[11] Denote cash holdings for bank i going into stage 1 as c_{i1}, and assets as $12 - c_{i1}$.

At the beginning of stage 1, four randomly selected banks receive a shock of \$8, while the remaining four banks receive a shock of \$0. Following the shock, banks with excess cash are informed of the aggregate cash deficiency, d_1, and are given the opportunity to supply excess cash that will be used to purchase assets under the condition that assets will be sold at a price of P_1=\$1.00 per unit if the supply of cash is less than or equal to the aggregate demand for cash, and P_1= \$2.00 otherwise.
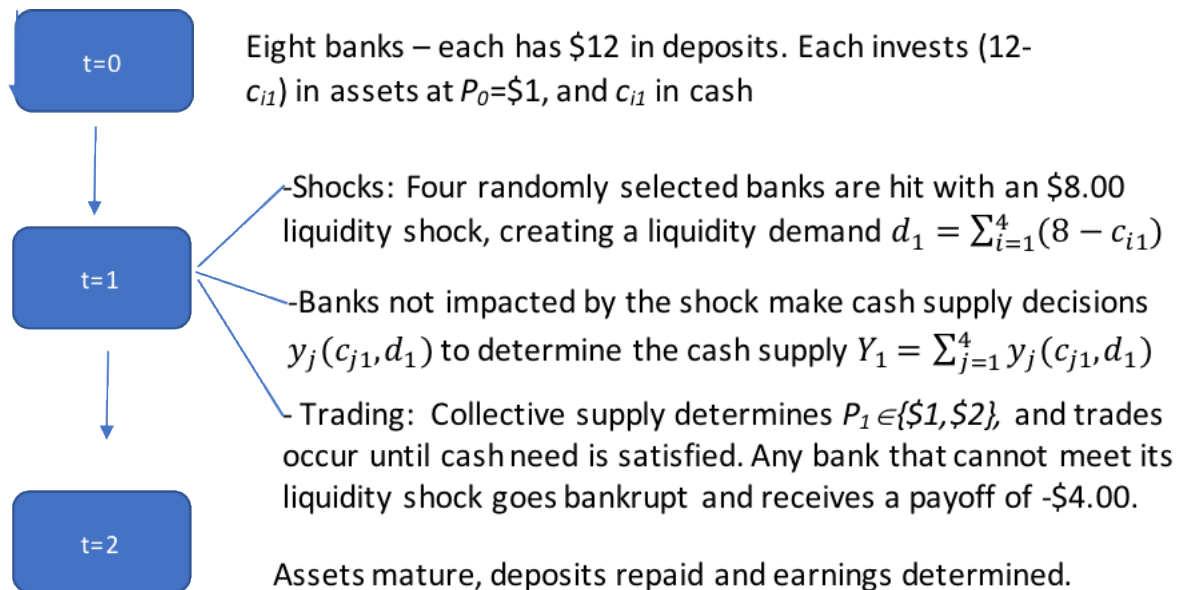
Formally, denote $y_i(d_1, c_{i1}) \geq 0$ as the amount of cash bank i makes available in the first stage if it is not hit with a shock and let $Y(d_1) = \sum y_i(d_1, c_{i1})$ be the total cash made available. Then, prices are

$$P_1 = \begin{cases} \$1 \; if \; Y(d_1) \leq d_1 \\ \$2 \; if \; Y(d_1) > d_1 \end{cases}.$$

t=0	Eight banks – each has \$12 in deposits. Each invests $(12-c_{i1})$ in assets at $P_0=\$1$, and c_{i1} in cash

-Shocks: Four randomly selected banks are hit with an \$8.00 liquidity shock, creating a liquidity demand $d_1 = \sum_{i=1}^{4}(8 - c_{i1})$

t=1	-Banks not impacted by the shock make cash supply decisions $y_j(c_{j1},d_1)$ to determine the cash supply $Y_1 = \sum_{j=1}^{4} y_j(c_{j1},d_1)$

- Trading: Collective supply determines $P_1 \in \{\$1,\$2\}$, and trades occur until cash need is satisfied. Any bank that cannot meet its liquidity shock goes bankrupt and receives a payoff of -\$4.00.

t=2	Assets mature, deposits repaid and earnings determined.

Figure 1. Illustration of the simple shock game.

Following the determination of the aggregate available cash, assets are exchanged, with purchases rotated among liquidity-deficient banks until either $d_1=0$ or $Y(d_1)=0$.[12] Any bank with a cash deficiency following the asset exchange becomes bankrupt and must pay a \$4 liquidation fee. Otherwise, in stage 2, assets mature, deposits are repaid, and earnings are determined. Figure 1 provides a schema of the simple shock environment. We label this unrestricted (baseline) simple shock game SB.

The Trading Mechanism. In practice, interbank trade typically occurs as bilateral over-the-counter (OTC) exchanges, an institutional practice made necessary by the heterogeneous nature of bank portfolios. Moreover, these exchanges take place among banks of asymmetric size and potential access to counterparties. Enriching the design to include these features

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[12] If $Y(d_1) \le d_1$, then the rotation works by sequentially allocating one unit of cash to liquidity-deficient banks until the cash runs out. The rotation order is determined randomly each period, so in the case that cash is insufficient to make all liquidity-deficient banks solvent, those banks that become insolvent are determined randomly. If $Y(d_1) > d_1$, then all liquidity-deficient banks remain solvent. In this case, the sequence of asset purchases is again determined randomly. Unlike the case of insufficient demand, however, the order of purchases is a matter of indifference to banks. Since the purchase price just equals the value of the asset at maturity, banks are indifferent between purchasing assets and holding cash to return to depositors at the end of period 2. In the game variant with a probabilistic second-stage shock, discussed below, the conclusion that given $Y(d_1) > d_1$ banks are indifferent between buying assets at $P_1 = R$ and holding cash may not remain true, since residual cash has the advantage of leaving a bank more prepared to address a second-stage shock. Importantly, however, changes in the relative desirability of purchase decisions off the equilibrium path do not affect banks' incentives to keep $Y(d_1) \le d_1$.

considerably complicates the analysis and, we fear, incentives in the subsequent environment. As a starting point, we use the uniform price trading rule standard in the pertinent theoretical literature (see, for example, Allen and Gale 2004a, 2004b).

A natural choice of trading mechanism for an initial analysis is the double auction, which is well known for its high trading efficiency and robustly competitive performance.[13] The double auction, however, also presents significant limitations here. First, the richness of the strategy space in the double auction makes it hard to solve for an equilibrium. Second, the results in DKL, who evaluate a similar interbank market environment, suggest that while use of the double auction trading reduces price variability, it hardly eliminates it. In particular, DKL observe that the sequential nature of contracting in a double auction conflates learning about underlying supply and demand conditions with possible strategic efforts to manipulate the terms of trade.

Our uniform pricing alternative, while stylized, is consistent with the analysis in the theoretical literature and allows us to solve for equilibria while eliminating the behavioral complications associated with participants being forced to learn the underlying supply and demand conditions for cash through the price discovery process, as occurs with a double auction. Finally, from a very practical perspective, our sequential mechanism speeds the trading process and allows a substantially larger number of trading periods than would be possible with a double auction.

Baseline Simple Shock Equilibria. To help analyze the experiment, we study the symmetric subgame perfect Nash equilibrium (SPNE) for this game. It will provide a useful benchmark for evaluating the experimental results. The savings decision in a symmetric SPNE for the SB game is $c_{i1} = \$4$. Proofs appear in Appendix A, but the result can be seen intuitively.[14] By holding $4 in cash and investing the remaining $8, banks maximize earnings and collectively avoid bankruptcy. In stage 1, the four banks experiencing a shock have a deficiency of $4 each, making $d_1 = \$16$. The symmetric SPNE strategy is for each unshocked bank to make $4 available, so $Y(\$16) = \$16$. To see this, first note that given $c_{i1} = \$4$, the

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[13] See, for example, Davis and Holt (1993), chapter 3.
[14] Appendix A presents proofs of the symmetric SPNE for this and each of the treatment combinations. In each case, we focus on an SPNE in which actions taken along the equilibrium path are ex-ante symmetric across banks. We also establish in Appendix A that asymmetric sub-strategies are needed off the equilibrium path, similar to the asymmetric equilibria in the game of chicken.

expected earnings for each bank is $\pi_i = \frac{1}{2}(\$4) + \frac{1}{2}(\$12) = \$8$. Now consider a deviation by a bank to $c_{i1} < \$4$ in stage 0. In this case, at stage 1, the amount of cash supplied depends on whether the deviating bank is hit by the liquidity shock. If it is, then $d_1 > 16$. The unshocked banks will supply all their cash because, if they didn't, they would be passing up a chance to buy assets at $P_1 = \$1.00$. Consequently, $Y(d_1) = \$16 < d_1$, $P_1 = \$1.00$, and the deviating bank goes bankrupt and receives a payoff of -\$4. If the deviating bank is not hit by the liquidity shock, then again the banks not hit by the shock supply all their cash because assets are cheap. Consequently, $Y(d_1) = \$12 + c_{i1} < d_1 = \$16$, $P_1 = \$1.00$ and the deviating bank receives a payoff of $2*(\$12-c_{i1}) + 2 * c_{i1} - \$12 = \$12$. The expected payoff is then $\pi_i = \frac{1}{2}(-\$4) + \frac{1}{2}(\$12) = \$4$. In other words, banks collectively provide exactly the amount of cash needed in the market up to the total amount they have available. Basically, there is no incentive to save less than \$4 because a deviating bank risks bankruptcy and the gains are no more than what a bank could get by holding 4 units of cash and buying assets in the interbank market. Furthermore, there is no incentive to save more than \$4 because cash cannot be more valuable than an asset, so the expected payoff cannot be higher than in the SPNE.

