Precautionary Hoarding of Liquidity and Interbank Markets: Evidence from the Sub-prime Crisis*

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JEL: G21, G28, E42, E58

Keywords: liquidity, counterparty risk, money market, funding risk, rollover risk

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Abstract: We study the liquidity demand of large settlement banks in the UK and its effect on the money markets before and during the sub-prime crisis of 2007-2008. We find that the liquidity demand of large settlement banks experienced a 30% increase in the period immediately following August 9, 2007, the day when money markets froze, igniting the crisis. Following this shift, liquidity demand had a precautionary nature in that it rose on days of high payment activity and for banks with greater credit risk. This caused overnight interbank rates to rise, an effect virtually absent in the pre-crisis period.

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1. Introduction

The financial crisis of 2007–2009 has highlighted the important role played by money markets[1] (short-term borrowing and lending markets between banks and bank-like institutions) in allocating liquidity around the financial system. Globally, these markets experienced severe stress starting on August 9, 2007. On this date, BNP Paribas suspended withdrawals from some of its hedge funds invested in sub-prime mortgage-backed securities due to the inability to mark these assets to market. The result was a freeze in the market for wholesale funding, most notably, in the market for asset-backed commercial paper. This, in turn, caused rollover problems for structured investment vehicles and conduits set up by banks as off-balance sheet vehicles for liquidity and regulatory arbitrage purposes. As the wholesale funding liquidity dried up, banks had to take the risk of assets from structured investment vehicles and conduits they sponsored back on their balance sheets (e.g., Acharya et al., 2009). In the period that followed, interbank markets for borrowing and lending also seemed to get adversely affected.

Interbank markets are generally the private lender-of-last-resort for banks' short-term liquidity needs. Inadequate liquidity flow through these markets has the potential to substantially impair real and financial sectors. For instance, if liquidity does not get channeled through the banking system to its most efficient use, then intermediation to households and corporations could stagnate. In addition, central banks' transmission mechanisms for monetary policy could be rendered less effective if its liquidity provision gets trapped on the balance-sheets of some banks instead of lubricating the flow of credit

[1] Throughout the paper we use the terms "*money market*" and "*interbank market*" interchangeably.

among banks. In turn, central banks may be forced to resort to emergency lending operations, as was done by the New York Federal Reserve, the Bank of England (BoE), the European Central Bank (ECB), and other central banks during the crisis.

Our paper is an attempt to understand some of these effects by examining the bank demand for liquidity and its effect on interbank markets during the crisis. We hypothesize and confirm a precautionary motive to liquidity demand by banks during this period and investigate its causal effect on interbank rates.[2] Our broad conclusion is that events unfolding since August 9, 2007 increased the funding or rollover risk of banks, in response to which banks, especially the weaker ones, hoarded liquidity. Given their increased opportunity cost of giving up liquidity to other banks, interbank rates rose in *both* secured and unsecured markets, suggestive of interest rate contagion through the interbank market.

Specifically, we study the liquidity demand of large, settlement banks in the UK and its effect on sterling money markets before and during the sub-prime crisis – from January 2007 till the end of June 2008. We focus on settlement banks since they can be considered the market makers for money. In other words, most payment flows occur through these banks. Hence, studying their demand for liquidity in response to the risks they face and how this demand affects market-wide and bank-specific interbank rates provides a natural setting to answer various questions. We examine bank liquidity in terms of their reserve balances with the central bank and the price of this liquidity in terms of overnight

[2]Such a motive and its effect on markets and the economy have been mentioned often since the inception of the crisis. See, for example, *Financial Times,* August 12, 2007, "Scramble for cash reflects fears for system"; *Financial Times,* March 26, 2008, "Hoarding by banks stokes fear over crisis"; and *Financial Times,* May 19, 2008, "Loans to banks limited despite market thawing."

interbank rates.

The reserve balances held by banks at a central bank can be understood as their "checking accounts." A bank's portfolio decision involves whether to keep reserves in the form of liquid balances in its checking account for ready draw-down during the day to meet payments; or, to have illiquid claims by extending its own reserves to others in the economy in the form of loans to households and corporations and, to other banks through interbank markets, purchasing assets such as mortgage-backed securities, and so forth. Each financial transaction taking place in the economy (e.g., a retail depositor withdrawing from an ATM or a corporation depositing into a money market fund) involves a "debit" from some bank's reserve balance and "credit" into another bank's balance.

Not all banks at each point in the day necessarily have the reserves to meet all of their payment activity. Hence, they use the interbank market to exchange reserves. In turn, the total financial activity in the economy ends up being a large multiplier of the quantity of circulating reserves. For instance, aggregate reserves of £20 billion can support over £1 trillion of transaction activity and, conversely, a reduction in the mobility of a small quantity of reserves can slow down transaction activity by a significant multiplier.

While the aggregate reserves in the economy stay constant (unless altered by the central bank), by and large a few banks –typically the large ones – play a bigger role in these transactions and determine the price at which reserves are exchanged in the interbank market. Banks have access to the central bank's discount window to borrow reserves overnight, but at a penalty. Generally such borrowing is also associated with the stigma where, if borrowing in isolation, a bank may be perceived to be riskier than others, triggering a run on the bank.[3]

Thus, in practice, it is often not the central bank's lending rate at the discount window that ends up determining banks' opportunity cost in lending reserves to others. Instead, this opportunity cost is determined by the liquidity of asset markets and wholesale borrowing markets that banks can access to meet their daily requirement of reserves. During the crisis, these markets became significantly impaired. We investigate how this affected the portfolio decisions of large, settlement banks in the UK to hold liquidity in the form of reserves and, in turn, how this affected the price at which they were willing to extend reserves in the interbank market.

Our choice of the sterling money markets is driven primarily by the fact that the BoE monetary policy framework offers an attractive way of measuring a bank's overnight liquidity as its reserves with the BoE. As we explain in Section , the remuneration offered by the BoE on these reserves (within a band) implies that it was optimal for banks to park their liquidity in the form of these reserves.[4]

Further, under the BoE monetary policy framework, banks are allowed to determine their own reserve targets at the beginning of each maintenance period (roughly a month), which the BoE subsequently meets through its open market operations (OMOs). This provides a strong and direct measure of bank *demand* for liquidity (what we term their "overnight liquidity"), allowing for its separation from fluctuations in bank reserves due

[3] Armantier et al. (2010) provide compelling evidence of the stigma attached to borrowing from the discount window during the financial crisis of 2007-2008.

[4] In contrast, the U.S. Federal Reserve did not pay interest on reserves until October 2008 so that bank liquidity over and above the reserve requirement would typically not be parked there.

to the *supply* of reserves by the central bank.[5] Finally, since we focus on reserves held by settlement banks, which form a subset of banks that hold the total reserves of the economy, there are daily shifts in our measure of settlement bank liquidity even when there is no change in the aggregate reserves in the UK economy.

As our first piece of evidence, we show that settlement bank liquidity experienced a significant upward jump upon the onset of the sub-prime crisis (see Figure 1).

As our second piece of evidence, we show that this build up of bank liquidity was precautionary in nature. First, we verify that settlement banks held more liquidity on days with greater predictable aggregate payment activity; indeed funding needs arising from idiosyncratic payments fluctuations are more easily met through borrowing from other banks in the overnight market.[6] Such a response of settlement bank liquidity to payment activity was non-existent in the pre-crisis period.

Next, we employ bank-level variations in liquidity, funding risk proxies, solvency risk proxies, and economic health during the crisis. We find that banks that during the crisis had higher funding or rollover risk, and higher solvency risk hoarded more liquidity.

[5] We also studied "total liquidity," which includes bank collateral, since under "double-duty" this can be employed for intra-day borrowing from the BoE. This collateral, which is held in fulfillment of prudential requirements, cannot, however, be used to borrow overnight on the market. Our results are qualitatively similar for overnight liquidity, as well as for total liquidity.

[6] We focus on predictable activity for the natural reason that realized activity is not known to banks at the time they set their overnight reserves. Similarly, we focus on aggregate activity, since even though no individual bank knows its own exact activity for the next day ahead of time (and, it is difficult for an econometrician to estimate this well), there are strong calendar effects in aggregate payment activity (e.g., US and UK holidays or end-of-quarter effects).

Further, these banks held more liquidity in response to increases in payment activity. Even though, on average, there was no increase in variability in payment activity in the sterling money markets during the crisis, our results confirm that, given the funding problems, settlement banks viewed the same variability of payment activity during the crisis with greater precaution. This setting therefore allows us to focus on a broader factor, that is, financial constraint driving precautionary demand, rather than factors internal to the payment system (such as an increase in the variability of payment activity).

In our third piece of evidence, we study the effect of settlement banks liquidity demand on interbank markets. To subsume any step-variations induced by policy changes, we examine spreads of the interbank rates to BoE's policy rate. We obtain secured market data (with the UK government's gilt as collateral), and unsecured market data from the British Bankers' Association and Wholesale Markets Brokers' Association and from the BoE, respectively. In normal times, the "arbitrage" hypothesis in money markets postulates that if interbank rates become higher than the BoE policy rate, then banks that experience an exogenous rise in their liquidity that day release the liquidity to other needy banks to capture the spread. This should induce a negative relation between settlement bank liquidity and interbank spreads. We call this the "arbitrage" effect. Our crucial observation is that this relation may be reversed when the rise in liquidity demand of settlement banks is *endogenous*, in particular, a precautionary response to heightened risks and funding concerns. In this case, settlement banks need to be compensated more for releasing liquidity to others. We call this the "liquidity" effect.

The results reveal a strong effect of settlement bank liquidity on interbank rates, but in a manner that differs sharply between pre-crisis and post-crisis periods. We find evidence supportive of the *liquidity* effect: the effect of liquidity is to raise overnight interbank rates in the period *during* the crisis. In contrast, the relation between liquidity and interbank rates was significantly negative in the period *prior* to the crisis, consistent with the *arbitrage* effect of settlement bank liquidity on interbank rates. It is striking that the effect of settlement bank liquidity on secured rates – in transactions secured by UK gilts – is as high and significant as on the unsecured rates, if not stronger.

We interpret these findings to imply that, since access to capital markets and wholesale borrowing in commercial paper markets was impaired for banks, especially for banks with significant rollover or credit risk, these weaker banks engaged in liquidity hoarding as a precautionary response. Such hoarding raised borrowing rates for safer banks too, suggesting a contagion-style systemic risk operating through interbank markets. In particular, the overnight sterling interbank rates in the first year of the crisis did not seem to have been driven purely by the counterparty risk concerns of lending banks about the borrowing banks. In addition, since smaller, second-tier banks borrow mainly from large settlement banks in the secured interbank market, the latter market was also substantially affected by the liquidity hoarding of large settlement banks.

Finally, we use bilateral transaction data, which allow us to more cleanly separate out the precautionary effect from the counterparty risk effect, and we find further supportive evidence for our interpretation. The rate charged by one bank to another (the bilateral spread) during the crisis is negatively associated with the borrower liquidity buffer, but more importantly, the rate is positively associated with the lender liquidity buffer: a lender who has a higher demand for liquidity during the crisis charges a higher price to release it during the crisis. This finding confirms that the positive relationship between rate and liquidity demand observed in the aggregate data during the crisis contains a precautionary demand effect. We also show that high risk banks participate less in the market (lending and borrowing less and trading with fewer counterparties), but this is true both before and during the crisis.

Our paper is most closely related to that of Ashcraft et al. (2011), who offer a theory of precautionary demand for liquidity and graphical evidence that US banks that experience more payment volatility carry higher reserves during the day, consistent with their theory for precautionary reserves being driven by unexpected payment shocks. In contrast, we provide an explanation of liquidity demand during the crisis that involves factors which are not specific to the interbank market (e.g., payment uncertainty). We focus in particular on the tightening of financial constraints for banks that causes their precautionary demand for liquidity, which anecdotally appears to have affected many markets besides the interbank market. Hence, in contrast to the evidence of Ashcraft et al. (2011), we provide an analysis of liquidity demand as a function of bank funding risk rather than just payment shocks.

Before proceeding to the remainder of the paper, we stress that our analysis stops at the end of June 2008 (when this paper was initiated). It would be no doubt interesting to examine the period after June 2008, especially around the collapse of Lehman Brothers. On the one hand, counterparty risk concerns in interbank markets – even at overnight horizons – are likely to have been a much greater concern for lending banks in this period (as shown in the fed funds market by Afonso et al., 2011). On the other hand, a large number of central bank interventions were already in place by this time to help banks manage their liquidity better and more were designed within two to four weeks of Lehman's collapse, rendering it far more difficult to isolate outcomes attributable to bank behavior rather than to policy responses. From an empirical identification standpoint, the onset of the ABCP funding freeze on August 9, 2007 provides a more attractive event.

Section provides the relevant institutional details of the UK payment system and money markets. Section documents the regime switch in liquidity reserves of banks and Section demonstrates the precautionary aspect of banks' liquidity hoarding. Section establishes the effect of liquidity hoardings on interbank rates at the aggregate and the bilateral levels. Section relates our study to additional literature and Section concludes the paper.

2. Institutional Background

This section provides important background information. Section provides an overview of the BoE monetary policy framework. Section describes the structure of the payment system and money markets in the UK, as well as institutional and operational boundaries within which banks are able to manage the liquidity requirements arising from their daily payment activity. Appendix A summarizes the range of adjustments to the framework the BoE undertook from August 2007 to restore orderly conditions in money markets.

2.1 THE MONETARY POLICY FRAMEWORK[7]

[7]This section relies heavily on "The Framework for the Bank of England's Operations in the Sterling Money Markets (The "Red Book")," available at

In May 2007 the BoE assigned the operational responsibility of monetary policy to its newly created Monetary Policy Committee (MPC). The MPC meets at least once a month to set the interest rate. The MPC is responsible for setting the appropriate rate to meet the inflation target (based on the consumer price index) set by the Chancellor of the Exchequer. The inflation target is 2%, with a 1% tolerance range. The BoE implements monetary policy by lending to the money market at the official repo rate chosen by the MPC. Eligible assets include gilts, Treasury bills and other government bonds. Keeping the (secured) overnight market rates close to the official rate is the primary objective. A combination of *reserve accounts, reserves averaging,* and *the standing facility corridor* is used to limit volatility in overnight interest rates over each *maintenance period.* We explain these concepts and tools next.

The 37 UK banks and building societies that are members of the reserve scheme set their target balances at the beginning of each maintenance period and undertake to hold balances, remunerated at the official BoE rate (or the *policy* rate). The reserve balances should, on average, meet the pre-set target over the maintenance period. Participation in the reserves-averaging scheme is voluntary other than for the settlement banks, which join the scheme automatically because their role in the payment system entails them having reserve accounts, and thereby maintaining balances, with the central bank. If a member's average balance is within a +/- 1% range around the target (averaging reserves balances at the end of each calendar day over the maintenance period as a whole), the balance

http://www.bankofengland.co.uk/publications/news/2006/054.htm; Clews (2005); various issues of the BoE's Quarterly Bulletin (Q3 2007 to Q4 2008); and unpublished notes by BoE staff.

would be remunerated at the official BoE rate.

The averaging of reserves is expected to help keep overnight market interest rates in line with the official BoE rate throughout the maintenance period since it leads banks to manage their balances actively and continuously arbitrage between running down their reserves balances and borrowing from the market.

The BoE uses OMOs to provide the amount of money needed to enable reserves banks, in the aggregate, to achieve their self-determined reserves targets. Hence, in the BoE monetary policy framework, except for emergency injections, the aggregate quantity of reserves is a response to the demand of reserves banks.[8] These OMOs comprise short-term repos at the policy rate, long-term repos at market rates determined in variable-rate tenders, and outright purchases of high-quality bonds. The BoE accepts the following as counterparties in its OMOs: (1) banks and building societies eligible to participate in the reserves scheme; and (2) other banks, building societies, and securities dealers authorized under the Financial Services and Markets Act 2000 that are active intermediaries in the sterling markets.

If money markets are disrupted the BoE can increase its lending via OMOs above the

[8]The BoE *Red Book* says, "The quantity of central bank money, and equivalently the size and composition of the Bank's sterling liabilities, is largely demand-determined... The Bank ensures that its stock of short-term repo lending on Banking Department is always at least as large as aggregate reserves targets, so that it can adjust the size of its weekly OMOs to offset any change in banks' aggregate reserves targets or any other sterling flows (so-called autonomous factors) between the banking system and the Banking Department's balance sheet. Matching aggregate reserves with short-term repo lending also avoids interest rate exposure on Banking Department as the Bank pays the official Bank Rate on targeted reserves and earns the official Bank Rate on its short-term repo lending."

aggregate target chosen by banks, while keeping control of market interest rates by paying the official rate on these larger balances either by increasing reserves targets pro rata or by widening the range (+/- 1% in normal times) around existing targets.

Standing deposit and (collateralized) lending facilities are also available to eligible UK banks and building societies and may be used on demand as emergency sources of financing. In normal circumstances they carry a penalty, relative to the official BoE rate, of +/- 25 basis points (bps) on the final day of the monthly reserves maintenance period, and a penalty of +/- 100 bps on all other days. Their usage, however, is subject to the stigma problem, especially during a crisis, as explained in the introduction (Section).

2.2 STRUCTURE OF THE PAYMENT SYSTEM AND MONEY MARKETS

There are about 400 active banks in the UK. The UK large-value payment system has a tiered structure. Tiering means that many (usually smaller) second-tier banks do not settle at the central bank but do so on the accounts of a few (larger) first-tier banks also referred to as settlement banks or clearers. A total of 15 banks are direct participants in the Clearing House Automated Payment System (CHAPS), the large-value payment system. Two of the direct participants are foreign owned banks with narrow retail activity in the UK. We exclude these two foreign banks from our sample of large settlement banks since their liquidity, kept in the form of BoE reserves, underestimates their overall liquidity, possibly substantially. We also exclude the BoE and the CLS bank (the clearing bank) and the one bank that became a settlement bank only in October 2008 (outside of our sample period). Hence, we are left with 10 large settlement banks.

The payment system CHAPS is used for business-to-business payments, for example, by solicitors/licensed conveyancers to transfer the purchase price of a house between the bank accounts of those involved, and by individuals buying or selling a high-value item, such as a car, who need a secure, urgent, same-day guaranteed payment. Hence most high-value wholesale payments go through CHAPS. There is, however, no lower limit on transaction values, and the system can be used for low-value (retail) payments when same-day finality is required. It is important to note however, financial transactions are not settled through CHAPS but through the securities settlement system.

Money markets or interbank markets allow participants to manage short-term liquidity positions that arise from their daily payment activity. The tiered structure described above for the payment system is also reflected in money market activities. The key players in the sterling markets across all instruments and maturities are the UK clearing banks, other large UK banks, and large US and European banks. The provision of liquidity through the system operates via a 'top-down' structure. Along the top tier, the big four clearers provide funding horizontally to each other and vertically to other counterparties (typically building societies and European banks with whom they have an established relationship). Smaller players are not inclined to provide liquidity horizontally to competitors; instead, they pass it vertically up the system. Therefore below the top tier, horizontal movement is very limited.

Besides playing a role in the interbank markets, banks manage short-term liquidity needs via their reserves balances held at the central bank. Subject to meeting the monthly target balance and avoiding overnight overdrafts, reserves balances can be varied freely to meet day-to-day liquidity needs. For example, funds can be moved on and off reserves accounts up to the close of the payments system to accommodate unexpected end-of-day payment inflows and outflows. In this way, reserves balances can be used by banks as a liquidity buffer.

Reserves banks can also change their reserve target from month to month in response to, for example, variations in the size or uncertainty of their payment flows. Settlement banks can also draw on reserves balances during the day to bridge any gap between payments made and expected receipts. For this purpose, holding reserves is an alternative to borrowing from the central bank during the day against eligible collateral. The routine provision of intra-day liquidity to settlement banks against eligible collateral, together with reserves balances, provides the necessary lubricant for the working of the sterling payment system, ensuring that settlement banks are able to make payments in advance of expected receipts later in the day. Intraday lending from the BoE to the settlement banks is interest-free, but, if not reimbursed by the end of the day it entails a large penalty (not publicly specified in the BoE's *Red Book* describing its monetary policy).

Individual institutions also tend to have plans to manage liquidity in times of stress. Smaller banks can obtain liquidity insurance from larger banks by paying for committed lines of credit, but larger banks generally cannot buy insurance from each other without imposing an unacceptable level of (contingent) counterparty credit risk. Thus, they have to self-insure, which they do, as discussed before: (1) by holding balances on their reserves account at the BoE; (2) by keeping high-quality assets that can be exchanged for central bank money in the OMOs; and, (3) through the BoE's standing (or semantically equivalent, emergency) lending facility.

3. Regime Shifts in Settlement Banks' Liquidity Demand

We now turn to our first result which uses an event study approach to investigate the settlement banks' liquidity demand during the crisis.

3.1 DESCRIPTIVE STATISTICS

We measure the settlement banks' *overnight liquidity* as the sum of the reserves accounts held by the 10 UK first-tier banks at the central bank and measured at 5 am each day. This daily measure of liquidity at time integrates two components: (1) the cumulative borrowing from the central bank in weekly OMOs, which is set by the choice of a reserves target; and (2) the cumulative daily net borrowing from the interbank market. While aggregate reserves circulated by the BoE remain constant for the economy, except when changed by the BoE, the reserves with the large settlement banks fluctuate on a daily basis based on their transactions with the other banks in the interbank market and directly with their own corporate and household borrowers.

The data are obtained from the BoE. All data are daily and cover the period January 2, 2007 to June 30, 2008. The first row of Table I (under "aggregate variables") reports various descriptive statistics (mean, standard deviation, minimum, maximum, quantiles) of the liquidity held by first-tier banks. This is reported for the whole sample period along with a test of the difference in means between the two sub-periods (before and after August 9, 2007). We see from the difference that liquidity held by first-tier banks is 27% higher after August 9, 2007. These differences are also seen in Figure 1 and are significant statistically at the 1% level.

3.2 EVENT STUDY

To understand these shifts in bank liquidity without pre-supposing the break points, we statistically identify the exact periods when settlement banks revised their liquidity demand and relate these to relevant market news obtained from Bloomberg's real-time news service. We employ Bai and Perron's (1998) test that estimates the timing of permanent level shifts in a time series. This method applies a sequential algorithm that searches all possible sets of breaks and determines for each number of breaks the set that produces the maximum goodness-of-fit. Statistical tests then determine whether the improved fit produced by allowing an additional break is sufficiently large given what would be expected by chance (due to noise). We apply the test to the logarithm of liquidity to mute the effect of outliers (and in subsequent tests to allow for the interpretation of coefficients in terms of elasticities).

Table II reports the results. The test identifies two breaks in the overnight liquidity. The first break, a 24.7% increase in overnight liquidity, occurred around September 11, 2007. This is one month later than BNP Paribas' decision to suspend redemption on August 9, 2007, which initiated a freeze in US wholesale funding markets. This lag in the response is due to the fact that UK settlement banks are allowed to revise their reserves targets only from one MPC meeting to the next. The first increase in the aggregate reserves target therefore occurred on September 6, 2007, the date the first MPC meeting took place after the sub-prime crisis took hold.[9] It may also be that some banks

[9] One can observe further increases in the overnight liquidity from mid-September onward, following the BoE decisions to inject extra liquidity in its regular weekly OMOs (see Appendix A for details on the adjustments to the monetary policy framework undertaken during the crisis).

anticipated the instability that would be created by the collapse of the UK lender Northern Rock which became public on September 14, 2007, and may have caused a stronger reaction by UK banks than BNP's decision.

At the second break, March 13, 2008, first-tier banks increased their overnight liquidity by an additional 15.5%. The second break coincides exactly with the collapse of Bear Stearns. The Bear Stearns episode reflected yet another (potential) freeze, this time in the wholesale market for borrowing secured (repo) against highly rated asset-backed securities. Traditionally, banks had always assumed they would be able to access the repo market for short-term liquidity needs. The Bear Stearns collapse revealed, however, that banks could no longer assume that the worst-case liquidity stress scenario was simply the drying up of unsecured funding: secured funding could dry up too. This further intensified the funding needs and rollover risks faced by banks.

Thus, the liquidity response of banks on March 13, 2008, is also consistent with a precautionary motive. Note that, in contrast to the delayed response following August 9, 2007, the liquidity demand of banks reacted more or less immediately to Bear Stearns' collapse. This was possible due to the BoE decision on October 4, 2007, to widen the band around target within which reserves are remunerated from +/-1% to +/-30% (as described in Appendix A).[10]

4. Further Evidence of the Precautionary Motive

[10]In particular, if there is an upward shock to reserves demand within a maintenance period, the band widening allowed banks to demand additional reserves without incurring penalty for deviating from targets, and allowed the BoE to supply additional reserves without needing to drain reserves later in the maintenance period.

While the higher reserves targets may have reflected anticipation of heightened funding needs and rollover risks, one needs to also consider the fact that banks had access to BoE's standing facilities as an alternative. Hence, the preference for reserves as a way of building liquidity can also be interpreted as a reduced tolerance for the risk of using BoE's standing facilities, most likely due to the potential stigma of accessing them during a period of market stress. Specifically, the marginal benefit of an additional unit of reserves is the insurance it provides against the risk of having to use the standing facilities following an unexpected payment shock in late trading. The expected cost of using the standing facility is a function of the direct penalty for using it (which remained constant or was lowered by the BoE during the crisis), the indirect penalty due to stigma, and the size of unexpected payment shocks. This cost must be traded off against the opportunity cost of not deploying elsewhere an additional unit of reserves, which is typically the spread between the policy rate and the overnight (secured) market rate.

Across maintenance periods, that is, from one MPC meeting to the next, reserves targets can themselves be varied. However within a maintenance period, settlement banks can increase their liquidity buffer only through other means: by reducing lending to households and firms, by selling assets, or by reducing net lending to second-tier banks. We do not observe the exact actions taken by banks to vary their liquidity buffers. For instance, lending data are available only for five of the banks and, then, only monthly. No data on asset sales are easily available. In addition, lending volumes can be reasonably imputed at the individual bank level only for overnight unsecured lending, but not for secured and term lending. Nevertheless, we explain below that we can still design empirical tests that enable inference about the reasons for variations in the demand for liquidity.

Our first test of the precautionary motive consists of estimating changes in the liquidity demand of settlement banks in response to changes in aggregate payment activity. The underlying idea is that on days of high aggregate payment activity, some individual banks may end up with significant payment needs but the distribution – that is which individual banks will face these needs – is uncertain. The data for payment activity are from the BoE payment database. The daily payment activity is measured as the sum of all transactions that flow through CHAPS, net of interbank loan activity.

Table I shows the summary statistics for payment activity pre-crisis and during the crisis. Strikingly, there is virtually no difference in the economic magnitude of payment activity by itself over the two periods. This is important for our identification to follow, since it suggests that any differential response of the settlement banks' liquidity demand to payment activity likely arises from bank-level differences in the perceived cost of managing payment fluctuations through means other than central bank reserves. Figure 2 plots the logarithm of payment activity. At first sight, this series appears to be a white noise process.[11]

Importantly though, a significant fraction of payment activity is predictable by banks due to calendar effects. Appendix B reports the effects on the aggregate payment activity of a non-exhaustive set of calendar dummies, which includes holidays in the US and the UK, and fixed effects for days of the week, quarters, and beginnings and ends of each

[11] A Portmanteau test confirms this observation. The lag-1 autoregressive coefficient is small (not reported). The Portmanteau test for lag-1 has a *p-value* of 0.29 rejecting the null hypothesis that the first lag autocorrelation is different from zero.

month. With these few dummies we are able to predict about 40% of the variation in payment value.

Economically important calendar effects are (1) US holidays, which are associated with a 58% drop in the value of payments activity, (2) days around the UK holidays, when there are, for instance, higher than usual deposit withdrawals; and (3) a fourth-quarter effect, which is negative.

To investigate how banks adjust their liquidity demand at the start of the day in response to fluctuations in aggregate payment activity for the day (which we have shown to be predictable due to calendar effects), and to determine whether this adjustment differed before and during the crisis, we estimate the following specification:

$$OLiq_{it} = \omega_i + \sum_{s=1}^{2} \delta^s \cdot break_t^s + \alpha \cdot P_t + \sum_{s=1}^{2} \beta^s \cdot P_t * break_t^s + \varepsilon_{it} \ , \qquad (1)$$

where i is a bank subscript, t is the time subscript, $OLiq_{it}$ is the overnight liquidity of settlement banks, ω_i is a bank fixed effect, and P_t is the aggregate payment activity predicted by calendar effects. Predicted aggregate payment activity is in logarithm (to reduce the impact of outliers). Bank liquidity is in percentage of a standard deviation variation from the average liquidity in the first half of 2007 (so as to represent abnormal variations in bank liquidity demand). The breaks are based on estimations in Table II: $break_t^1$ is a post September 11, 2007, dummy; $break_t^2$ is a post March 13, 2008, dummy. We also include maintenance period fixed effects in all specifications reported.

Again, we focus on predictable activity for the natural reason that realized activity is not known to banks at the time they set their overnight reserves. Similarly, we focus on aggregate activity since, even though no individual bank knows its own exact activity for the next day ahead of time (and, at any rate, it is difficult for an econometrician to estimate this well), aggregate activity is predictable. Perhaps a more important reason to focus on aggregate payment activity rather than individual bank payment activity is that funding needs arising from idiosyncratic payment fluctuations are more easily met through borrowing from other banks in the overnight market than *self-insurance*.

The overall results for the estimation of the benchmark specification are reported in Table III. The results in columns (1) through (6) suggest that following the events that unfolded since mid-September 2007 (the failure of Northern Rock), UK banks hoarded liquidity.