While we focus on a symmetric SPNE to organize our analysis, we recognize that a wide variety of initial investment decisions can be supported as asymmetric subgame perfect Nash equilibria. For example, if bank A holds \$5 in cash, bank B holds \$3 in cash, and the rest hold \$4, no profitable deviation is possible because bank A's extra cash just compensates for bank B's cash deficiency. The critical condition is that banks in the aggregate restrict initial investment to the maximum sustainable level of 64 assets and hold \$32 in cash. Regardless of the combination of banks that are impacted by the shock, given maximum sustainable initial investment, the available cash will always just equal the stage 1 cash deficiency and no deviation, particularly in the form of cash withholding, can increase earnings.

In an efficient SPNE, neither over-investment nor liquidity hoarding occurs. In the SPNE, over-investment, or free riding off the stock of aggregate cash, is unprofitable because each dollar held in cash is either used to address a period 1 liquidity need or converted into an asset at $P_0 = \$1$. Off the equilibrium path, however, individual banks may find it profitable to over-invest if they believe that the rest of the banking system will collectively under-invest. Similarly, off the equilibrium path banks have a strategic motive to hoard liquidity. For any

deviation where $Y(d_1) > d_1$, banks may profitably withhold available cash in order to reduce the supply of cash on the market, so $P_1=\$1$ rather than $P_1=\$2$. As will be seen in the results, we see some evidence of such behavior.

3.1.2. The Compound Shock Regime. The compound shock regime appends to the simple shock environment a possible second-stage liquidity shock. Specifically, following the exchange of assets in stage 1, we add a stage 2 in which, with probability ½, two of the four banks not impacted by the stage 1 shock experience a liquidity shock of $8 each. Which two banks receive the shock is random. In the event of no shock, stage 2 passes to stage 3 and the period ends.

In the event of a realization of a shock in stage 2, a second round of interbank trade follows. Banks with excess cash are shown the aggregate cash deficiency d_2 and submit an amount of cash to make available, under the condition that the stage 2 asset price will equal $1 if the aggregate supply of cash is less than or equal to the cash deficiency, and $2 otherwise. Formally, denote the cash held by bank i going into stage 2 as c_{i2}, the cash bank i makes available upon observing d_2 as $z_i(d_2, c_{i2})$, and the aggregate cash made available in the second stage as $Z(d_2)$.

Then, as in the first stage, the price is determined by the relative supply and demand for cash by

$$P_2 = \begin{cases} \$1 \; if \; Z(d_2) \leq d_2 \\ \$2 \; if \; Z(d_2) > d_2 \end{cases}.$$

As in stage 1, following the determination of available cash, assets are exchanged with purchases rotated among liquidity-deficient firms until either $d_2=0$ or $Z(d_2)=0$. Any bank with a cash deficiency following the asset exchange becomes bankrupt and must pay a $4 liquidation fee. Otherwise, in stage 3, assets mature, deposits are repaid, and earnings are determined. Figure 2 provides a schema of the complex environment. We label this compound shock game CB.

Baseline Compound Shock Equilibria. As with the SB game, we analyze the SPNE to provide a benchmark against which we may compare with experimental outcomes. In the CB game, two symmetric SPNE exist: a no-exposure equilibrium in which banks hold cash sufficient to insulate themselves against a bankruptcy in the event of a second shock, and an exposure equilibrium, in which banks choose to stand exposed to bankruptcy in the event of a second shock.
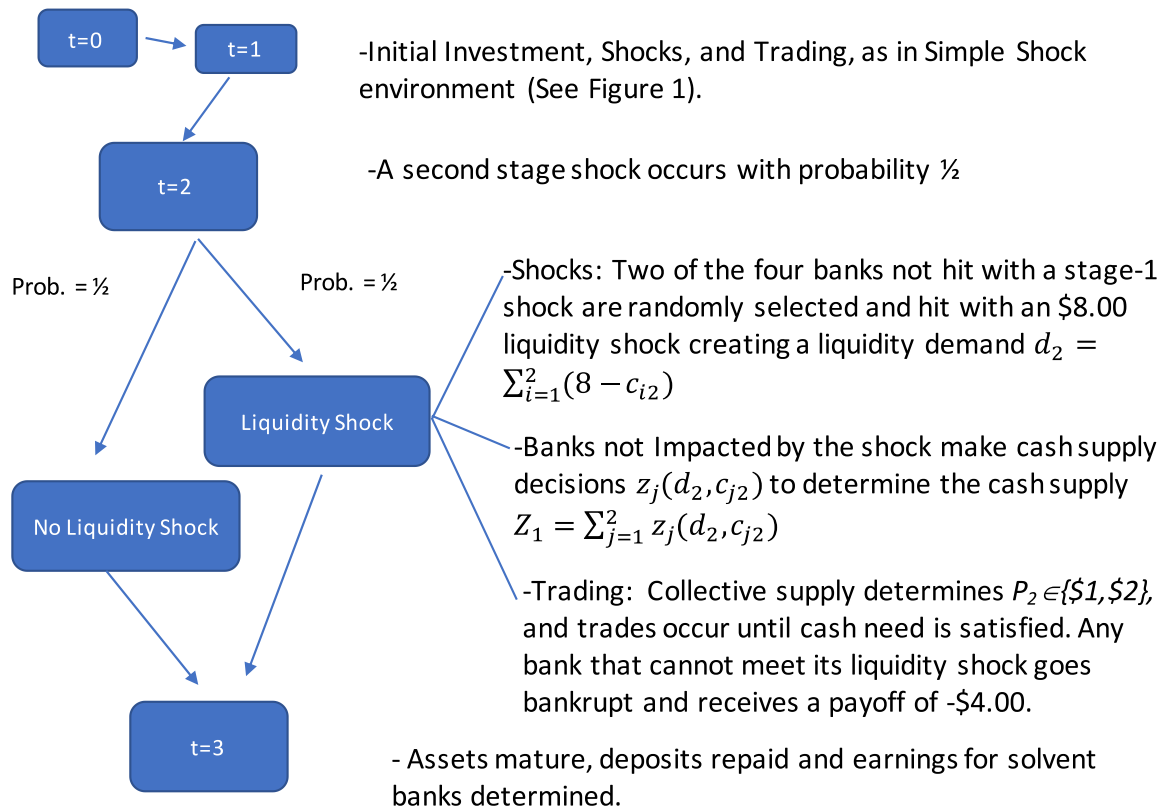
Figure 2. Illustration of the compound shock game.

In the no-exposure equilibrium, each bank holds $\rho_i = \$6$, in cash. The reasoning driving this equilibrium is analogous to that for the SB game and can be seen intuitively. In stage 1, the four banks experiencing a shock each have a deficiency of $2, so $d_1 = \$8$, and the symmetric prediction is that each bank without a shock makes $2 available, leaving the unshocked banks with $4 each. In stage 2, a second shock occurs with a 50 percent probability. In the case of a second shock, the two banks experiencing an $8 demand for cash each have $4 and would thus need $4 more, so $d_2 = \$8$, which matches the $2 made available by each of the remaining two banks resulting in $Z(\$8) = \$8$. The symmetric SPNE requires the off-path behavior of $Y(d_1) = \min\{d_1, \$8\}$ and $Z(d_2) = \min\{d_2, \sum_i \rho_i^{M2}\}$.

Notice that in this equilibrium, there is no general under-investment. Banks, however, do withhold liquidity for precautionary reasons in stage 1. Given their initial savings decisions, those banks not impacted by the stage 1 shock maintain $4 in excess cash out of concern for the possibility of a second shock. On the equilibrium path, the trading price of assets is $1 in both periods, and no bank can increase profits by saving less cash or making more cash available.

Banks earn \$1 for every asset held in period 4, and the expected profit in equilibrium is: $\frac{1}{2}(\$4) + \frac{1}{4}(\$8) + \frac{1}{8}(\$12) + \frac{1}{8}(\$4) = \$6$.

Consider now the exposure equilibrium. In this case, banks choose to bear the bankruptcy costs of a second shock and hold $\rho_i^{M1} = \$4$ in cash, as in the simple shock environment. In this equilibrium, the four banks experiencing a shock in stage 1 have a deficiency of \$4, so $d_1 = \$16$, and the symmetric prediction is that each bank without a shock makes available all their cash, making $Y(d_1) = d_1$, leaving no cash in the banking system. If a second shock occurs in stage 2, the two shocked banks go bankrupt, leaving them each with a loss of \$4. In expectation, the payout from the higher investment levels in periods with no second shock compensates for bankruptcies in the event of a second shock and expected earnings are: $\frac{1}{2}(\$4) + \frac{1}{4}(\$12) + \frac{1}{8}(\$12) + \frac{1}{8}(-\$4) = \$6$, the same as in the no-exposure equilibrium.

Importantly, the exposure equilibrium is not an artifact of our parameter choices but is a general feature of this game. Although increases in bankruptcy costs reduce the expected profitability of the exposure equilibrium, even the relatively high 25 percent probability of needing cash after a second-stage shock used here damps expected profits only mildly. Quite large bankruptcy costs are needed to eliminate the equilibrium. Given our other parameters, an exposure strategy remains an equilibrium strategy until the cost of bankruptcy exceeds \$20.[15]

3.1.3. The Liquidity Requirement. We examine the simple shock and compound shock environments both with and without liquidity requirements. The idea driving liquidity regulations is that banks maintain liquid assets sufficient to cover a short-term liquidity drain. An extreme interpretation of such a requirement in our environment would be to require each bank to hold \$8, since in both the simple shock and compound shock regimes banks may need \$8. Such an interpretation, however, is uninteresting in that it effectively eliminates the interbank market, which is certainly not a policy objective.

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[15] To see this, observe that the most profitable deviation from an {8 asset, \$4} portfolio in the exposure equilibrium is the autarkic {4 asset, \$8} portfolio, which yields a profit of \$4 with certainty each period. Labeling the bankruptcy liquidation cost as *B,* it follows that the exposure equilibrium will exist until ½(4) + ¼ (12) + 1/8(12) + 1/8 (-B)<4, or B>20. More generally, we observe that in natural contexts the probability of a second shock (some non-idiosyncratic event) is substantially less than ½, making the cost of bankruptcy necessary to eliminate the exposure equilibrium much higher. Labeling *p* as the probability of a second shock, the pertinent condition becomes ½(4) + ½ (1-*p*) (12)+ ¼ *p* (12) + ¼ *p* (-*B*)<4. Solving *B*> 16/*p* -12. Thus, for example, a second shock probability of 1/8 would imply *B*>\$116.

As an alternative, we require all banks to hold $4. Although a $4 requirement does not fully insulate banks from liquidity risk, it does guarantee that the required liquidity in the banking system matches aggregate liquidity needs. Alternatively, viewing the liquidity requirement as a means of stabilizing the banking system in the case of a probabilistically occurring second shock, a $4 requirement just equals the expected value of the second-stage shock. Finally, to sidestep the rather obvious concerns that liquidity requirements undermine stability simply by requiring banks to hold cash that is unavailable in the case it is needed, we allow banks to use required reserves for their own liquidity shocks. Banks, however, may not use required cash holdings to resolve the liquidity needs of other banks.

Equilibria with Liquidity Requirements. The restriction that banks must hold cash unless needed to satisfy a unilateral liquidity deficiency alters the symmetric SPNE predictions in both the simple and compound shock environments. In the liquidity-restricted simple shock (*SL*) game, the initial SPNE savings decision is $c_{i1} = \$6$. In period 1, the four shocked banks have a need of $2, so $d_1 = \$8$, and the remaining four banks have $6 each, but because the LCR = $4, they each have only $2 available, which exactly equals the demand for cash, so $Y(\$8) = \$8$. As in the SB treatment, banks respond to a deviation by providing exactly the amount of cash needed up to the amount they can provide given the LCR. Equilibrium expected profits are $\frac{1}{2}(\$4) + \frac{1}{2}(\$8) = \$6$.

In the liquidity-restricted compound shock (CL) game, there are two SPNE. In the no-exposure equilibrium, initial cash holdings increase to $c_{i1} = \$7$. In stage 1, the four shocked banks need $1 each, and in equilibrium, the unshocked banks provide exactly $1, leaving them with $6. If a stage 2 shock occurs, the two shocked banks need $2 each, and the two remaining banks have exactly $2 available. Similar to the no-exposure equilibrium in the BC game, off-path actions must satisfy $Y(d_1) = \min\{d_1, \$4\}$ and $Z(d_2) = \min\{d_2, \sum_i \max\{c_{I2} - 4, 0\}\}$. Once again, banks have a precautionary motive to hoard cash in period 1 in case they are shocked in period 2. Expected earnings are: $\frac{1}{2}(\$4) + \frac{1}{4}(\$6) + \frac{1}{8}(\$8) + \frac{1}{8}(\$4) = \$5$.

Treatment Equilibrium	Period 0 Cash	Expected Payoff	Aggregate Investment
SB	$4	$8.00	64
CB$_{ne}$	$6	$6.00	48
CB$_e$	$4	$6.00	64
SL	$6	$6.00	48
CL$_{ne}$	$7	$5.00	40
CL$_e$	$6	$4.50	48

Table 1. Reference equilibrium predictions. Each row in the table summarizes individual cash holdings and expected payoffs along with aggregate investment for SPNE listed in the left column of the table. For the compound shock environment, the *ne* subscript refers to the no-exposure SPNE and the *e* subscript refers to the exposure SPNE.

In the liquidity-restricted exposure equilibrium, initial cash holdings $\rho_i^{M1} = \$6$. Following the stage 1 shock, the four shocked banks each need $2, which they acquire from the unshocked banks, which then each have $4. No cash remains available, so in the case of a stage 2 shock, the impacted banks go bankrupt. Expected earnings in the exposure equilibrium are

$\frac{1}{2}(\$4) + \frac{1}{4}(\$8) + \frac{1}{8}(\$8) + \frac{1}{8}(-\$4) = \$4.50$.

As with the CB game, the existence of the exposure equilibrium is a fairly general feature of the CL game and exists as long as bankruptcy costs do not exceed $8.[16] Our parameter selection, however, does give liquidity restrictions a best shot at reducing the incidence of bankruptcies in the compound shock environment. In distinction to the CB game, where expected earnings in the exposure and no-exposure equilibria are the same, at $6.00, in the CL game, the exposure equilibrium is less attractive in the sense that equilibrium expected earnings are $4.50, less than the $5.00 expected earnings available in the no-exposure equilibrium.

Table 1 summarizes reference equilibrium predictions for the four games that make up our experiment. The aggregate initial investment predictions for each treatment are shown in the right-most column of the table. The benchmark aggregate initial investment predictions for both the simple shock treatments and the no-exposure equilibria in the compound shock treatments

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[16] To see this, observe that the most profitable deviation from a {6 asset, $6} portfolio in the exposure equilibrium is the autarkic {4 asset, $8} portfolio, which yields a profit of $4 with certainty each period. It follows that the exposure equilibrium will exist until ½(4) + ¼ (8) + 1/8(8) + 1/8 *(-B)*<4, or *B*>8. Lower second-stage shock probabilities inflate the minimum bankruptcy cost necessary to eliminate the exposure. Given a second-stage shock probability of *p*, the exposure equilibrium exists until ½(4) + ½ (1-*p*) (8)+ ¼ *p* (8) + ¼ *p* (-*B*)<4. Solving, *B*> 8/*p* -8. Thus, for example, a second-stage shock probability of 1/8 would imply *B*>$56.

define the maximally sustainable investment levels in the sense that these are the levels of investment that banks may collectively sustain without running the risk of bankruptcies. Collectively, we refer to these as the sustainable equilibria, which we distinguish from the exposure equilibria in the compound shock treatments, where bankruptcy is predicted.

4. Experiment Procedures

The experiment was conducted as a series of 12 sessions, three in each of the four treatment cells identified in Table 1. In each session, a cohort of 16 participants was randomly seated at visually isolated computer terminals and given a printed set of instructions. A monitor then read the instructions aloud, assisted by a copy projected on a screen at the front of the lab, as participants followed along on their printed copies.[17] Following the instructions, participants completed a short quiz to determine their understanding of the rules. Any errors in the quiz answers as well as all other participant questions were addressed privately by the monitor. Participants were then also anonymously divided into two 8 player markets. As explained to the participants, these markets remained fixed throughout the session, creating two independent markets per session.

Sessions were programmed with the Z-Tree software (Fischbacher, 2007) and consisted of 25 trading periods. The first two periods of each session were practice periods conducted under the SB treatment condition. During the practice periods, participants were free to privately ask any questions they might have about market procedures. Three additional paid periods in the SB treatment then followed, after which the session was paused and instructions for one of the four treatment sessions was distributed and read aloud.[18] Following a short review and quiz to determine understanding, the second part of each session commenced. As with the first part, two initial practice periods preceded the paid periods, followed by 18 paid periods. At the end of the 20th treatment period, the session ended, and participants were privately paid and dismissed one at a time.