Column (1) of Table III shows that before the crisis predictable increases in aggregate payment activity are associated with a decline in the reserves balances of settlement banks which means an outflow of liquidity from settlement banks to either second-tier banks or households. In contrast, column (2) shows that starting September 11, 2007 ($break_t^1$), there is a significant positive incremental relationship between the reserves balances of settlement banks and payment activity, that is economically large: 24% of a standard deviation shift in liquidity demand for a one standard deviation increase in predictable payment activity. In other words, reserves held by settlement banks rose with a higher value of payment activity, during the crisis relative to before. This is consistent with settlement banks hoarding liquidity away from second-tier banks and households.

Column (3) shows the incremental response is not magnified following March 13, 2008 ($break_t^2$). Column (4) shows that the results are robust to controlling for the lagged deviation of the banks' reserves balance from target which controls for the fact that calendar effects may coincide with (end of maintenance period) adjustments by banks to meet their target. Column (5) controls for maintenance period fixed effects because throughout our sample period liquidity demand varies significantly from one maintenance period to another as banks revise their target during the crisis and at the same time there can be important monthly fluctuations in payment activity due to end of year or end of quarter effects. Focusing on variations within the maintenance period in payment activity allows us to eliminate this source of correlation between liquidity demand and payment activity.

In column (6) we include a dummy for the uncovered OMO that occurred at the end of June 2007 because it induced a significant decline in the amount of borrowing from the central bank and at the same its timing coincides with periods of important fluctuations in payment activity (end-of-month and end-of-quarter effects).[12] In columns (4) through

[12] An important event in sterling money markets prior to the onset of the crisis in August 2007 was the so-called "uncovered" OMO. In an OMO, counterparties bid for a quantity at a fixed rate. This fixed rate bidding has the potential undesirable consequence that, given the amount of reserves each counterparty actually desires, the size of their bid is determined by their guess as to how much other counterparties will bid for. As a consequence, reserves required by banks to meet their targets may be undersupplied (or uncovered) through the OMO if, for example, a banks underbids because it thinks that other banks will not bid for more than they desire. Through such a dynamic in June 2007 (before the turmoil), reserves were eventually undersupplied and interbank rates went up dramatically due to a lack of reserves relative to banks' targets. From the standpoint of our analysis, the uncovered OMO raises the issue that any differential effect we observe before and during the crisis may be due to this June/July 2007 episode, which precedes the most interesting period of our analysis (August 2007 onward). Hence we check the robustness of our results by controlling for the uncovered OMO episode through a dummy variable.

(6) the results are stable.

In column (7) we redefine the break dummies to check whether the change in bank behavior is temporary, that is, lasting until the end of the current maintenance period, rather than permanent. We redefine $break_t^1$ to be a dummy that takes value one from September 11, 2007, until the last day of the September 2007 maintenance period and $break_t^2$ to be a dummy that takes value one from March 13, 2008, until the end of the March 2008 maintenance period. The results show that if we do that, the estimates are no longer statistically significant confirming our prior that the crisis causes a permanent rather than a temporary shift in UK banks' liquidity management strategy.

In Table IV we explore the relationship between bank liquidity demand and bank risk. We employ five specifications with different bank characteristics (lagged, wherever applicable) that capture the bank's funding risk and realized health during the crisis:

1. Mismatch-I: the ratio of loan assets to retail deposits as an indicator of maturity mismatch.

2. Mismatch-II: total assets divided by retail deposits, as another measure of maturity mismatch.

3. Deposit structure: the ratio of sight deposits to time deposits[13] , as an indicator of funding risk in the bank's liability structure.

4. Equity price fall: the cumulative equity price fall in number of standard deviation

[13] Sight deposits are short-term deposits that can be withdrawn on demand at no cost for the depositor. Time deposits in contrast are long-term deposits.

units from the average price in 2006, as a measure of solvency shock.

5. Risk-weighted assets: the ratio of risk-weighted assets to total assets, as a regulatory measure of asset risk.

The fall in retail deposits could help account for the fact that while some banks were directly threatened by the meltdown of the asset backed commercial papers market, they were rendered especially fragile if they had little in terms of retail deposits to start with, or also experienced a flight of retail deposits to safer banks.[14] While losses disclosed are an imperfect measure of realized solvency issues (since some banks were prompter at reporting losses than other banks), deterioration implied by market measures (equity prices) should incorporate better public information available on the financial condition of a bank, including the anticipation of future losses and not just realized losses.

Table I reports the descriptive statistics of these variables. There is significant variability across banks in the measures of bank health and funding risk. Equity prices displayed dramatic swings over the sample period for many banks. While some banks gained retail deposits relative to assets (a fall in the assets to deposits ratio), others experienced significant losses.[15]

[14] A classic example of this was the run on Northern Rock in September 2007. Shin (2009) provides descriptive statistics showing that Northern Rock's problems stemmed from its high leverage coupled with reliance on institutional investors for short-term funding. An analysis of the structure of its balance sheet pre- and post-run shows that the first and most damaging run on the bank took place in its short- and medium-term wholesale liabilities, but that once its problems materialized, it also experienced a retail run, mainly through electronic deposit accounts.

[15] The summary statistics reported are for the whole sample period. The top and bottom 5% of the

We find that higher bank risk is associated with increased liquidity demand during the crisis. Greater funding risk (captured by the two maturity mismatch proxies) and greater solvency risk (captured by the equity price fall and the risk-weighted assets ratio) are both associated with higher demand for liquidity during the crisis. A one standard deviation increase in any measure of funding risk is associated with about 20% of a standard deviation increase in liquidity demand.

Figure 4 depicts this effect graphically and shows a dramatic rise in liquidity demand among high-risk banks relative to low-risk banks as the crisis unfolds, the risk measure being, respectively, whether the bank is in the top or bottom three banks in terms of loans to retail deposits during the crisis. The figure looks similar with other risk measures. The figures underscore results of Table IV, that high-risk banks revised their reserves targets soon after inception of the crisis, whereas low-risk banks did so only in 2008 (and less strongly, at that).

We complement this benchmark analysis with a specification that allows for further heterogeneity in the precautionary behavior of banks. We do this by interacting bank risk characteristics with predictable payment activity. We split the sample of banks into high-risk, medium-risk, and low-risk banks based on the top three, middle four, or bottom three banks, respectively, in terms of the risk measure.

The estimation results are reported in Table V. They show a more pronounced economic magnitude for the precautionary reaction to payment activity during the crisis among banks with troubled balance-sheet conditions (i.e., among high and medium-risk

distribution of losses gives an idea of how the variables looked during the crisis.

banks relative to low-risk banks). For the high-risk banks the shift in liquidity demand is about twice as large as the average effect we estimate in Table III. The difference between strong and weak banks is statistically significant at the 5% level for all risk metrics we employ, except for deposit fragility.[16]

To sum up, the findings in Tables III to V and Figure 4 confirm our hypothesis that the increase in the settlement bank liquidity witnessed during the crisis reflected precautionary intent. During the crisis banks hoarded liquidity against payment risks, but not so pre-crisis. Further, this precautionary reaction was unequal across banks, being more pronounced at banks with greater balance-sheet funding risk and greater solvency concerns.

5. Effect of Liquidity Hoarding on Money Market Rates and Volumes

[16] Appendix C reports corroborating (though overall weaker) results when we focus on an alternative source of liquidity UK banks can draw from during the day to fund their payment activity: intraday collateralized credit from the central bank. Every morning banks are required to post a sufficient amount of collateral at the central bank to cover their expected intraday funding needs. Using the Bai-Perron structural break test, we found a break in intraday liquidity demand (i.e. collateral posting) on August 8, 2007. We estimated the regressions in Table V with intraday liquidity as a dependent variable and August 8, 2007, as the break date instead of September 11, 2007. The conclusion is similar for three out of five of our measures of funding risk. For the risk-weighted assets ratio the results are reversed but this is not surprising: there is a mechanically negative relationship between the amount of collateral posted and the risk-weighted assets ratio since banks that have a smaller proportion of high quality assets in their balance sheet have less good quality assets to post (the central bank requires assets posted to have a zero risk weight). The results are also robust if September 11, 2007, is kept as the break date.

In the second half of our empirical analysis, we explore the consequences of the increase in hoarding of liquidity by settlement banks for interbank markets. In particular, we document how movements in liquidity demand by banks altered interbank rates and volumes before and during the crisis.

Theoretically, banks set reserves targets to equal the marginal cost and the marginal benefit of holding one additional unit of reserves. In normal times, the cost of finding alternative sources of funding and even using the central bank's emergency standing facilities to meet liquidity needs is low due to the absence of stigma. Then, reserves averaging over a maintenance period ensures that market interest rates do not diverge materially from the policy rate.

This money market "arbitrage effect" works as follows. Suppose that overnight market interest rates are higher on a particular day than the policy rate. Then a bank can run down its reserves balance in order to lend in the market, expecting to be able to borrow more cheaply in the market in order to hold a higher reserves balance on subsequent days. By contrast, if market rates are lower than the policy rate, then a bank can borrow in the market in order to build up its reserves balance.

Typically, the effectiveness of this arbitrage mechanism is affected by the width of the range of reserves allowed by the monetary policy implementation. It is also affected by the willingness of banks to take reserves close to the edge of their ranges given that unexpected late payment flows could leave them needing to use a standing facility at the end of the day. In stressed funding conditions, the difficulty of raising wholesale funding and the stigmatization of the standing facility is high. This can curb active liquidity management by banks in the form of arbitraging deviations in money market rates from the policy rate. In essence, there are limits to the arbitrage (as argued in the context of broader financial markets by Shleifer and Vishny, 1997).

With such limits to arbitrage, the incentive for banks is to hold larger reserves over the maintenance period to reduce the risk of having to use the standing facilities to meet unexpected late payment shocks. The private benefit of holding one additional unit of reserves is high and hence banks charge a high liquidity premium to release their reserves. In other words, in stressed conditions banks release their liquidity only if the return on liquidity exceeds the high private benefit due to their precautionary demand, causing interbank rates to be higher. We call this the “liquidity" effect.

Our empirical work, aims to identify both these effects: first, the arbitrage effect that *exogenous* increases in settlement banks' liquidity demand would drive interbank rates toward the policy rate, and the liquidity effect that *endogenous* (in our case, precautionary) increases in settlement banks' liquidity demand would drive interbank rates above the policy rate.

5.1 REGRESSION SPECIFICATION

5.1.a Ordinary Least Squares (OLS) Approach

The specification we estimate to link settlement bank liquidity to market-wide interbank rates is as follows:

$$Y_t = \alpha_y \cdot OLiq_t + \beta_y^1 \cdot OLiq_t * break_t^1 + \delta_y \cdot break_t^1 + \varepsilon_t^y \quad (2)$$

where Y_t is either the interbank rate spread to the policy rate in bps or the logarithm of the volume of interbank activity in billion of pounds, $OLiq_t$ is overnight liquidity aggregated across the 10 UK settlement banks and expressed in logarithm, and $break_t^1$ is a post September 11, 2007, dummy. The specifications reported below also include a full set of maintenance period fixed effects. The estimates are however robust to not including maintenance period fixed effects, which has the advantage of capturing variations in liquidity demand from one maintenance period to another (i.e., changes in the banks' reserves targets).

Our hypothesis is that in the pre-crisis period, the effect of settlement bank liquidity on interbank rate spreads is negative (the arbitrage effect) whereas during the crisis period, the effect is positive (the liquidity effect). And that the effect on volume is negative during the crisis but not before the crisis.

5.2.b Two-Stage Least Squares (2SLS) Approach

To isolate the exogenous and endogenous components of settlement banks' liquidity, we once again exploit variations in payment activity. Section 2.1 highlighted mechanisms whereby aggregate payment activity correlates with the settlement banks' overnight liquidity and Section 4 provides supporting empirical evidence. We take advantage of this relationship in our econometric approach to address potential reverse causation and the omitted variables bias.

Formally, we specify bank liquidity on day t (measured at the start of the day) l_t as an autoregressive process of order one:

$$l_t = \alpha l_{t-1} + \beta P_t + \varepsilon_t^l \ , \tag{3}$$

where the precautionary demand for liquidity is captured by the dependence of l_t on P_t, the payment activity on day t (assuming banks are able to make a reasonable forecast of the aggregate payment activity). Then, Equation (3) can be rewritten as:

$$l_t = \alpha^2 l_{t-2} + \alpha\beta P_{t-1} + \beta P_t + \varepsilon_t^l \ . \tag{4}$$

Note that such an autoregressive structure would be natural when a bank chooses reserves subject to a target it committed to the previous target-setting day.

Specifically, a bank's liquidity demand can be modeled as:

$$\Delta_t \equiv l_t - l_{t-1} = \theta \left(\bar{l} - l_{t-1} \right) + \beta P_t + \varepsilon_t^l, \tag{5}$$

where $\bar{l}$ is the reserves target of the bank. Then, up to a constant (the reserves target), bank liquidity l_t follows an autoregressive structure as proposed. Thus, within a maintenance period, bank liquidity at time t is a function of all the past history of payment activity.

Next, we hypothesize that the interbank market rate r_t is a linear function of both settlement bank liquidity l_t and payment activity P_t :

$$r_t = \gamma l_t + \delta P_t + \varepsilon_t^r \ . \tag{6}$$

That the market rate on a given day is a direct function of the payment activity on that day follows from Furfine (2000). The argument goes as follows. Payment flows on any given day are positively correlated with reserves balance uncertainty. Since uncertainty generates a precautionary demand for reserves, days with higher payment flows are associated with upward pressure on the market rate. In other words, on busier days, banks desire to hold a larger cushion of reserves to protect against penalties for overnight overdrafts. In equilibrium, this generates a positive relationship between payments activity and the market rate.

If this argument holds P_t is not a valid instrumental variable for l_t, in studying the effect of liquidity l_t on the interbank rate r_t. However, because P_t is a white noise process (see Figure 2, where the correlation between P_t and P_{t-1} is only 4%), P_{t-1} is potentially a valid instrument for l_t. In other words, interbank rates on a given day depend on the liquidity reserves of settlement banks on that day (measured at 5 am), which we naturally assume includes a component of reserves adjusted to the previous day's payment activity (the instrument) and a component adjusted in anticipation of today's payment uncertainty (the endogenous component).

The use of this instrument also helps address another issue, that of omitted variable bias. It is plausible that during the crisis period, there were day to day fluctuations in counterparty risk in the interbank markets. Such risk would simultaneously raise interbank rates and generate a precautionary demand for liquidity among banks. Thus, instrumenting bank liquidity l_t with P_{t-1} also helps isolate the effect of liquidity on the interbank rate r_t which is unrelated to a counterparty risk factor.

The first-stage equation is:

$$OLiq_t = \omega_m + \delta_m \cdot break_t^1 + \alpha_m \cdot P_{t-1} + \beta_m \cdot P_{t-1} * break_t^1 + \zeta_m \cdot P_t + \varepsilon_{mt} \qquad (7)$$

where ω_m are the maintenance period fixed effects, $break_t^1$ is a post September 11, 2007, dummy, and P_{t-1} is a vector of instrumental variables that includes both the lagged value of payment activity and the lagged number of payments[17].