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[17] Instructions are available in the unpublished Appendix B.
[18] One of the four treatments was the SB treatment, even though it is the same as the first five periods.
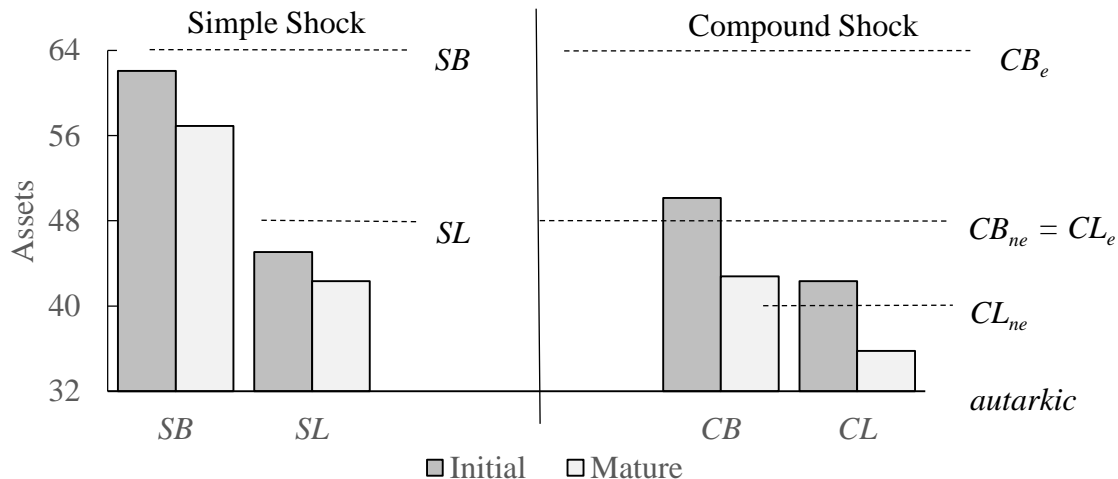
Figure 3. Mean investment levels for each treatment relative to the benchmark SPNE. Initial refers to mean initial investment decisions. Mature refers to the mean level of investments that were not liquidated due to bankruptcy. Dashed lines refer to benchmark SPNE investment levels. The autarkic outcome of 32 units in each treatment refers to an allocation in which each bank invests 4 assets and does not need to use interbank trade to meet withdrawal shocks.

Participants were undergraduate students enrolled at Virginia Commonwealth University in the spring semester of 2017 recruited with the ORSEE recruiting system (Greiner, 2015). Most were upper-level engineering, math, business, and economics students. Sessions lasted 60 to 90 minutes. Lab dollar earnings were converted to U.S. currency at a 1 lab dollar = $0.20 U.S. rate. Earnings ranged from $15.60 to $45.00 and averaged $29.20.

5. Experiment Results

We organize this section by first considering two aspects of the banking system that are of primary policy interest: investment decisions and bank stability (or the incidence of bankruptcies). We then combine these results to analyze what determines the number of assets that reach maturity, that is, the number of successful investments.[19] We close this section with a discussion of the way liquidity requirements impact liquidity management decisions across treatments.

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[19] Price (interest) stability is a third dimension of results that would, in general, merit attention. As Allen, Carletti, and Gale (2009) argue, price (interest rate) stability is an essential feature of the performance of a banking system, since stable prices facilitate consumer and business planning decisions. In our design, our restriction of prices to just two possible outcomes makes the price results less interesting.

5.1 Initial Investment Decisions. The dark columns in the bar chart shown as Figure 3 summarize mean initial investment decisions in the simple and compound shock regimes. Looking generally across the bars in the figure, observe first that banks do rely heavily on interbank trade in making investment decisions. In all treatments, banks collectively invest at substantially higher rates than is sustainable under the autarkic narrow bank solution of 32 assets. Observe further that, in a comparative statics sense, banks collectively respond as predicted to regime changes: within each environment liquidity restrictions reduce investment levels.

Turning to the simple shock environment, summarized on the left side of the figure, notice that over-investment does not appear to be a generic problem. In fact, in both the SB and SL treatments, mean initial investments lie below the equilibrium benchmark predictions. This result was largely expected in this environment, since the idiosyncratic shock affects the banking system by a constant amount each period, and in equilibrium, banks never find cash unused.

On the other hand, in the compound shock treatments shown on the right side of Figure 3, unregulated banks do exhibit some modest propensity to over-invest. In the CB treatment, banks collectively invest about two assets above the no-exposure equilibrium prediction. Nevertheless, investment in the CB treatment remains far below the exposure equilibrium benchmark, suggesting that banks do not coordinate on this alternative equilibrium. Similarly, in the CL treatment, mean investment also exceeds the no-exposure equilibrium benchmark by about two units, suggesting that while the regulations reduce investment activity, they fail to reduce banks' propensities to invest at above sustainable levels.

To more formally evaluate investment activity, we regress initial investment levels against a series of indicator variables D_j, $j \in \{C, L\}$ that delineate the incremental effects of the shock environment (C for compound) and regulatory regime (L for liquidity regulated). Using the SB treatment as the default condition, combinations of these variables allow us to distinguish each of the remaining three treatment/shock realization conditions. The regression uses a random effects specification. Specifically, we estimate

$$y_{it} = \beta_0 + \beta_L D_L + \beta_C D_C + \beta_{LC} D_L D_C + \varepsilon_i + u_{it} \tag{1}$$

where y_{it} denotes collective initial investment, 'i' identifies a market (1 to 24) and 't' a period (1 to 18). We cluster data by markets and use a robust (White "sandwich") estimator to control for possible unspecified autocorrelation or heteroscedasticity.

(1) Treatment	(2) $\overline{inv}$	(3a) i_{ne}	(3b) $\overline{inv}\text{-}i_{ne}$	(4a) i_e	(4b) $\overline{inv}\text{-}i_e$	(5) SB-SL	(6) CB-CL
SB	62.08	64	-1.92*				
SL	45.06	48	-2.94***			17.02***	
CB	50.15	48	2.15**	64	-13.85***		
CL	42.34	40	2.34***	48	-5.66***		7.81***

Table 2. Initial investments. $\overline{inv}$ denotes mean initial investment, i_{ne} denotes aggregate investment in the no-exposure SPNE for the SB, SL, CB and CL treatments, i_e denotes aggregate investment in the exposure SPNE for the CB and CL treatments.
Note: *, **, and *** denote rejections of the null that the listed difference equals zero, $p<0.10$, 0.05, and 0.01, respectively. In all treatments, $\overline{inv}$ exceeds the autarkic level of 32 units at $p<0.01$.

Treatment averages are generated by adding coefficient estimates, and Wald tests are subsequently used to assess differences across treatments.[20] Table 2 summarizes the results. Column (2) lists mean investment levels for each treatment cell. In each case we can reject the null hypothesis that initial investment does not differ from the 32 assets available from the narrow banking autarkic solution ($p<.01$ in each case). Comparing initial investments with the sustainable equilibrium benchmarks in each treatment, listed in column (3a), observe that while initial investment decisions across treatments move with these reference benchmarks, banks nevertheless deviate systematically from these predictions, as seen in column (3b). In the simple shock environment, banks collectively under-invest relative to the equilibrium benchmark by 1.92 units in the SB treatment and 2.94 assets in the SL treatment. In the compound shock treatments, banks collectively over-invest relative to the no-exposure benchmark, by 2.15 units in the CB treatment, and 2.34 units in the CL treatment. Nevertheless, while initial investment in the compound shock treatments exceeds the no-exposure benchmark predictions, banks exhibit little tendency to coordinate on exposure equilibria, as seen in columns 4(a) and 4(b). Mean investment is 13.85 assets below the exposure equilibrium prediction in the CB treatment and is 5.66 units below the comparable prediction in the CL treatment. As seen by the asterisks beside the deviations listed in column (3b) and (4b), these deviations are uniformly significant.

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[20] Primary regression results appear as Table C1 in Appendix C.
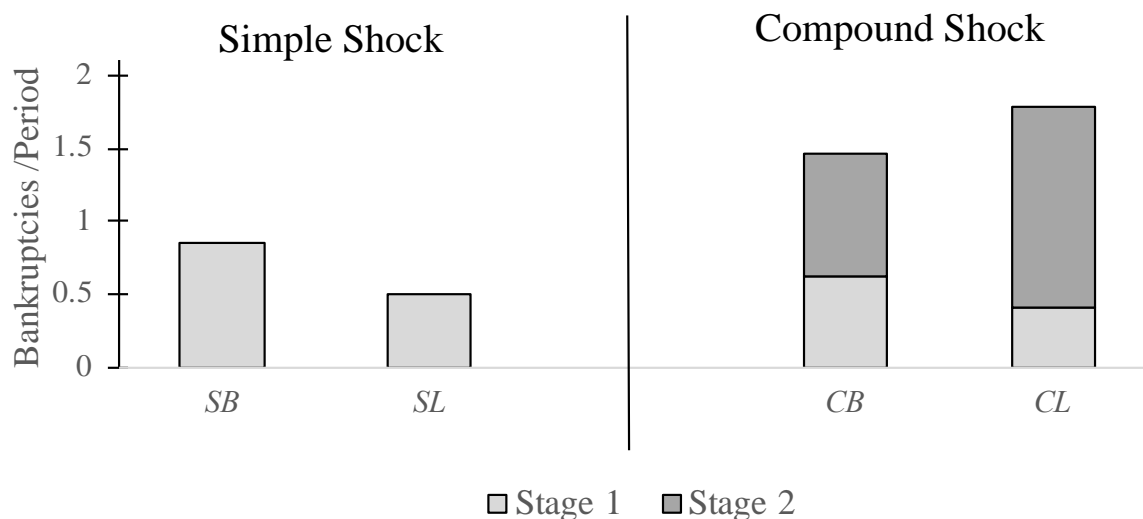
Figure 4. Bankruptcy rates for all idiosyncratic shock periods and for stage 2 periods where a second-stage shock occurred.

The across-treatment differences, listed in columns (5) and (6) of Table 2, highlight the high costs of the liquidity requirement in terms of forgone investment. In the simple shock environment, the liquidity regulations reduce initial investment by 17.02 assets, more than half of the 32-asset gain that interbank trade allows compared with autarky. Similarly, liquidity regulation cuts initial investment by 7.81 assets in the compound shock environment, only slightly less than half the 16-asset gain in investment that interbank trade allows compared with autarky.

In summary, interbank exchange motivates banks to invest at levels above those consistent with autarkic narrow banking. In the simple shock treatments, banks exhibit no generic tendency to invest at above sustainable equilibrium levels and, in fact, tend to hold too much cash on average. In the compound shock treatments, although banks do exhibit a modest propensity to over-invest relative to the no-exposure equilibrium benchmark predictions, they do not coordinate on exposure equilibria. Turning to the effects of a liquidity requirement, we observe that the requirement dramatically reduces initial investments in both the simple shock and compound shock regimes, reducing in each case the potential gains from exchange that interbank trade allows compared with autarky by roughly 50 percent.

5.2 Bankruptcies. The bars in Figure 4 illustrate the average incidence of bankruptcies. Looking first across the figure generally, observe that bankruptcies occurred frequently. In each

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treatment, an average of at least one bank suffered bankruptcy every second period. Turning to the simple shock environment, shown in the left half of the figure, notice that despite failing to improve the efficiency of initial investment decisions, liquidity regulations do noticeably reduce the incidence of bankruptcies. The mean incidence of bankruptcies in the SL treatment is considerably lower than in the SB counterpart. In the compound shock treatment, summarized in the right panel of the figure, we distinguish stage 1 and stage 2 bankruptcies with light and dark gray bars, respectively. To coherently reflect the consequences of a second-stage shock realization, stage 2 bankruptcy rates are calculated *only* for those periods where a second-stage shock occurred. Notice first that, as in the simple shock environment, liquidity restrictions in the compound shock treatment do reduce the incidence of first-stage bankruptcies. The regulations, however, do nothing to improve the capacity of banks to respond to a second-stage shock. Although second-stage bankruptcy rates are high in the CB regime, these rates nearly double in the second stage of the CL treatment.

To assess quantitatively the effects of a liquidity requirement on bankruptcies, we conduct a series of OLS regressions that estimate the number of bankruptcies occurring per period following the first-stage shock, following the second-stage shock, and overall. For first-stage bankruptcies, we regress bankruptcies per period against the indicator variables in equation (1). In the simple shock treatments as well as in those periods in the compound shock treatment where no second-stage shock subsequently occurred, all bankruptcies occur following the first-stage shock, so first-stage bankruptcies are equivalent to total bankruptcies. In those compound shock treatment periods with a realized second-stage shock, we regress both second stage and overall bankruptcies against the first two variables in (1). In all regressions we again cluster the data by markets and use a robust (White "sandwich") estimator to control for possible unspecified autocorrelation or heteroscedasticity. Table 3 reports treatment averages as linear combinations of coefficients from primary regression results.[21] From the overall results printed in the top panel of the table, observe that in the simple shock environment, liquidity-regulated banks suffered 0.34 fewer bankruptcies than did unregulated banks in the baseline treatment (difference significant at $p<.01$). In the compound shock environment summarized in the bottom two rows of Table 3, notice in column (2) that following the first-stage shock, the incidence of bankruptcies again falls in the liquidity-regulated regime, although the difference

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[21] Primary regression results appear as Table C.2 in Appendix C.

(1)	(2)		Periods with a 2nd Stage Shock			
Treatment	1st Stage		(3) 2nd Stage		(4) Total†	
	Rate	*B* vs. *L*	Rate	*B* vs. *L*	Rate	*B* vs. *L*
Simple Shock Environment						
SB	0.85					
SL	0.51	0.34***				
Compound Shock Environment						
CB	0.68		0.86		1.47	
CL	0.45	0.23	1.38	-0.52**	1.77	-0.30

Table 3. Average bankruptcies per period. Note: *, **, ***, indicates that the bankruptcy rate in the Baseline treatment significantly differs from the rate for the comparable Liquidity Requirement treatment at $p<.10$, $p<.05$, and $p<.01$, respectively.† Total bankruptcy rates in column (4) do not exactly decompose into entries in columns (2) and (4) because the estimates in (2) are based on all compound shock periods, while (3) and (4) are based only on periods with a second-stage shock realization.

across the CB and CL treatments is smaller than in the simple shock environment, at 0.23 fewer bankruptcies, and not significantly different from zero.[22] As seen in column (3), however, following the realization of a second-stage shock, the incidence of bankruptcies is considerably higher in the CL treatment than in the CB counterpart, at 0.52 banks (a difference significant at $p<.05$). The very high incidence of bankruptcies following the realization of a second-stage shock erases entirely the beneficial effects of liquidity regulation observed in the simple shock environment. In fact, the incidence of bankruptcies in compound shock treatment periods where a second-stage shock occurred is 0.30 banks higher in the CL treatment than in the CB treatment, although this difference is not significant.

In summary, we find that in the simple shock environment, liquidity restrictions do reduce the incidence of bankruptcies. In the compound shock environment, the liquidity regulation may again reduce the incidence of bankruptcies following a first-stage shock, although the effect is weaker than in the simple shock environment. The overall incidence of bankruptcy in the compound shock environment, however, is no lower in the liquidity-regulated treatment than in the baseline, because banks in the CL treatment respond so poorly to the realization of a second shock.

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[22]The difference in bankruptcy rates between the CL and CB regimes just misses significance ($p<.105$).

(1) Treatment	(2) $\overline{inv}_m$	(3) i_{ne}	(4) $\overline{inv}_m$-i_{ne}	(5) SB-SL	(6) CB-CL
SB	56.90	64	-7.10***		
SL	42.33	48	-5.67***	14.56***	
CB	42.88†	48	-5.12***		
CL	35.85†	40	-4.15***		7.03***

Table 4. Mature investments. $\overline{inv}_m$ denotes mean mature investment and i_{ne} denotes benchmark investment for the no-exposure SPNE in each treatment.
Note: *, **, and *** indicate rejection of the null hypothesis that the listed difference equals zero, at $p<0.10$, 0.05, and 0.01, respectively. $\overline{inv}_m$ exceeds the autarkic level of 32 units at $p<0.01$ in all cases. † CB and CL results are averages of shock and no-shock periods.

5.3. Mature Investments. We refer to investments that are not liquidated owing to bankruptcy as mature investments, that is, those that make it to maturity. The light gray bars in Figure 2 illustrate mature investment outcomes in each treatment. Like initial investments, mature investments move with the sustainable equilibrium benchmarks for each treatment. Unlike initial investments, however, mature investments fall below maximum sustainable levels in all treatments, and often by large amounts.

Table 4 reports linear combinations of OLS regression estimates of mature investment outcomes on the indicator variables for treatments specified above in equation (1).[23] In the simple shock envirionment, the deviation from the equilibrium benchmark level is 7.10 assets in the SB treatment and 5.67 assets in the SL treatment (differences from zero both significant at $p<.01$). In the compound shock environment, deviations of mature investments for the no-exposure equilibrium benchmark for each treatment shift from the roughly 2 units in excess of the benchmark for initial investments to 5.12 assets below the benchmark in the CB treatment and 4.15 assets below it in the CL treatment (differences from zero both significant at $p<0.01$).[24]

Comparing initial and mature investments within treatments allows an evaluation of bankruptcy costs in terms of assets. These differences are seen visually by comparing the heights

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[23] Primary regression results appear in Table C1 of Appendix C. Reported results vary slightly from equation (1) in that we generated separate estimates for compound shock periods with and without second-stage shocks, and then generated the average treatment effect by taking the average of shock and no-shock estimates for each treatment. This adjustment allows us to control for the effects of differences in the number of second-stage shock realizations across treatments.

[24] In the periods with a second shock, mature investments fell even further below maximum sustianable levels, at 8.45 assets below msi in the CB treament and 7.54 assets below msi in the CL treatment

of the dark and light gray bar pairs in Figure 3. More quantitatively, they are the difference between column 2 in Table 2 and column 2 in Table 4. In the baseline (unregulated) treatments, 5.18 assets were lost as a result of bankruptcies in the simple shock environment, while 7.27 assets were lost due to bankruptcies in the compound shock treatment. Turning to treatments with liquidity requirements, observe that the requirements led to relatively modest gains in asset maturity rates, illustrated in Figure 3 as the difference in the gaps between bar pairs across baseline and liquidity-regulated treatments. In the simple shock environment, liquidity restrictions reduced the cost of bankruptcies by about half, from a 5.19 asset loss in the SB treatment to a 2.73 asset loss in the SL treatment. In the compound shock treatment, liquidity restrictions helped even less, reducing bankruptcy costs from 7.27 assets in the CB treatment to 6.49 assets in the CL treatment.[25]

The very sizable reductions in initial investments that the liquidity requirements impose dwarf these modest maturity rate improvements. The across-treatment differences, listed in columns (5) and (6) of Table 4, highlight the high costs of the liquidity requirement in terms of mature assets. In the simple shock environment, 14.56 fewer mature assets are realized in the SL environment than in its unregulated SB counterpart. The difference is just less than half of the 32-asset gain that interbank trade allows compared with autarky. Similarly, in the compound shock treatment, 7.03 fewer mature assets are realized in the CL treatment than in the CB treatment, again slightly less than half of the 16-asset increase that interbank trade allows compared with autarky.