[17] The correlation between these two measures of payment activity is only 50%, and the correlation between payment activity at time t and payment activity at time *t-1* is only 4%. This is true whether payment activity is measured by the value settled or the number of payments settled. The results are

The second-stage equation is:

$$Y_t = \omega_z + \alpha_z \cdot \widehat{OLiq_t} + \beta_z \cdot \widehat{OLiq_t} * break_t^1 + \zeta_z \cdot P_t + \delta_z \cdot break_t^1 + \varepsilon_{zt} \qquad (8)$$

where ω_z are maintenance period fixed effects, $break_t^1$ is a post September 11, 2007, dummy, P_t is the contemporaneous vector of measures of payment activity, which includes the value of payment activity and the number of payments settled, and $\widehat{OLiq_t}$ is the liquidity demand predicted from the first stage.

5.2 MONEY MARKETS DATA

To estimate Equation (2), we use daily market-wide interest rates and volume data from the British Bankers' Association and the Wholesale Markets Brokers' Association. The secured rate is the gilt collateral (GC) rate. The unsecured overnight rate is the SONIA rate.[18] Table I reports descriptive statistics of the rates and volume data. The secured rate spread to the policy rate is 6.25 bps on average with a large standard deviation of 12.65 bps, whereas the unsecured rate spread to the policy rate is 11.47 bps with a variability of 13.31 bps.

Figure 3 shows that sharp movements in the overnight rate spreads, especially in August and September 2007 (rising in the 50 to 100 bps range) and again in March 2008 (rising up to 35 bps), have coincided with negative market news, for example, loss announcements and bailouts (see the news timeline in Table II).[19] Figures 5 and 6 show

robust if we use only one of these two measures of payment activity as instrument.

[18] The SONIA rate tracks actual sterling overnight funding rates experienced by market participants.

[19] We explain in footnote 14 that an "uncovered" OMO caused a peak in overnight rates in the last week of June 2007. As a result of this peak in the pre-crisis period, the unsecured rate spread is on average unchanged from before the crisis to the crisis period, and the secured rate spread is also only

that both secured and unsecured volume trend upward, but that there is an increase in the volatility of interbank volumes from August 2007 on. In what follows we check whether this is the consequence of volumes becoming more sensitive to liquidity demand pressures, that is, greater and more frequent recourse to rationing during the crisis.

The last two columns of Table I, also report the differences in rates, volumes, and liquidity between the pre-crisis and post-crisis periods, and in parentheses we report these differences, excluding the week of the uncovered OMO. It may seem a surprising observation that the secured rate has increased more than the unsecured rate, even if by a small margin, + 2.4 bps, on average, for the secured rate and + 0.66 bps for the unsecured rate.

A deterioration in the quality of collateral pledged cannot explain why secured rates have increased more from before crisis to during the crisis, compared to unsecured rates, because we focus on the gilt rate, where the quality of collateral was close to unquestionable (at least until the Lehman bankruptcy). In secured transactions banks can also manage risk by varying haircuts. Available data, however, show that for transactions secured by government bonds haircuts have barely moved during the crisis (see Allen and Carletti, 2008, and Table 1 of the Bank for International Settlements, 2010).

Coincidentally, both the secured volume and the unsecured volume have increased post August 9, 2007, but the increase has been more than twice as large as for secured lending (45% against 13%). Hence, one possibility for the greater rise in the secured spread is heightened market segmentation during the crisis, that is, different sets of banks

2.41 bps higher during the crisis than before it.

borrowing in the two markets. Even before the crisis, the unsecured market was reserved mostly to large, high quality settlement banks, while second-tier banks have access to secured borrowing only. Greater distortion in the secured market than in the unsecured market is therefore suggestive that second-tier banks are more affected than first-tier banks and that liquidity hoarding by first-tier banks has negative spillover effects on second-tier banks.

5.3 AGGREGATE EVIDENCE

Table VI reports the OLS and 2SLS estimates of the liquidity effect, where the dependent variable is either the spread to policy rate in bps or the logarithm of the volume (to smooth out outliers).[20] The OLS estimates reported in columns (1) and (2) indicate that for both secured and unsecured spreads a higher liquidity demand by settlement banks is associated with a significant decline in overnight spreads (the "arbitrage effect") in the period before the crisis. However, during the crisis the incremental effect is positive (the "liquidity effect"). The 2SLS estimates of the post crisis effect reported in columns (3) and (4) are qualitatively in line with the OLS estimates; the pre-crisis 2SLS estimates, however, are statistically insignificant. In addition, in terms of magnitude, the 2SLS estimates are about five times larger. It is important to note that our estimates of the liquidity effect tend to be of similar magnitude for the secured and unsecured rates, and, in fact, are

[20] The difference in the number of observations between the OLS and 2SLS regressions is due to the fact that we use lagged payment activity as an instrument and exclude Mondays in the 2SLS regressions because Mondays correspond to strong calendar effects in payments activity (see Appendix B) and simultaneous strong calendar effects in liquidity due to weekly OMOs. Our first-stage estimates would be otherwise significantly distorted.

somewhat stronger for the secured rate (columns (3) and (4)). A one standard deviation increase in liquidity demand (25%) is associated with a 10 bps increase in the secured spread (corresponding to about one standard deviation). Note that the over-identification and under-identification tests lead to non-rejection of the instruments. The instruments are also strong predicators of liquidity demand, with the first-stage F-statistics consistently above 10, ruling out issues of weak instrumentation. The conclusions are robust if the model is estimated using a limited information maximum likelihood more robust to weak instrumentation or if only one of the two measures of payment activity is used as an instrument.[21]

In sum, we find that all the OLS effects are qualitatively present in the 2SLS specifications, but the magnitude of the liquidity effects is about five times as large. This effect, combined with the statistical significance of the instruments, suggest that lagged payment activity indeed helps isolate the effect of bank liquidity on interbank rates that is not driven by common factors such as counterparty risk concerns.

Columns (5) to (8) report results where the dependent variable is either the secured volume or the unsecured volume. Overall, while the effects on volume during the crisis tend to be negative, they are not statistically significant and not very robust. As shown in Figures 5 and 6, aggregate interbank volumes (both secured and unsecured) have trended upward, including during the crisis. A better way to understand how volumes were affected and the heterogeneous effects across banks would be to analyze more disaggregated data, which we do in the next section.

[21]These robustness checks are available upon request.

All these findings hold true if we measure liquidity as the percentage deviation of aggregate reserves balances from the aggregate reserves target (see Appendix D).

One other factor that may affect the secured rate is the quantity of collateral available in the market. Figure 7 shows that the total quantity of UK gilts and Treasury bill collateral rose sharply from the fourth quarter of 2007 onward. Holdings by UK banks and building societies of this collateral skyrocketed even more sharply, and continued to do so after April 2008, which corresponds to the time when the BoE started the operation of its Special Liquidity Scheme (SLS) program. Banks swapped about £185 billion of low-quality assets against Treasury bills under the program.[22] It is clear, however, that the banks' quantity of this collateral grew more sharply than the overall increase in the quantity of collateral.

This increase in the banks' share of UK gilts and Treasury bill collateral could reflect an increase in the demand for secured lending relative to unsecured lending. Such migration to the secured market, in turn, is likely to be caused by the fact that secured transactions contain less counterparty risk and that banks value the resulting anonymity associated with secured transactions during the crisis. The analysis that follows accounts for this hypothesis by using the instrumental variables approach (employing lagged payment activity as the instrument, as explained in Section 5.2), which helps correct for such an omitted variables issue in our specification. In addition, we run a number of robustness checks controlling for the introduction of the SLS program and directly controlling for the

[22] The time series data of the SLS drawdowns is confidential and only the aggregate amount was disclosed. Note also that the Treasury bills issued by the BoE for the purpose of the SLS do not count as public debt and are therefore not fully reflected in the Debt Management Office (DMO) data.

stock of gilts and Treasury bills and holdings by UK banks. Table VII presents these results. In column (1) we include a dummy for the period following the start of operation of the SLS program in the equation where the dependent variable is the secured spread. In column (2) we exclude from our sample the period following the SLS introduction (to address the issue that the introduction of the SLS might be endogeneous to market conditions). In columns (3) and (4) we control directly for the stock of gilts and Treasury bills, and separately for the proportion of that stock held by banks and building societies. In columns (5) to (6) we repeat these robustness checks for the secured volume. In all these specifications we find the results of Table VI for the liquidity effect on money market spreads and volumes to be robust and the effect of the additional control variables to be weak and not robust.

All in all, these results confirm our hypotheses: in stressed conditions banks release their (precautionary) excess liquidity only at a liquidity premium that compensates them for the cost of alternatives, such as the direct cost of using the standing facility, the indirect stigma cost, and costs of liquidating assets or raising wholesale finance in illiquid and frozen markets. Overall, we interpret our findings – especially the fact that the nature and the magnitude of arbitrage and liquidity effects on interbank rates are similar for secured and unsecured interbank lending – as implying that sterling money markets did not experience stress during the crisis just due to counterparty risk concerns of lending banks about borrowing banks. Instead, the findings suggest that the stress was (also) due to banks engaging in precautionary liquidity hoarding because of their own credit risk and funding risk. Such hoarding raised the lending rates charged in secured as well as unsecured interbank markets.

5.4 EVIDENCE FROM BILATERAL DATA

We find corroborating evidence for our interpretation when we analyze bilateral transactions data. We analyze bilateral spreads and volumes in the unsecured interbank market, after employing the Furfine (1999) algorithm to identify interbank borrowing and repayment transactions from the BoE CHAPS payment database. Note that such data are unavailable for the secured market, since it works largely through a third-party broker arrangement.[23] The sample covers 10 UK banks that make up the unsecured market over 22 maintenance periods from January 2007 to June 2008. Figure 8 confirms that the sample of banks covered here is pretty much the same as that covered in the aggregate broker-dealer data analyzed in the previous section: the average interest rate we calculate from the loans identified in the CHAPS database tracks very closely the broker-dealers' aggregate SONIA rate.

To obtain maintenance period-level data from the transaction-level data we aggregate volumes transacted between two banks within a maintenance period and obtain the volume-weighted average interest rate by maintenance period. Table VIII reports descrip-

[23] In light of the Bear Stearns case, we think it would have been interesting to assess the extent to which market participants perceived credit risk was really absent from secured transactions. And to investigate the extent to which such effects would have been exacerbated by the occurrence of settlement failures. In any case we conjecture (based partly on discussions with the BoE money markets staff) that the unsecured market was more relevant to examine for credit risk effects. Our analysis shows that even in the unsecured market it is the precautionary hoarding effect that dominates the credit risk effects, at least for our sample period (pre-Lehman). Note also that in the UK, settlement failures in gilt repo transactions have remained remarkably low (98% success on average) throughout the crisis period.

tive statistics of the data. There is considerably more variability in the bilateral data than that reflected in the aggregate data. For example, the unsecured interbank spread (transaction rate minus the policy rate) charged by one bank to another varies between -87 bps and 110 bps. Variability in volume is also important. The proportion of non-active bilateral trades (zero volumes) in our sample increased from about 20% before August 2007 to above 30% after August 2007.

We estimate the relationship between these dependent variables (bilateral spread and volume) and lender and borrower liquidity, before and during the crisis. If lender liquidity affects a given borrower's cost of borrowing, then it would suggest that, in deciding to extend a loan and at what price, a bank is also concerned by its own future ability to borrow rather than by just its counterparty's characteristics.

Note that the bilateral spread is observed only for non-zero volumes. Since between 20% to 30% of the bilateral relationships in our data are inactive, we use a specification that corrects for sample selection where the probability of a positive trade between two parties is predicted in the first stage by the amount of bilateral payments between them net of interbank loans. Since UK banks have recourse to the overnight interbank market to raise liquidity to fund their payment activity, there is a strong link between bilateral lending activity and bilateral payment activity. The estimation of the selection equation is reported in Appendix E.

Then, the specification used for the bilateral spread is as follows:

$$r_{ijt} = \alpha_r + X_{it}\beta_r^1 + X_{jt}\beta_r^2 + X_{it}\beta_r^3 * crisis + X_{jt}\beta_r^4 * crisis + \omega_r + \gamma_r mills_t + \varepsilon_{rt} \quad (9)$$

where t is the time subscript (changes with maintenance period); r_{ijt} is the spread charged by lender i to borrower j; X_i and X_j are the lender and borrower reserve targets respectively (scaled by their respective payment activities to control for size); $crisis$ is a post August 2007 dummy; ω_r are maintenance periods fixed effects; and $mills$ is the inverse mills ratio derived from a selection equation that expresses the probability of a positive trade between two banks as a function of their bilateral payment activity, using estimates from Appendix E. Note that banks choose their reserves target at the start of a maintenance period and that their choice cannot be revised until the next maintenance period.

To explore both the intensive and extensive margin of trade, we also test a Tobit specification for bilateral volume as follows:

$$V_{ijt} = \alpha_v + X_{it}\beta_v^1 + X_{jt}\beta_v^2 + X_{it}\beta_v^3 * crisis + X_{jt}\beta_v^4 * crisis + \omega_v + \varepsilon_{vt} \qquad (10)$$

where V_{ijt} is the bilateral volume transacted (scaled by the lender payment activity as a proxy for lender size), and other variables are as in the bilateral spread specification of Equation (3).

Columns (1) and (2) of Table IX show that borrower and lender liquidity holdings (scaled by payment activity) are important determinants of the spread during the crisis (not before): the slopes of the liquidity demand and supply curves become steeper during the crisis. Importantly the positive relationship between rate and liquidity observed in the aggregate data is confirmed in the bilateral data by a positive relationship between lender liquidity and the rate they charged to release that liquidity during the crisis. The effect is also economically meaningful: a one standard deviation increase in lender reserves target is associated with a 1.3 bps increase in the spread charged.

Further, the important concern that the aggregate relationship is the result of a positive correlation between borrower credit quality, borrower liquidity hoarding, and the borrowing rate does not find support in the bilateral data. In fact, the correlation between borrower liquidity holdings and the rate is insignificant pre-crisis and negative during the crisis.

It is equally interesting to simultaneously consider the volumes of bilateral activity. Tobit estimates for interbank activity in columns (3) and (4) of Table IX show that bilateral activity in interbank markets tends to be negatively related with both borrower and lender liquidity. During the crisis, the interbank activity became somewhat less negatively associated with lender liquidity, but the overall effect remained negative and economically large. Put together with columns (1) and (2), this suggests that, consistent with an endogenous view of bank liquidity, banks hold liquidity to reduce their costs of borrowing in the interbank market (potentially leaving the market altogether) and, when they do so, they also charge more for lending in the interbank market (again, potentially not lending in the market at all).

To summarize, we find that the positive aggregate relationship between interbank rate and bank liquidity during the crisis is driven by a positive relationship between the liquidity balances of lenders and the rate they charged on the loans they extended during the crisis. This is consistent with a precautionary demand effect: lenders who had a higher "demand" for liquidity during the crisis charged a higher rate to release it.