In summary, combining initial investment decisions with bankruptcies, we find that liquidity restrictions lead to dramatic reductions in mature assets. In both the simple and compound shock environments, the liquidity regulations yield modest reductions in assets lost due to bankruptcies. These gains, however, are dwarfed by the substantial reduction in initial investments that the liquidity requirements impose. In both the simple shock and the compound shock environments, liquidity restrictions reduce by roughly half the potential gains from exchange that interbank trade allows compared with autarky.

5.4 LCR Regulations and Liquidity Management Decisions. The above results raise a series of questions, the most pressing of which regard bankruptcies. First, in the simple shock

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[25] If we confine attention to periods in which a second-stage shock occurred, liquidity regulations reduced asset losses from bankruptcy even less, from 10.6 in the CB treatment to 9.88 assets in the CL treatment.

treatment, what explains the high incidence of bankruptcies when collective initial investments on average are less than the maximum sustainable level? Second, in both the simple shock environment, and in the first stage of the compound shock environment, why does the liquidity requirement reduce the incidence of bankruptcies? Third and finally, why are liquidity-regulated banks so frequently less prepared to respond to a second-stage shock than in the counterpart baseline treatment? This subsection addresses these interrelated questions.

Consider first the factors that drive bankruptcies in the simple shock environment. The interbank market is distinct from more standard investment games in that investment decisions, combined with subsequent shocks, create both the supply of and demand for cash.[26] In this context, banks effectively play a complicated coordination game in which they maximize profits only when they invest exactly at the maximally sustainable level. Collective over-investment yields a collective cash deficiency post-shock, which drives asset prices to their minimum, forcing bankruptcies in the process. Collective under-investment yields an aggregate cash surplus, driving asset prices to their upper bound, and reducing to zero the return on cash acquired through interbank exchange.

In fact, although supported by an SPNE, the efficient solution has little explanatory power. The distributions of realized net needs for the simple shock treatments are shown in Figure 5. In the figure, "realized net needs" reflect the aggregate need for reserves following a shock and the subsequent trade of cash for assets. Net needs of zero indicate an efficient outcome, negative net needs indicate an excess of available cash, while positive net needs reflect instances of collective cash deficiencies and the consequent bankruptcies. As can be seen in the figure, in both the SB and SL treatments investment decisions collectively resulted in the efficient solution in no more than 25 percent of periods.

The high incidence of bankruptcies in the simple shock environment is driven largely by the heterogeneity of initial individual investment decisions. This heterogeneity generated a high frequency of periods where banks collectively held too little cash. Comparing realized net need

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[26] DKL explore this issue in more detail.
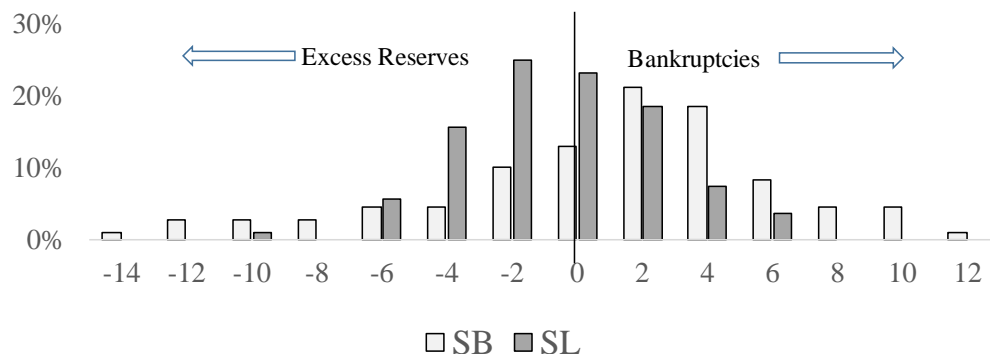
Figure 5. Distribution of realized net cash needs in the simple shock environment

distributions across treatments further suggests why liquidity requirements reduce bankruptcies in the simple shock environment: net need realizations in the SB treatment are considerably more variable and thus yield more periods with larger deficiencies. Liquidity restrictions contract the effective investment strategy space for banks from [4, 12] assets to [4, 8] assets.[27] This reduction reduces the range of individual investment decisions and, in this way, the range of collective investment outcomes. We note also that the distribution of realized net needs for the SB treatment are shifted slightly to the right of that for the SL treatment. The increased variability of investment outcomes may also contribute to this rightward shift, since the high variability may induce increased caution in the cash availability decisions on the part of those banks with cash post-shock, which have an interest in keeping the post-shock asset price at $1.

Regression estimates of realized cash deficiency incidences in the SB and SL treatments listed in the top two rows of Table 5 provide a summary measure of the effects of liquidity regulation in the simple shock environment.[28] As shown in the table, the banking system

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[27] In the experiment sessions, we restricted investment to be at least 4 assets because investment fewer than 4 is strictly dominated in expectation, and allowing this option would only generate an added variability induced by confusion.

[28] We report linear probability estimates for ease of interpretation. Probit estimates yield similar results. These estimates use as regressors the combinations of indicator variables in equation (1). As with Tables 2-4, the treatment averages reported in Table 5 are generated by assembling coefficient estimates, and Wald tests are subsequently used to assess differences across treatments. Primary regression results appear as Table C3 of Appendix C. Results using a probit estimation procedure appear as Tables C4 and C5 of Appendix C.

Treatment	(1) Realized	(2) Initial	(3) Withholding Induced
Simple Shock Environment			
SB	51.85%	38.89%	28.70%
SL	29.63%[***]	14.8%[***]	21.20%
Compound Shock Environment 1st Stage			
CB	38.90%	55.60%	13.89%
CL	31.50%	65.70%	5.50%[*]
Compound Shock Environment 2nd Stage			
CB	53.00%	40.15%	25.00%
CL	79.8%[**]	75.12%[***]	25.90%

Table 5. Incidences of aggregate cash deficiencies. Note that: [*], [**], and [***] indicate rejection of the null hypothesis that the incidences of cash deficiencies for the Baseline and Liquidity Requirement treatments do not significantly differ, at $p<0.10$, 0.05, and 0.01, respectively.

experienced an aggregate cash deficiency in 51.85 percent of SB treatment periods, compared with 29.63 percent of SL treatment periods (difference significant at $p<0.01$).

Two factors contribute to the realized net needs shown in column (1): initial investment decisions, where collective over-investment can result in cash shortages in the banking system, and a strategically motivated sort of hoarding behavior intended to keep asset prices low.[29] The estimates of initial and withholding-induced net need incidences shown in columns (2) and (3) of Table 5 reveal that, to a large extent, the higher incidence of bankruptcies in the SB treatment is driven by initial investment decisions. As seen in column (2), following initial investment decisions, banks collectively held insufficient reserves in only 14.8 percent of SL periods, compared with 38.89 percent of SB periods (difference significant at $p<0.01$). Turning to column (3), observe that the incidence of increased reserve deficiencies due to post-shock withholding was also somewhat higher in the SB treatment (28.70 percent in the SB treatment, vs. 21.20 percent in the SL treatment).[30] The difference, however, is comparatively small and not

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[29] Note that the incidences of initial and withholding-induced cash deficiencies do not sum to the incidence of realized cash deficiencies. A withholding-induced deficiency arises when the total cash deficiency in a period exceeds an initial cash deficiency. Thus, instances of initial and withholding-induced cash deficiencies can occur in the same period.

[30] The increased incidence of withholding-induced deficiencies in the SB treatment is quite possibly also due to the higher variability of initial investment outcomes. Large variations in announced cash needs across periods may

statistically significant. Thus, we conclude that in the simple shock environment, the high incidence of bankruptcies is driven primarily by the heterogeneity of investment decisions across periods. Liquidity restrictions reduce the variability of collective investment outcomes and, as a consequence, reduce the incidence of periods where the cash needs of banks go unsatisfied. Consider next the effect of liquidity requirements in the compound shock environment. The critical additional observation in this case is that liquidity restrictions substantially increase the complexity of banks' equilibrium investment strategies. In the CB treatment, coming to appreciate that banks must boost cash buffers to address a possible second-stage shock requires a fairly straightforward assessment: the additional $2 needed in the symmetric SPNE is simply each bank's expected liability in the case of an aftershock. In the CL regime, however, the reasoning supporting the equilibrium adjustment is considerably more involved. Here, because banks must maintain $4 in reserves, they must on average hold an additional $3, a total that can be determined only by reasoning recursively from cash needs in the second stage. Given the added complexity of equilibrium play in the CL treatment, it would be unsurprising to observe weaker conformance with equilibrium behavior.[31]

The distributions of realized net needs for the compound shock treatments, shown as Figure 6, illustrate clearly the behavioral consequences of the additional complexity that liquidity requirements create. As seen in the upper panel of the figure, in the first stage, realized net needs are again more heterogeneous in the unregulated CB, as was the case for the baseline treatment in the simple shock environment. Moving to the bottom panel, however, observe that in the second stage, CL banks quite generally find themselves with cash buffers insufficient to respond to a second-stage shock.[32]

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complicate the process of learning appropriate cash supply responses. To avoid the risk of driving the period 1 asset price to $2, banks with excess cash may curtail their offers.