As further evidence in support of our interpretation we report the reduced-form effects of lender and borrower risk on bilateral spread and volume in Appendix F. These reduced form results confirm that only lender (liquidity and solvency) risk matters and is positively related with the spread during the crisis. Further, only risk metrics that proved significant in driving liquidity demand, namely, Mismatch I, Mismatch II, and the risk-weighted assets ratio, are significant determinants of rates and volumes, and appear with the expected sign in estimations of the reduced-form equations. This is supporting evidence that the effect of bank risk on rates and volume works primarily through its effect on liquidity demand and hence is fully captured in our structural-form estimates reported in Tables VI, VII and IX.

6. Related Literature

Our paper cuts across a number of different strands of literature, particularly, regarding (1) reasons why firms hoard cash, (2) the function played by interbank markets and the reasons why they may experience stress, (3) the transmission of bank-level stress as contagion in the financial sector, and (4) the micro-structure of interbank markets in terms of reserves requirements by central banks and the monetary policy.

The fact that the onset of the sub-prime crisis led banks to hoard liquidity as a precaution against funding risk finds its parallel in the corporate finance literature on financial constraints. In this literature (see, e.g., Almeida et al., 2004, and the references therein), when firms cannot pledge a sufficient portion of their future cash flows in capital markets, they attempt to hedge by managing cash. The result is reduced contemporaneous investments. Large banks in the payments system settle a large volume of transactions on a daily basis and when the volume becomes large or uncertain, they hold extra liquidity simply to be able to effect these transactions smoothly. If their access to external financing dries up, this theory predicts they will hoard more cash. The rationale for banks to hoard liquidity against *aggregate* financing shocks has also been modeled in several papers.[24]

The theory of interbank markets generally agrees on their role as one of liquidity insurance and peer monitoring. The reasons why these markets sometimes fail or experience severe stress differ across studies. Allen et al. (2008) and Freixas et al. (2008) focus on the incompleteness of contracting on liquidity shocks; Bhattacharyya and Gale (1987), Flannery (1996), Bhattacharyya and Fulghieri (1994), Freixas and Jorge (2007), and Heider et al. (2008) focus on asymmetric information and/or counterparty risk and related inefficiencies; finally, Acharya et al. (2008) focus on issues arising due to the market power and strategic behavior of liquidity-surplus banks. Our findings suggest that the stress in interbank markets witnessed in the first year of the sub-prime crisis is unlikely to have been due (entirely) to counterparty risk concerns, since we find almost identical effects in the sterling money markets for overnight lending in secured as well as unsecured transactions.

While our results on transmission of an individual bank's funding risk, and its precautionary hoardings, to other banks do not find a direct parallel in the literature, this form of contagion is similar in its overall spirit to that considered in models of aggregate liquidity shortages. These include the models of Freixas and Rochet (1996), Allen and Gale (2000), Freixas et al. (2000), Caballero and Krishnamurthy (2001), Diamond and Rajan (2005), and Acharya (2009), wherein banks are reliant on a common pool of liq-

[24] See, for example, Holmstrom and Tirole (1998), Allen and Gale (2000), Diamond and Rajan (2001), and Allen et al. (2008).

uidity and one bank's adversity reduces the available pool for others due to the fire sales of assets, deadweight losses from bad assets, or drawdowns of interbank deposits. Theoretical analysis wherein precautionary hoardings of affected banks are explicitly modeled and shown to raise the cost of borrowing for healthier banks giving rise to an interest-rate contagion has been analyzed in Acharya and Skeie (2011).

Our paper also relates to the literature on the microstructure of interbank markets. Hamilton (1997) studies the role of bank liquidity in affecting the federal funds rate by employing as an instrument the "errors" in the Federal Reserve forecasts of the effect of its operations on bank reserves. In contrast, we rely on the extent of payments activity as an instrument. On this front, our approach is similar to that of Furfine (2000), who calibrates a model as well as empirically demonstrates that daily fed funds rate variability is linked to that of payment flows, and that higher payment flows lead to greater precautionary reserves which put an upward pressure on the funds rate. We take a step further in explaining that liquidity demand varies across banks as a precaution against their different funding risks. Fecht et al. (2010) study the German banks' behavior in ECB's repo auctions during June 2000 to December 2001. They examine the effect of bank-specific and market-wide factors on prices that banks pay for liquidity, measured as their borrowing rates in repos with the ECB, and find (as we do) that the rate a bank pays for liquidity depends on other banks' liquidity, and not just its own.

Ashcraft and Duffie (2007) also provide evidence consistent with the precautionary targeting of reserves balances maintained by banks at the Federal Reserve and the role played by the "arbitrage" activity of banks using their reserves to ensure an over-concentration of reserves does not arise in some banks. Our results show that such arbitrage activity, prevalent before the sub-prime crisis, diminished substantially during the crisis. In contrast to the crisis of 2007-2008, Furfine (2002) finds that the interbank markets functioned remarkably well in transferring liquidity in the banking system during the fall of 1998, when Long Term Capital Management's problems surfaced.

7. Conclusion

By examining the effect of a full-blown financial crisis (starting August 9, 2007) on the liquidity demand of large settlement banks, and its effect on interbank market rates, we uncover an important precautionary channel that caused stress in the sterling money markets. The economics underlying these effects suggest that the channel was likely at work in other countries, since they too had their fair share of weakened financial institutions. Perhaps most interestingly, our results show that contagion-style systemic risk can exist in interbank markets whereby an increase in the precautionary demand of liquidity by some adversely affected banks leads to a rise in the costs of borrowing liquidity for all other banks, in both secured and unsecured markets.

On the policy front, our evidence suggests that regulatory attempts to thaw such money market stress and reduce the variability of interbank rates, if successful, can have salubrious effects on healthier parts of the banking sector. Our results, however, suggest that, to the extent that a part of the stress emanates from the liquidity hoardings of banks with troubled funding and balance-sheet conditions, such a thawing should involve addressing insolvency concerns (e.g., early supervision and stress tests, and the recapitalization of troubled banks), and not just provisions of emergency liquidity.

There are several important avenues for future work. Within the aggregate setting, the substitution of liquidity demand between term (three-months) and overnight borrowing seems an intriguing issue to investigate. Further, our study focuses on identifying the precautionary motive for liquidity. An additional channel – the "strategic" one – may also be at work. There are two aspects to this channel. One is the strategic behavior in terms of the market power of some large players in the interbank markets as suggested theoretically by Acharya et al. (2008) and supported empirically by Fecht, et al. (2010). The second is the strategic behavior due to adversely affected banks not disclosing their losses early enough and delaying asset sales (Diamond and Rajan, 2010), and safer banks hoarding cash with the motive to acquire these assets at deep discounts in future (Acharya et al., 2011 and Diamond and Rajan, 2010). It is our prior that this kind of strategic effect was prevalent *after* the failure of Lehman Brothers, when the returns on various kind of assets and trading strategies rose sky-high and an overall freeze resulted in the global financial system.

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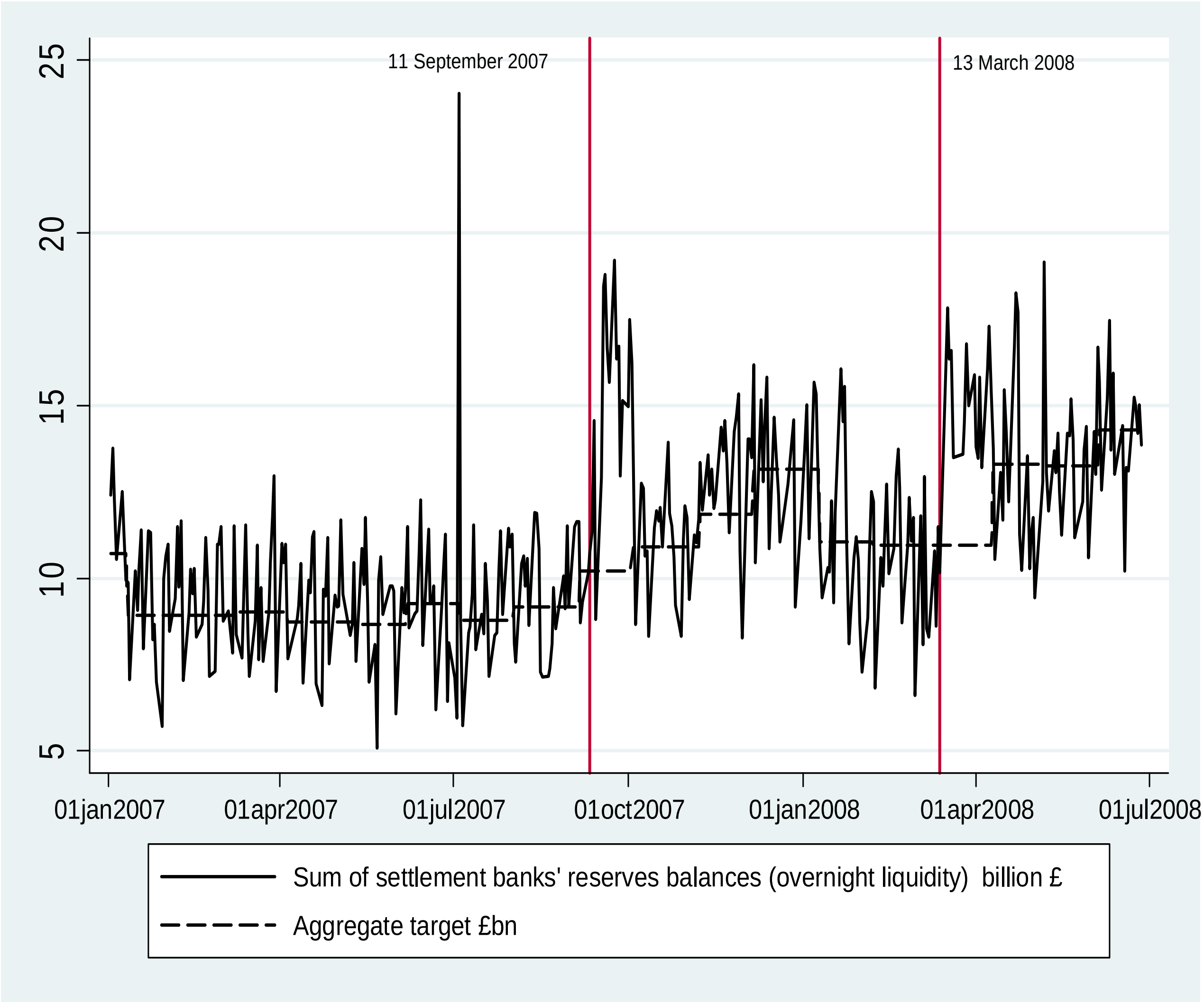

Figure 1. Overnight liquidity held by settlement banks and their aggregate targets. The overnight liquidity is the sum of the reserve accounts of all settlement banks balances measured at 5 am each day. Under the current monetary policy framework UK settlement banks *choose* a reserve target that they are required to achieve on average within a maintenance period. They reset their reserve targets at the start of each maintenance period. The data are for 10 UK settlement banks (foreign banks and subsidiaries are excluded).

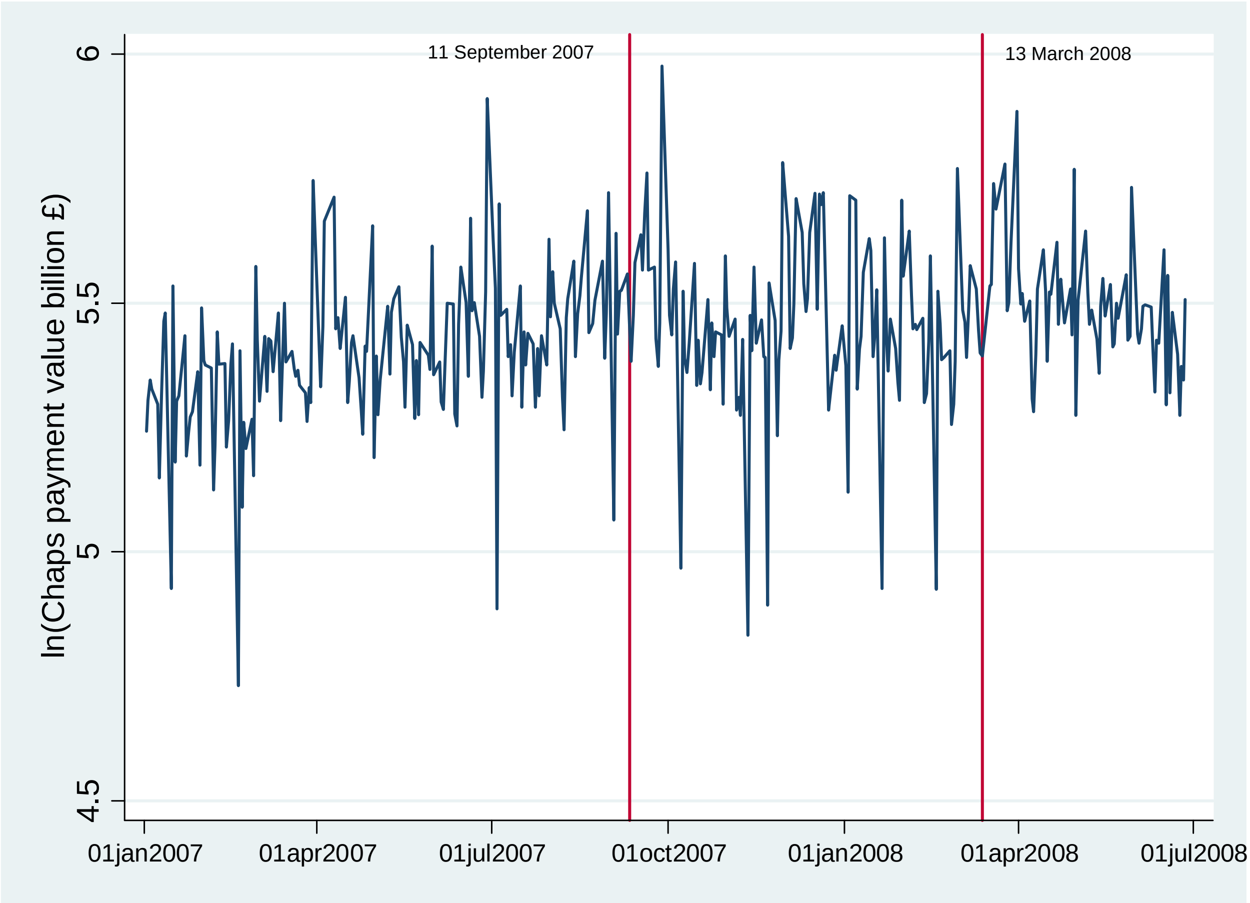

Figure 2. CHAPS payment activity (in logarithm). The payment activity (value) is the sum of all transactions that flow through CHAPS, the UK large-value payment system (the real-time-gross settlement system operated by the BoE). It is net of overnight interbank loans activity.

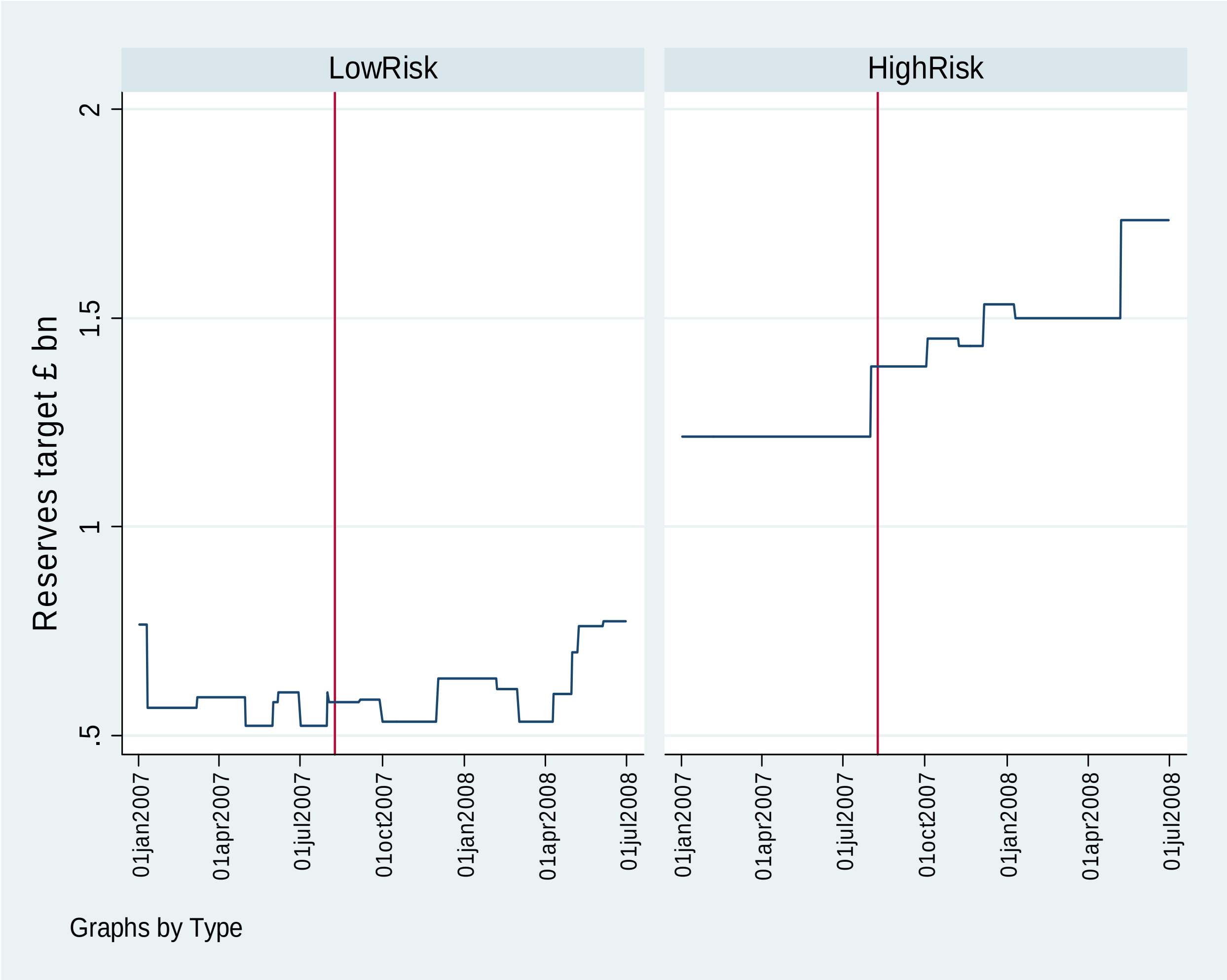

Figure 3. Average reserve targets of the high-risk banks (three banks with highest loan to retail deposits ratio), and the low-risk banks (three banks with lowest loan to retail deposits ratio), in billions of pounds. The data cover 10 UK settlement banks (foreign banks are omitted). See Figure 1 and Table I for a definition of the reserve target. The red vertical line indicates the start of the crisis.

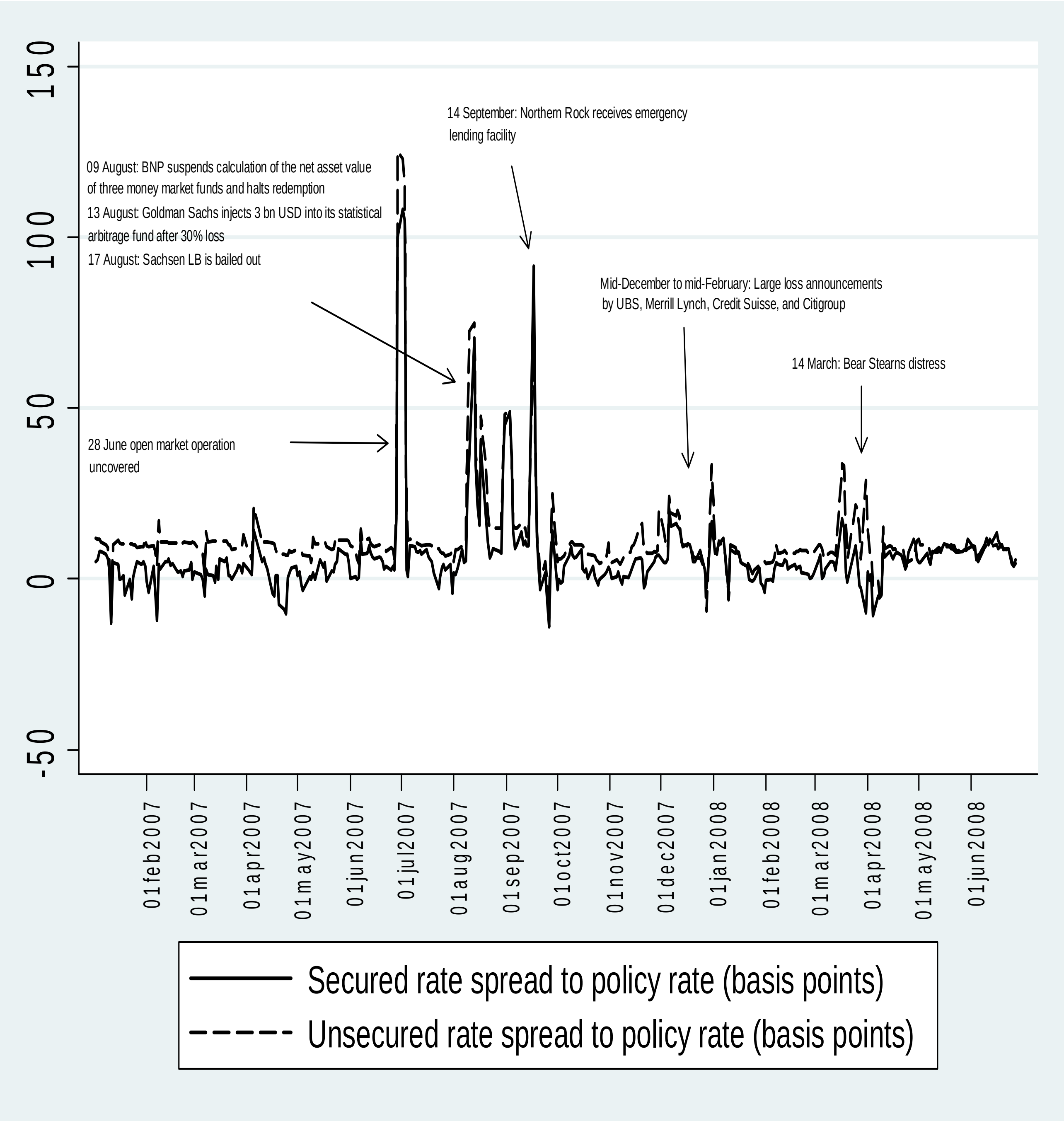

Figure 4. Overnight money market spreads (basis points) and key market events. The data are daily and cover the whole market. The secured rate is the gilt collateral rate. The unsecured overnight rate is the SONIA rate.

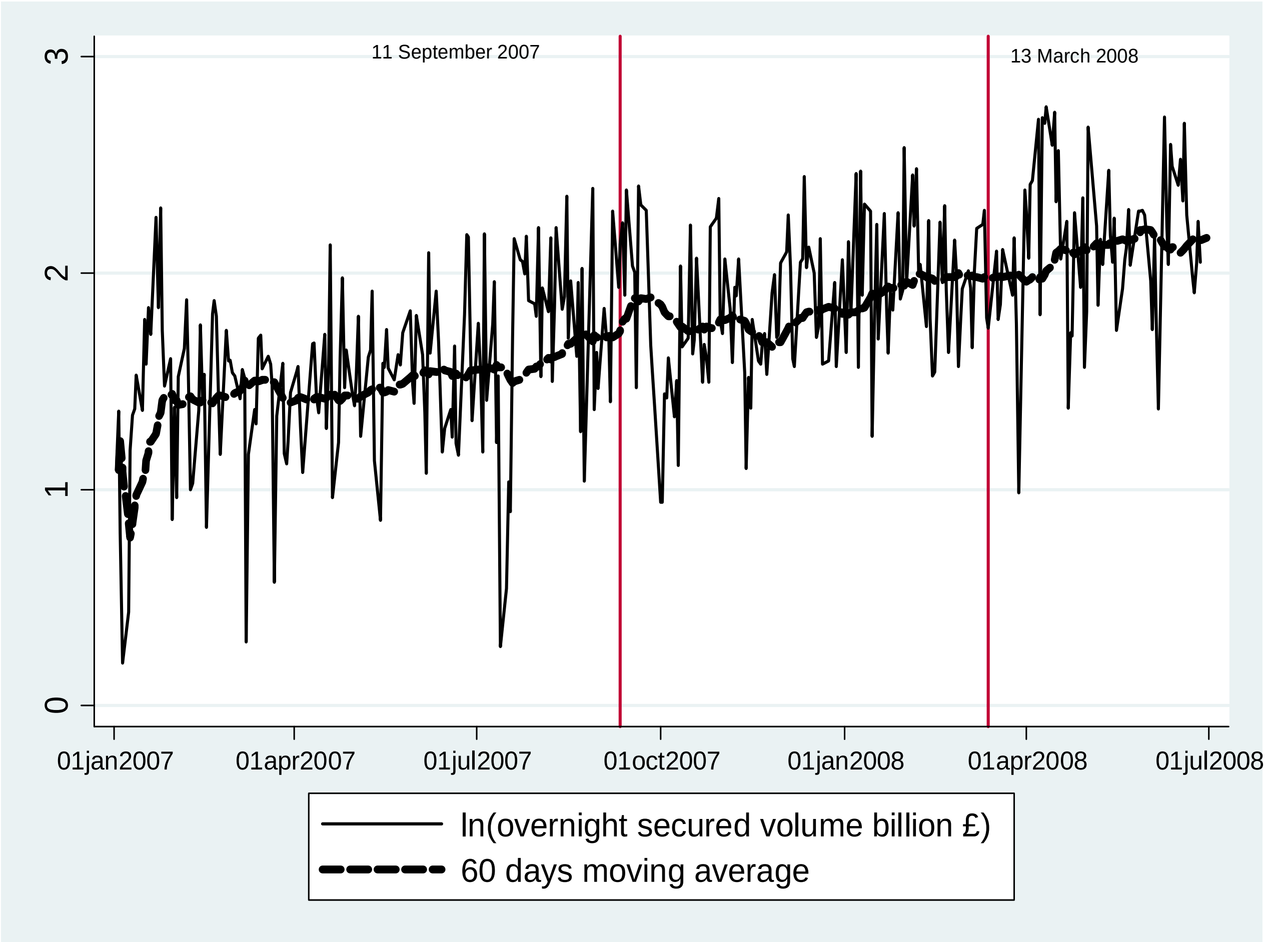

Figure 5. Secured overnight market volume. The data are from the British Bankers' Association and the Wholesale Markets Brokers' Association. The volumes reported are for activity secured by gilt collateral.

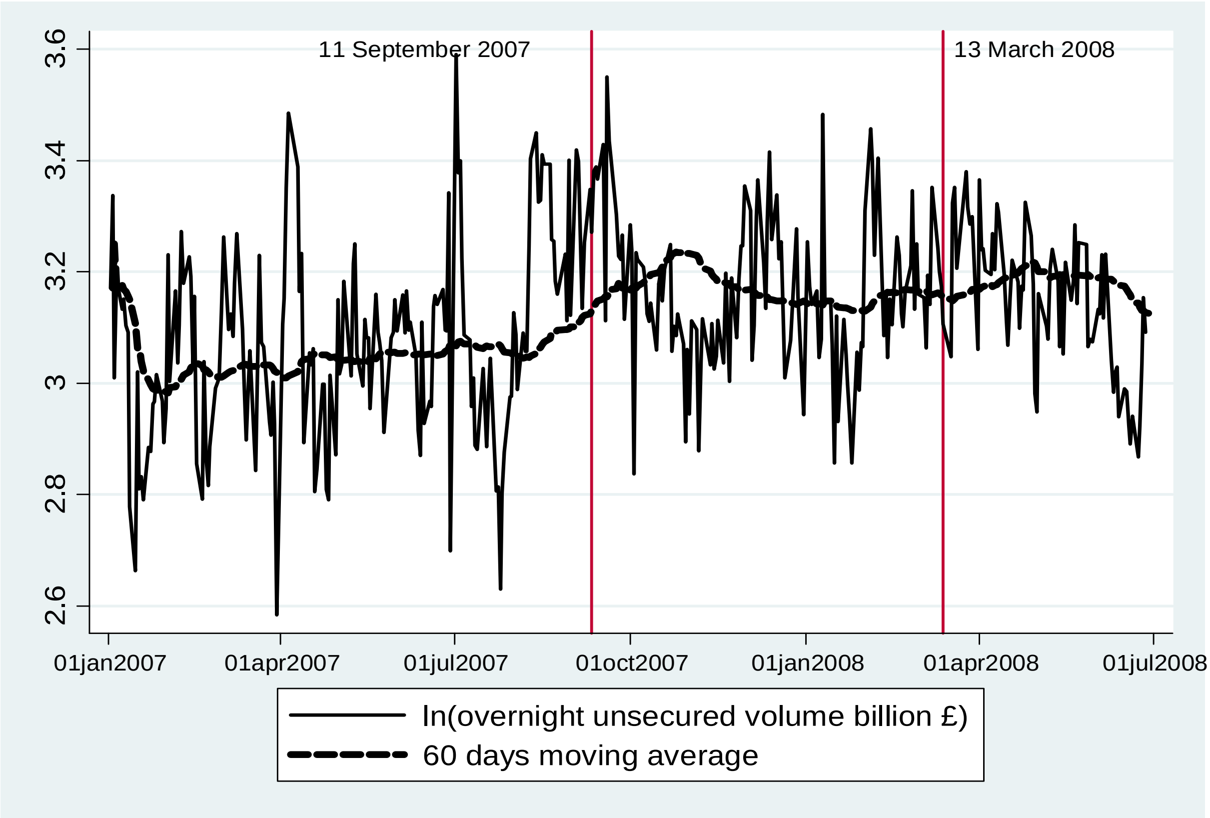

Figure 6. Unsecured overnight market volume. The data are from the BoE's statistics department. The data cover all activity settled by first-tier banks that are direct participants in the large-value payment system.