[31] Essentially, this is an implication of the taxi stand analogy of the effects of liquidity requirements famously articulated by Milton Friedman, Charles Goodhart, and others (see, for example, Goodhart, 2008). Following a first-stage shock, liquidity-regulated banks all have at least $4 in cash because of the regulation. Post-shock, however, banks with excess cash can't make that cash available to a bank needing liquidity, even if holding the cash will force insolvency on the liquidity-deficient bank, since the law requires that taxis (required cash) remain at the station even in the worst crises (downpour). What seems not to be obvious to our players is that because of the liquidity requirement, they must hold even more cash than would be needed in the unregulated case in order for the banking system to have liquidity sufficient to address a shock.

[32] The bottom panel of Figure 6 illustrates realized net needs only for periods in which a second-stage shock is realized. Absent a second-stage shock, net needs are by definition zero.
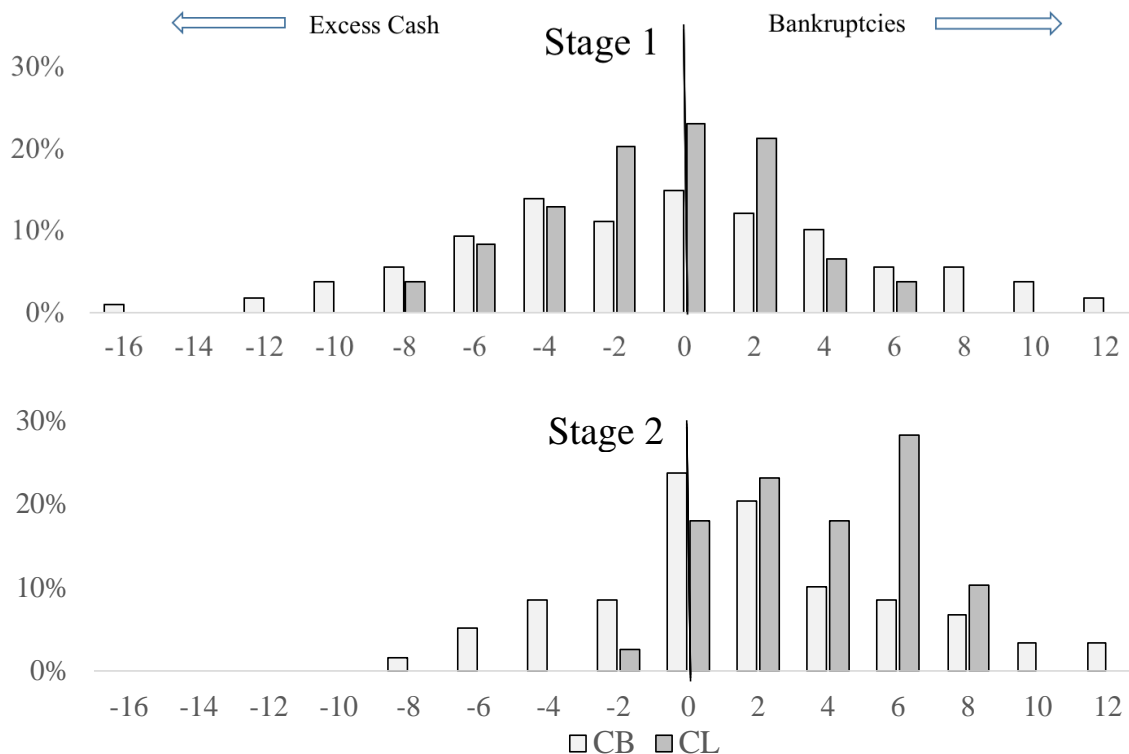
Figure 6. Distribution of net realized cash needs in the complex environment for both stages.

Regression estimates of incidences of net cash deficiency for the compound shock treatments, shown in the middle and bottom panels of Table 5, both summarize these effects overall and allow some insight into the relative importance of hoarding behavior in the compound shock environment.[33] Looking first in column (1) in the middle panel of Table 5, notice that realized cash deficiencies following the first-stage shock are a bit higher in the CB treatment (at 38.9 percent) than in the CL treatment (at 31.5 percent). While positive, this difference is considerably smaller than in the simple shock environment and not significant at conventionally accepted levels.

Separating the factors driving realized cash deficiencies in the first stage of the compound shock treatment, columns (2) and (3) of Table 5 reveal a markedly different response to an idiosyncratic shock among the liquidity-regulated banks from that observed in the simple shock environment. Unlike the case of the unregulated simple shock environment, the higher incidence

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[33] Parallel to the data used in generating the lower panel of Figure 6, linear probability estimates, for the second stage of the compound shock treatments, limit observations to periods in which a second-stage shock occurred, and estimate only the effect of switching from baseline to the liquidity-regulated regime.

of realized cash deficiencies in the first stage of the unregulated compound shock environment is driven by an increased incidence of withholding-induced deficiencies (rather than by an increased propensity for unregulated banks to initially over-invest). In fact, the incidence of initial cash deficiencies in the CB treatment (at 55.6 percent) was 10.1 percentage points *lower* than in the CL counterpart (at 65.7 percent). Instead, withholding-induced cash deficiencies occurred in 13.89 percent of CB periods, compared with only 5.10 percent of CL periods (difference significant at $p<.10$).

Thus, in the first stage, liquidity-regulated banks initially over-invested more frequently, in the sense that they collectively failed to maintain a cash buffer necessary to keep the banking system solvent in the event of a second-stage shock. Then, following the first-stage shock, the liquidity-regulated banks tended to further deplete their cash buffers by making too much of their limited cash available.[34]

Combined with buffers that are initially too small to address a second-stage shock, the use of these buffers by liquidity-regulated banks to address first-stage liquidity needs comes at the cost of making the banking system chronically unprepared for a second-stage shock. As seen in column (1) in the bottom rows of Table 5, the 79.7 percent incidence of realized aggregate cash deficiencies in the CL treatment is nearly 27 percentage points higher than the 53.0 percent aggregate cash deficiency rate in the in the CB treatment. The difference is driven entirely by the cash deficiency at the beginning of the second stage. In the CB treatment, the banking system held insufficient cash to address a second-stage shock in 40.15 percent of periods, compared with a 75.12 percent rate in CL treatment periods. Second-stage hoarding behavior also occurred in both the CB and the CL treatment periods; however, the incidences of withholding-induced shortages are virtually identical in each treatment (25.00 percent in CB vs. 25.90 percent in CL).

In summary, in the compound shock environment, liquidity requirements increase the difficulty of identifying the equilibrium investment strategy. In the first stage, liquidity-regulated banks frequently invest too much initially in the sense that they hold cash buffers too small to cope with the event of a second-stage shock. Subsequently, liquidity-regulated banks

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[34] The incidences of initial cash deficiencies for the compound shock treatments listed in column 2 of Table 5 reflect the frequency of periods in which banks collectively held buffers insufficient to respond to both an initial and a second-stage shock (for example, $16 in the CB treatment and $8 in the CL treatment). The incidences of withholding-induced deficiencies reported in column (3) indicate periods in which banks with sufficient second-stage buffers created or exacerbated deficiencies in their first-stage solvency needs ($8 in the CB treatment and $4 in the CL treatment) by withholding cash.

often hoard less following the initial shock. Combined, these tendencies reduce the incidence of stage 1 bankruptcies, but at the cost of chronically deficient buffers for the possible stage 2 shock. As a consequence, liquidity-regulated banks experience markedly higher bankruptcies following the occurrence of a second-stage shock.

6. Conclusions

This paper reports an experiment conducted to examine the capacity of a liquidity requirement to improve the stability of an interbank market, as well as the costs in terms of forgone liquidity transformation. In a simple shock environment, where the banking system is subject to a predictable shock each period, we find that the liquidity requirement does, to some extent, reduce the incidence of bankruptcies, largely because the liquidity requirement reduces the heterogeneity of aggregate investment outcomes. In a more complex compound shock environment, where an initial idiosyncratic shock is followed by a stochastically occurring second shock, liquidity requirements have little effect on the incidence of bankruptcies. A slightly reduced incidence of bankruptcies among liquidity-regulated banks following an idiosyncratic shock is offset by a general propensity for these banks to be chronically unprepared for a second-stage shock. Additionally, in both environments, the liquidity requirements impose a very high cost in terms of forgone investment. In each environment, on net, liquidity requirements reduce by about half the potential gains from exchange that interbank trade allows compared with autarky.

Although we found that there were costs to liquidity requirements in our experiment, we do not view our results as a cost-benefit analysis of liquidity regulations. The streamlined environment studied here is hardly a realistic description of existing interbank markets. The number of banks is small, the liquidity shocks are very large, the money supply is fixed, and there is no central bank. Moreover, we force interbank markets to operate by asset sales rather than loans and impose a stylized uniform price trading mechanism.