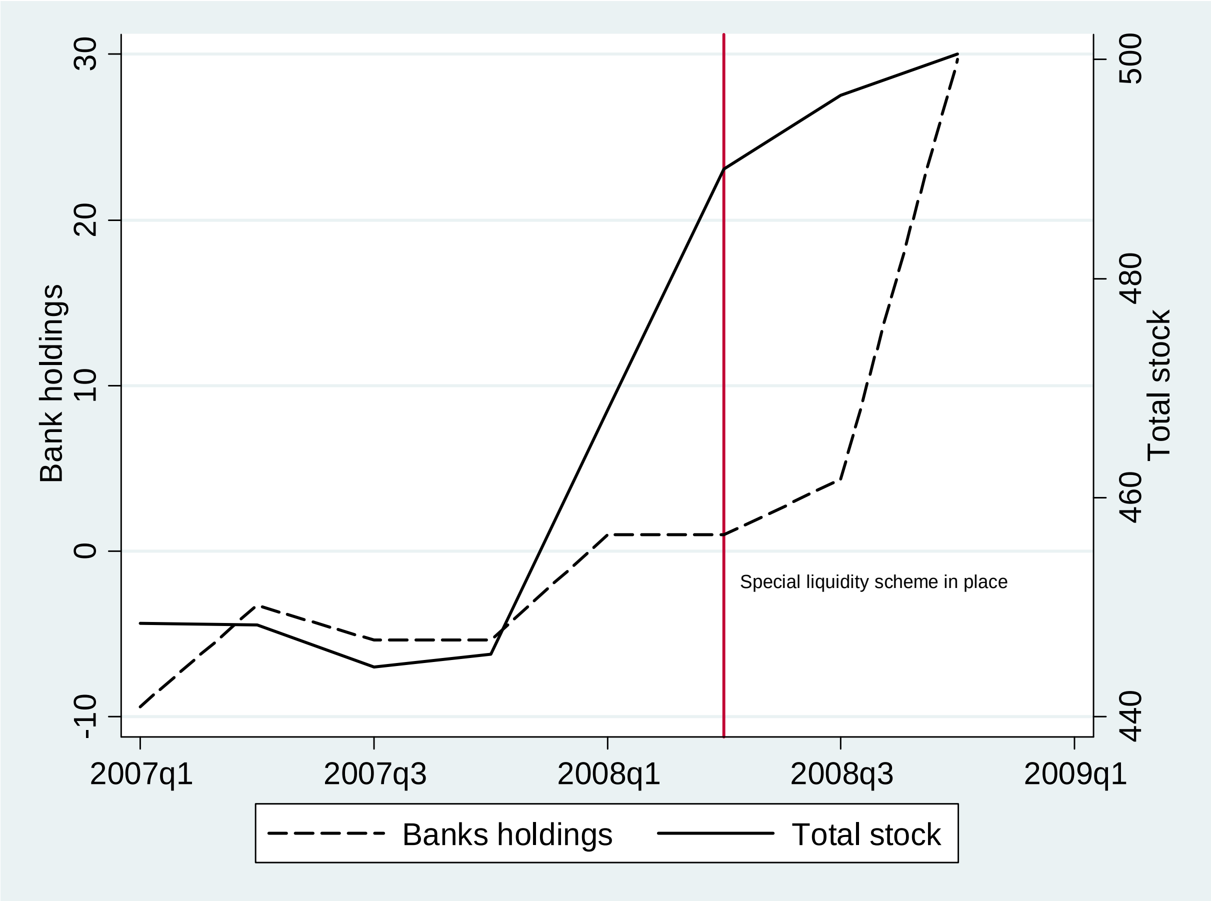

Figure 7. Total stock of gilts and Treasury bills (right axis) and banks’ holdings of gilts and Treasury bills (left axis) over time in billions of pounds. Quarterly data are from the UK DMO. The red vertical line indicates when the BoE started operation of its SLS.

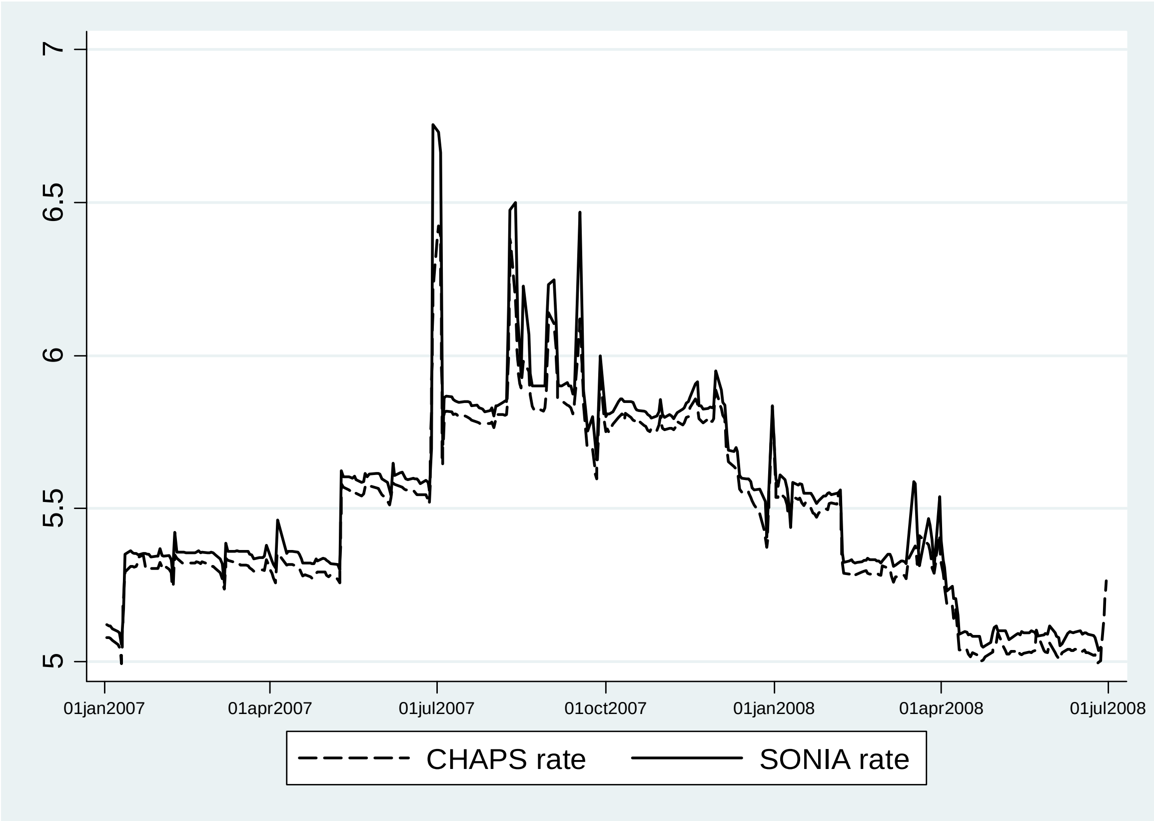

Figure 8. The CHAPS rate versus the SONIA rate. The chart shows the proximity between the unsecured rate calculated from loans identified from the CHAPS payments database using the Furfine algorithm and the Wholesale Markets Brokers' Association sterling SONIA rate.

Table I. Descriptive statistics

The data are from the BoE statistics division (when not specified otherwise) and most cover the period January 2, 2007 to June 30, 2008. Settlement (first-tier) banks are the 10 UK banks that settle their payment activity directly at the central bank. Overnight liquidity is the sum of the reserve account balances of these 10 UK settlement banks measured at 5 am each day. Intraday liquidity is measured by the amount of collateral posted by settlement banks every morning at the central bank to obtain collateralized intraday credit. Payment activity (value) is the sum of all transactions that flow through CHAPS in log(trillions of pounds), the UK large-value payment system (a real-time-gross settlement system operated by the BoE). The aggregate value of payments is net of interbank loans activity. Predicted payment activity is payment activity predicted by calendar effects as detailed in Appendix B. Aggregate (meaning covering the entire market) interest rates and volume data are from the British Bankers' Association and the Wholesale Markets Brokers' Association. The secured rate is the gilt collateral rate. The unsecured overnight rate is the sterling overnight index average (SONIA) rate. The data are daily, when not specified otherwise, and cover the period January 2, 2007 to June 30, 2008. Mismatch I is the ratio of loan assets to retail deposits, mismatch II is the ratio of total assets over retail deposits (divided by 1000), deposit fragility is the ratio of sight deposits to time deposits, and equity price fall is the cumulative decline in the equity price in number of standard deviation change relative to 2006 average. Balance-sheet data are monthly.

Variables	Mean	Standard Deviation	Min	Max	5th percentile	50th percentile	95th percentile	(pre-August 9th) - (post August 9th)	
								Difference	P-value
Variables used in bank-level regressions									
Settlement bank overnight liquidity (a)	0.10	1.07	-3.32	7.76	-1.18	-0.12	2.15		
Settlement bank intraday liquidity (a)	0.28	3.28	-12.38	63.60	-1.28	0.00	2.01		
Payment activity	0.26	0.04	0.13	0.43	0.21	0.26	0.34		
Predicted payment activity	0.23	0.02	0.12	0.28	0.22	0.23	0.25		
Aggregate variables									
ln(Overnight liquidity billion £)	2.39	0.25	1.62	3.18	1.96	2.40	2.79	-0.27	0.00
								(-0.26) (b)	(0.00)
Overnight liquidity in % deviation from aggregate target	25.00	23.35	-33.90	185.57	-10.19	23.36	63.82	2.44	0.32
								(3.34)	(0.17)
Secured overnight spread (c)	6.25	12.65	-14.17	108.33	-3.88	4.50	17.50	-2.41	0.04
								(-5.51)	(0.00)
Unsecured overnight spread (c)	11.47	13.31	-9.37	125.38	3.98	9.38	29.22	-0.66	0.61
								(-1.60)	(0.09)
Total collateral stock billion £ (d)	457.45	16.54	444.55	490.00					
Collateral held by banks billion £ (d)	-3.60	3.71	-9.39	1.00					

a. Normalized by subtracting the mean and dividing by the standard deviation both calculated over the first 12 sample months.

b. In parentheses we report values excluding the period spanning the uncovered OMO.

c. Spread to the policy rate in basis points.

d. Quarterly data from the UK DMO. Collateral available includes gilts and Treasury bills (gilts with maturity up to 12 months)

Table I. Continued

Variables	Mean	Standard Deviation	Min	Max	5th percentile	50th percentile	95th percentile	(pre-August 9th) - Difference	P-value
Log(secured volume billion £)	1.77	0.44	0.20	2.77	1.03	1.76	2.46	-0.45	0.00
								(-0.45)	(0.00)
Log(unsecured volume billion £)	3.12	0.16	2.58	3.59	2.85	3.12	3.39	-0.13	0.00
								(-0.14)	(0.00)
Risk metrics									
Mismatch I	1.68	1.19	0.90	6.50	0.90	1.40	4.80		
Mismatch II	0.14	0.27	0.01	1.13	0.01	0.03	0.88		
Deposit fragility	0.52	0.10	0.23	0.72	0.31	0.55	0.69		
Equity price fall	0.27	0.57	-0.17	3.98	-0.13	0.09	1.37		
Risk-weighted assets/total assets	0.45	0.29	0.15	1.53	0.16	0.44	1.08		

a. Normalized by subtracting the mean and dividing by the standard deviation both calculated over the first 12 sample months.

b. In parentheses we report values excluding the period spanning the uncovered OMO.

c. Spread to the policy rate in basis points.

Table II. Bai-Perron multiple level break test on settlement banks' liquidity

The Bai and Perron (1998) sequential algorithm is used to estimate the timing of (lasting) level shifts in the settlement banks' liquidity. This method applies an algorithm that searches all possible sets of breaks and determines for each number of breaks the set that produces the maximum goodness-of-fit. The WD max is used to investigate if at least one break is present. If there is evidence of one break the method continues to add breaks until the supLRT(l+1/l) test fails to reject the hypothesis of no additional structural changes at the 5% level or there is no room for more breaks. We allow for heterogeneous and autocorrelated errors as outlined in Bai and Perron (2003). The trimming parameter is set to 15%. This implies a minimal window length of about two months. The test result is reported in this table together with a timeline of relevant events put together using date from Bloomberg. See Table I for a definition of overnight liquidity.

Break Dates	95 % Interval	Estimates	Key Market News	Date
			BoE announces emergency lending facility to Northern Rock	**September 14, 2007**
September 11, 2007	[23/08/07;18/09/07]	2.474***	**BoEsupplies additional reserves to the banking system +25% (one week maturity)**	**September 13, 2007**
		(0.017)	UBS says it would make write downs of $3.4 bn to its fixed income portfolio	October 1, 2007
March 13, 2008	[04/03/08;08/04/08]	2.629***	Citigroup says Q3 earnings will fall 60% on a year ago	October 1, 2007
		(0.023)	Merrill Lynch announces it will make a loss in Q3 due to a $5.5bn write-down	October 5, 2007
UDmax	*SupLRt(2/1)*	*SupLRt(3/2)*	Merrill Lynch reports write-downs of $7.9 bn on sub-prime mortgages and asset-backed securities	October 24, 2007
112.673***	17.392***	8.936	Morgan Stanley announces a $3.7 bn loss on sub-prime structured credit	November 8, 2007
			Rumours of a $10bn write-down by Barclays relating to securities backed by sub-prime mortgages	November 9, 2007
			Bank of America's CEO pre-announces writedowns of $3bn in Q4.	November 13, 2007
			Bear Stearns announces an expected write down of $1.2bn in Q4	November 14, 2007
			Freddia Mac announces a Q3 loss of $2 bn	November 20, 2007
			UBS announces further write downs of $10 bn (dated to end November)	December 10, 2007
			Bank of America announces it may have to record more than its initial $3.3 bn losses and write-downs	December 12, 2007
			Citigroup announces it is to raise at least $14.5 bn in new capital	January 15, 2008
			Merrill Lynch reports $ 10.3 bn loss	January 17, 2008
			Ambac announces Q4 net loss of $3.225 bn	January 22, 2008
			XL Capital Ltd expects a Q4 net loss of up to $1.2 bn	January 23, 2008
			Credit Suisse announces additional $2.85 bn losses	February 19, 2008
			JP Morgan agrees to provide secured lending to Bear Stearns	**March 14, 2008**
			JP Morgan agrees to purchase Bear Stearns for $2 per share	**March 16, 2008**
			Fed gives primary dealers effective access to the discount window through a new credit facility	March 16, 2008
			HBOS equity price falls sharply on rumours of liquidity problems. HBOS denies any problem.	March 19, 2008

Note: The superscript *** stands for significance at the 1% level. Standard errors are in parentheses. Liquidity is measured as the sum of reserves accounts held at the central bank.