Instead, we view our experiment as providing two things. First, it identifies qualitative factors such as heterogeneous investment behavior, forgone investment opportunities, challenges in preparing for a large liquidity shock, and coordination problems in reallocating liquidity that could impact the evaluation of liquidity regulation. Second, it is an initial step toward designing market experiments that are useful for analyzing interbank markets. Future experimental work could build on our experiments to incorporate features such as more banks, different shock

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patterns, interbank network features as in Craig and Ma (2018) or Babus and Kondor (2018), or bilateral lending as in Afonso and Lagos (2015a,b).

References

Acharya, Viral V., Denis Gromb and Tanju Yorulmazer. (2012). "Imperfect Competition in the Interbank Market for Liquidity as a Rationale for Central Banking." *American Economic Journal: Macroeconomics*, vol. 4, 184–217. https://doi.org/10.1257/mac.4.2.184

Acharya Viral V. and Ouarda Merrouche. (2013). "Precautionary Hoarding of Liquidity and Interbank Markets: Evidence from Subprime Crisis." *Review of Finance*, vol. 17, 107-160. https://doi.org/10.1093/rof/rfs022

Afonso, Gara, Anna Kovner and Antoinette Schoar. (2011) "Stressed, not Frozen: The Federal Funds Market in the Financial Crises." *Journal of Finance*, vol. 66, 1109-1139. https://doi.org/10.1111/j.1540-6261.2011.01670.x

Afonso, Gara and Ricardo Lagos. (2015a) "The Over-the-Counter Theory of the Fed Funds Market: A Primer." *Journal of Money, Credit and Banking,* vol. 47, 127-154. https://doi.org/10.1111/jmcb.12216

Afonso, Gara and Ricardo Lagos (2015b) "Trade Dynamics in the Market for Federal Funds." *Econometrica*, vol. 83, 263-313. https://doi.org/10.3982/ECTA10586

Allen, Franklin, Elena Carletti and Douglas Gale. (2009). "Interbank Market Liquidity and Central Bank Intervention." *Journal of Monetary Economics*, vol. 56, 639–652. https://doi.org/10.1016/j.jmoneco.2009.04.003

Allen, Franklin and Douglas Gale. (2004a). "Financial Intermediaries and Markets." *Econometrica*, vol. 72, 1023-1061. https://doi.org/10.1111/j.1468-0262.2004.00525.x

Allen, Franklin and Douglas Gale. (2004b). "Financial Fragility, Liquidity and Asset Prices." *Journal of the European Economic Association*, vol. 2, 1015-1048. https://doi.org/10.1162/JEEA.2004.2.6.1015

Armentier, Olivier and Charles A. Holt. (2017). "Discount Window Stigma: An Experimental Investigation" Manuscript.

Ashcraft, Adam, James McAndrews and David Skeie. (2011). "Precautionary Reserves and the Interbank Market." *Journal of Money Credit and Banking*, vol. 43, 311-348. https://doi.org/10.1111/j.1538-4616.2011.00438.x

Babus, Ana and Peter Kondor. (2018). "Trading and Information Diffusion in Over-the-Counter Markets." Paul Woolley Centre Working Paper No. 57.

Bhattacharya, Sudipto and Douglas Gale (1987) "Preference Shocks, Liquidity and Central Bank Policy," in W.A. Barnett and K.J. Singleton, eds., *New Approaches to Monetary Economics*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511759628.005

Bosch-Rosa, Ciril. (2018). "That's How We Roll: An Experiment on Rollover Risk." *Journal of Economics Behavior & Organization,* vol. 145, 495-510. https://doi.org/10.1016/j.jebo.2017.11.005

Carlson, Mark A. (2013). "Lessons from the Historical Use of Reserve Requirements in the United States to Promote Bank Liquidity." FEDS Working Paper 2013-11. https://doi.org/10.2139/ssrn.2245601

Craig, Ben and Yiming Ma. (2018). "Intermediation in the Interbank Lending Market." Manuscript, Stanford Graduate School of Business.

Davis, Douglas and Charles A. Holt. (1993). *Experimental Economics.* Princeton: Princeton University Press.

Davis, Douglas, Oleg Korenok and John Lightle. (2018a). "Liquidity Regulation after Financial Crisis: An Experimental Investigation." Manuscript, Virginia Commonwealth University.

Davis, Douglas, Oleg Korenok and John Lightle. (2018b). "An Experimental Examination of the Interbank Loan Market." Manuscript, Virginia Commonwealth University.

Davis, Douglas, Oleg Korenok and Edward Simpson Prescott. (2014). "An Experimental Analysis of Market-based Contingent Capital Triggering Mechanisms." *Journal of Money, Credit and Banking*. vol. 46, 999-1033. https://doi.org/10.1111/jmcb.12132

Davis, Douglas and Edward Simpson. Prescott. (2017). "Fixed Prices and Regulatory Discretion as Triggers for Contingent Capital Conversion: An Experimental Examination." *International Journal of Central Banking,* vol. 13, 33-71.

Davis, Douglas and Robert J. Reilly. (2016). "On Freezing Depositor Funds at Financially Distressed Banks: An Experimental Analysis." *Journal of Money Credit and Banking*, vol. 48, 989-1017. https://doi.org/10.1111/jmcb.12324

Diamond, Douglas W. and Philip H. Dybvig. (1983). "Bank Runs, Deposit Insurance and Liquidity." *Journal of Political Economy,* vol. 91, 401-419. https://doi.org/10.1086/261155

Diamond, Douglas W. and Anil K. Kashyap. (2016). "Liquidity Requirements, Liquidity Choices and Financial Stability." In *Handbook of Macroeconomics, Vol. 2A.* (Eds. John B. Taylor and Michael Woodford). Amsterdam: North-Holland, 2263-2304. https://doi.org/10.1016/bs.hesmac.2016.03.011

Diamond, Douglas W. and Raghuram G. Rajan. (2011). "Fear of Fire Sales, Illiquidity Seeking and Credit Freezes." *Quarterly Journal of Economics*, vol. 126, 557–591. https://doi.org/10.1093/qje/qjr012

De Nicolo, Gianni, Andrea Gamba and Marcella Lucchetta. (2012). "Capital Regulation, Liquidity Requirements and Taxation in a Dynamic Model of Banking." IMF Working Papers 12/72, International Monetary Fund. https://doi.org/10.5089/9781475502244.001

Duffie, Darrell. (2012). *Dark markets: Asset Pricing and Information Transmission in Over-the-Counter Markets*. Princeton, NJ: Princeton University Press. https://doi.org/10.1515/9781400840519

Duffie, Darrell, Nicolae Garleanu and Lasse Heje Pedersen. (2005), "Valuation in Over-the-Counter Markets." *Review of Financial Studies*, vol. 20, 1865-1900. https://doi.org/10.1093/rfs/hhm037

Duffie, Darrell, Nicolae Garleanu and Lasse Heje Pedersen. (2005). "Over-the-Counter Markets." *Econometrica*, vol. 73, 1815-1847. https://doi.org/10.1111/j.1468-0262.2005.00639.x

Fischbacher, Urs. (2007). "z-Tree: Zurich Toolbox for Ready-Made Economic Experiments." *Experimental Economics*, vol. 10, 171-178. https://doi.org/10.1007/s10683-006-9159-4

Freixas, Xavier, Antoine Martin and David Skeie. (2011). "Bank Liquidity, Interbank Markets and Monetary Policy." *Review of Financial Studies*, vol. 24, 2656-2692. https://doi.org/10.1093/rfs/hhr018

Gale, Douglas and Tanju Yorulmazer. (2013). "Liquidity Hoarding." *Theoretical Economics*, vol. 8, 1555-1561. https://doi.org/10.3982/TE1064.

Goodfriend, Marvin and Monica Hargraves. (1983). "A Historical Assessment of the Rationales and Functions of Reserve Requirements." Federal Reserve Bank of Richmond *Economic Review*, vol. 69 (2), 3-21. https://doi.org/10.2139/ssrn.2117964

Goodhart, Charles A.E. (2008). "The Regulatory Response to the Financial Crisis." *Journal of Financial Stability*, vol. 4, 351-358. https://doi.org/10.1016/j.jfs.2008.09.005

Greiner, Ben. (2015). "Subject Pool Recruitment Procedures: Organizing Experiments with ORSEE." *Journal of the Economic Science Association*, vol. 1, 114-125. https://doi.org/10.1007/s40881-015-0004-4

Hartley, Peter. R. (1998). "Inside Money as a Source of Investment Finance." *Journal of Money, Credit and Banking,* vol. 30(2): 193-217. https://doi.org/10.2307/2601209

Heider, Florian, Marie Hoerova and Cornelia Holthausen. (2015). "Liquidity Hoarding and Interbank Market Spreads: The Role of Counterparty Risk." *Journal of Financial Economics*, vol. 118, 336–354. https://doi.org/10.1016/j.jfineco.2015.07.002

Ivashina, Victoria and David Scharfstein. (2010). "Bank Lending during the Financial Crisis of 2008." *Journal of Financial Economics*, vol. 97, 319-338. https://doi.org/10.1016/j.jfineco.2009.12.001.

Kowalik, Michal. (2013). "Basel Liquidity Regulation: Was it Improved with the 2013 Revisions?" Federal Reserve Bank of Kansas City *Economic Review* (Second Quarter): 65-87.

Sprague, O.M.W. 1910. *History of Crises Under the National Banking System*. Washington D.C.: U.S. Government Printing Office.