Table III. Precautionary liquidity demand

This table reports estimates of Equation (1). The dependent variable is the studentized individual settlement bank overnight liquidity demand expressed as a function of the predicted aggregate level of payment activity, allowing for a shift in this relationship during the crisis. See Table I for a definition of liquidity demand and payment activity. Predicted payment activity is payment activity predicted by calendar effects as detailed in Appendix B. Overnight liquidity is normalized by subtracting the mean and dividing by the standard deviation, both calculated over the first 12 sample months. The regressions are run on data covering the 10 UK settlement banks in the period January 2, 2007 to June 30, 2008. The variable Break1 is a dummy variable that takes value one post September 11, 2007; and Break2 takes value one post March 13, 2008. We report robust standard errors in parentheses. In column (6) the "uncovered OMO" is a dummy that takes value one in the last week of June 2007. In column (7) Break1 is a dummy variable that takes value one from September 11, 2007 to the end of the September 2007 maintenance period; and Break2 takes value one from March 13, 2008 to the end of the March 2008 maintenance period.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Predicted payment activity	-4.170**	-7.018**	-7.018**	-13.996***	-4.207*	-4.104*	-4.816***
	(1.327)	(2.317)	(2.317)	(4.082)	(1.985)	(1.965)	(0.931)
Predicted payment activity*Break1		5.125**	5.107**	8.831**	4.549**	4.404**	-1.334
		(2.105)	(2.077)	(3.435)	(1.907)	(1.881)	(3.407)
Predicted payment activity*Break2			-4.552				5.556
			(4.665)				(5.114)
Lagged deviation from target				0.002			
				(0.001)			

Table III. Continued

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Break1		-0.773	-0.846	-1.635*	-0.634	-0.607	0.144
		(0.536)	(0.523)	(0.866)	(0.502)	(0.494)	(0.783)
Break2			1.29				-0.777
			(1.144)				(1.226)
Uncovered OMO						-0.264	
						(0.197)	
Constant	1.067***	1.505**	1.505**	3.095**	0.949	0.928	1.201***
	(0.308)	(0.567)	(0.567)	(0.972)	(0.539)	(0.534)	(0.217)
R-Squared	0.01	0.05	0.05	0.06	0.07	0.07	0.02
Maintenance days fixed effects	no	no	no	no	yes	yes	no
Bank fixed effects	yes	yes	yes	yes	yes	yes	yes
Number of observations	3760	3760	3760	2950	3760	3760	3760

Note: The superscripts *, **, and **** indicate significance at the 10%, 5% and 1% levels, respectively.

Table IV. Relationship between liquidity demand and bank risk

We estimate an individual bank's studentized demand for liquidity as a function of alternative risk metrics. See Table I for a definition of overnight liquidity demand. Overnight liquidity demand is normalized by subtracting the mean and dividing by the standard deviation both calculated over the first 12 sample months. In column (1) risk is measured by the ratio of loan assets to retail deposits (Mismatch I), in column (2) risk is total assets divided by retail deposits (Mismatch II), in column (3) risk is the ratio of sight deposits to time deposits (deposit fragility), in column (4) risk is the cumulative equity price fall, and in column (5) risk is the ratio of risk-weighted assets to total assets. The regressions are run on data covering the 10 UK settlement banks in the period January 2, 2007, to June 30, 2008. The variable Break1 is a dummy that takes value one post September 11, 2007. We report robust standard errors in parentheses.

	Mismatch I	Mismatch II	Deposit Fragility	Equity Price Fall	Risk-Weighted Assets
	(1)	(2)	(3)	(4)	(5)
Risk	-0.062	0.003	-1.584	-0.877***	-1.228***
	(0.046)	(0.313)	(1.723)	(0.016)	(0.255)
Risk*Break1	0.164***	0.766***	-0.858	0.734***	0.764***
	(0.032)	(0.164)	(1.162)	(0.013)	(0.136)
Break1	0.779***	0.942***	1.228	0.973***	0.570***
	(0.233)	(0.228)	(0.705)	(0.235)	(0.221)
Constant	0.188	0.078	0.357	-0.076	0.040
	(0.159)	(0.144)	(0.889)	(0.143)	(0.254)
R-Squared	0.09	0.09	0.06	0.09	0.08
Maintenance period fixed effects	yes	yes	yes	yes	yes
Bank fixed effects	yes	yes	yes	yes	yes
Number of observations	3016	3016	3770	2582	3329

Note: The superscript **** indicates significance at the 1% level.

Table V. Relationship between liquidity demand, payment activity, and bank risk

We estimate an individual bank's studentized demand for overnight liquidity as a function of aggregate predicted payment activity interacted with alternative risk rankings. See Table I for a definition of liquidity and payment activity. Liquidity is normalized by subtracting the mean and dividing by the standard deviation, both calculated over the first 12 sample months. In column (1) risk is measured by the ratio of loan assets to retail deposits (Mismatch I), in column (2) risk is total assets divided by retail deposits (Mismatch II), in column (3) risk is the ratio of sight deposits to time deposits (deposit fragility), in column (4) risk is the cumulative equity price fall, and in column (5) risk is the ratio of risk-weighted assets to total assets. We split the sample of 10 banks in three groups according to the value of the risk metric used: high risk for top three banks (HR dummy), medium risk for middle four banks (MR dummy), and low risk for bottom three banks (LR dummy). The regressions are run on data covering the 10 UK settlement banks in the period January 2, 2007 to June 30, 2008. The variable Break1 is a dummy that takes value one post September 11, 2007. We report robust standard errors in parentheses.

	Mismatch I	Mismatch II	Deposit Fragility	Equity Price Fall	Risk-Weighted Assets
	(1)	(2)	(3)	(4)	(5)
Predicted payment activity*LR	-9.004***	-9.127***	-6.999*	-6.146	-8.723**
	(2.301)	(2.312)	(3.519)	(3.639)	(3.237)
Predicted payment activity*MR	-10.38***	-10.29***	-4.875*	-5.252*	-7.061***
	(2.625)	(2.675)	(2.439)	(2.449)	(2.021)
Predicted payment activity*HR	-5.272**	-5.272**	-9.364***	-5.482**	-9.553**
	(1.557)	(1.557)	(2.021)	(1.650)	(2.998)
Predicted payment activity*Break1*LR	4.208	4.070	2.854	1.352	2.434
	(2.469)	(2.284)	(2.276)	(2.504)	(2.622)
Predicted payment activity*Break1*MR	4.722	4.825	3.627	2.944	5.389**
	(2.563)	(2.755)	(2.718)	(3.001)	(2.107)
Predicted payment activity*Break1*HR	6.714**	6.714**	3.464	3.638	5.068**
	(2.854)	(2.854)	(1.943)	(2.922)	(2.008)
Break1	-0.102	-0.102	-0.019	0.447	-0.172
	(0.644)	(0.644)	(0.534)	(0.647)	(0.572)
Tests p-values X=Payment activity					
X*HR*Break1=X*LR*Break1	0.02	0.02	0.69	0.05	0.02
R-Squared	0.11	0.11	0.07	0.09	0.10
Maintenance period fixed effect	yes	yes	yes	yes	yes
Bank fixed effect	yes	yes	yes	yes	yes
Number of observations	3008	3008	3760	2632	3384

Note: The superscripts *, **, and **** indicate significance at the 10%, 5% and 1% levels, respectively.

Table VI. Impact of settlement banks' precautionary liquidity hoarding on overnight money market spreads and volumes

We report OLS estimates of the liquidity effect on market-wide overnight secured and unsecured rate spreads and volumes in columns (1) to (4). Columns (5) to (8) report 2SLS estimates using lagged measures of payment activity (volume and value) as instruments for liquidity demand. The spreads (from policy rate) are in basis points. All variables are defined and sources reported in Table I. The market data are aggregated daily data for the period January 2, 2007 to June 30, 2008. Liquidity is the sum of the 10 first-tier UK settlement banks' reserve balances held at the central bank. The variable Break1 is a dummy that takes value one post September 11, 2007. We report robust standard errors in parentheses.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	OLS				2SLS			
	Secured Spread	Unsecured Spread	Secured Volume	Unsecured Volume	Secured Spread	Unsecured Spread	Secured Volume	Unsecured Volume
Liquidity	-21.520***	-22.490***	0.136	0.064	-42.150	-26.000	0.748	-0.430
	(5.238)	(5.576)	(0.164)	(0.063)	(28.690)	(30.580)	(0.902)	(0.348)
Liquidity*Break1	20.480***	24.800***	-0.457**	-0.112	101.700***	93.470**	-0.177	0.488
	(7.124)	(7.583)	(0.223)	(0.086)	(34.910)	(37.210)	(1.098)	(0.424)
Break1	-51.680***	-65.000***	1.125*	0.331	-278.600***	-262.3***	0.0973	-1.174
	(19.970)	(21.260)	(0.625)	(0.241)	(95.450)	(101.700)	(3.001)	(1.158)
Constant	62.32***	67.560***	0.561	2.989	21.210	-63.02	0.427	3.852***
	(14.270)	(15.630)	(0.446)	(0.172)	(118.600)	(126.400)	(3.728)	(1.438)
Maintenance period fixed effects	yes	yes	yes	yes	yes	yes	yes	yes
First stage F-statistic					17.07	17.07	17.07	17.07
Underidentification test p-value					0.03	0.03	0.03	0.03
Hansen-Sargan test p-value					0.64	0.52	0.25	0.49
Number of observations	376	376	376	376	296	296	296	296

Note: The superscripts *, **, and **** indicate significance at the 10%, 5% and 1% levels, respectively.

Table VII. Robustness checks: controlling for the quantity of collateral

We report 2SLS estimates of the liquidity effect on the secured rate spread to policy rate and the secured volume (in logarithms), where we use lagged aggregate payment activity measures (volume and value) as instruments for liquidity demand. The markets data are aggregated daily data for the period January 2, 2007 to June 30, 2008. Liquidity is the sum of the 10 first-tier UK settlement banks' reserve balances held at the central bank in logarithm. The variable Break1 is a dummy that takes value one post September 11, 2007. SLS dummy is a dummy that takes value one after the introduction of the BoE special liquidity scheme. Collateral includes gilts and Treasury bills. All variables are defined and sources reported in Table I. We report robust standard errors in parentheses.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Spread				**Volume**			
Liquidity	-38.710	-35.490	-45.830	-39.730	1.147	1.115	0.855	0.712
	(29.310)	(31.150)	(29.820)	(27.510)	(0.953)	(0.989)	(0.930)	(0.904)
Liquidity*Break1	99.810***	108.300***	106.200***	95.960***	-0.323	0.191	-0.279	-0.096
	(34.420)	(41.170)	(35.490)	(32.440)	(1.119)	(1.306)	(1.107)	(1.066)
Break1	-274.500***	-300.0***	-289.900***	-262.800***	0.352	-1.101	0.345	-0.122
	(94.330)	(115.000)	(96.720)	(88.640)	(3.066)	(3.650)	(3.017)	(2.913)
SLS dummy	-6.082				-0.669***			
	(6.721)				(0.218)			
Collateral held by banks			-1.299				0.029	
			(0.904)				(0.028)	
Total collateral				-0.624**				0.009
				(0.263)				(0.009)
Constant	13.450	-4.105	38.670	333.200**	-0.553	-1.023	-0.068	-4.170
	(120.200)	(131.300)	(123.800)	(158.800)	(3.905)	(4.166)	(3.864)	(5.219)
Maintenance period fixed effects	yes	yes	yes	yes	yes	yes	yes	yes
First stage F-statistic	16.42	13.79	16.43	16.58	16.42	13.79	16.43	16.58
Underidentification test p-value	0.04	0.1	0.03	0.03	0.04	0.10	0.03	0.03
Hansen-Sargan test p-value	0.61	0.61	0.61	0.48	0.36	0.34	0.28	0.24
Number of observations	296	258	296	296	296	258	296	296

Note: The superscripts **, and **** indicate significance at the 5% and 1% levels, respectively.

Table VIII. Descriptive statistics: Bilateral money market data

The bilateral data on money market activity are derived from transaction level information extracted from the BoE payments database. The data cover the 10 UK settlement banks over 22 maintenance periods in the period January 2007 to June 2008. Spread is the bilateral spread, i.e. the cost of borrowing charged by one bank to another, and volume is the bilateral liquidity flow, the volume lent by one bank to another. The spread is the average value-weighted interest rate charged by one bank to another minus the policy rate, in basis points. It is observed for pairs of banks that trade a positive amount. The bilateral volume is the sum of all interbank loan transactions between any two banks within a maintenance period. Reserves target is the amount of reserves each bank chooses at the start of each maintenance period to target, on average, over the maintenance period. The reserve target of a bank is scaled by the bank payment activity, as a proxy for bank size. The volume lent is scaled by lender payment activity.

Variables	Number of observations	Mean	Standard Deviation	Min	Max	5th percentile	50th percentile	95th percentile
Spread	1203	6.15	9.15	-87.00	110.00	-1.88	5.67	19.94
Volume/payment activity	1694	0.31	0.26	0.00	0.87	0.00	0.33	0.71
Reserves target/payment activity	1694	0.19	0.22	0.02	1.24	0.02	0.12	0.69

Table IX. Sensitivity of bilateral trade volumes and spreads to lender and borrower liquidity endowments

The dependent variable is the bilateral spread or the bilateral volume. The specification for the spread corrects for sample selection (using a Heckman model) where the probability of a positive trade is predicted in the first stage by the amount of bilateral payments net of interbank loans. The selection equation is reported in Appendix E. The volume equation is estimated from a Tobit model. The sample covers 10 UK banks over 22 maintenance periods from January 2007 to June 2008. All specifications include maintenance period fixed effects. Standard errors clustered by bank-pairs are reported in parentheses. See Table VIII for a definition of the spread, volumes, and reserve. The reserve target of a bank is scaled by its payment activity. The volume lent is scaled by the lender payment activity.

	(1)	(2)	(3)	(4)
	Spread		**Volume**	
	Heckman model		**Tobit model**	
Borrower reserve target	-1.993	1.646	-1.361***	-1.332***
	(1.997)	(3.538)	(0.191)	(0.177)
Lender reserve target	3.840***	0.578	-0.914***	-1.051***
	(1.114)	(1.759)	(0.198)	(0.186)
Borrower reserve target*crisis		-8.017**		-0.063
		(3.408)		(0.149)
Lender reserve target *crisis		5.929***		0.247***
		(1.912)		(0.081)
Maintenance period fixed effects	yes	yes	yes	yes
Number of observations	1203	1203	1694	1694

Note: The superscripts **, and **** indicate significance at the 5% and 1% levels, respectively.

Appendix A. Adjustments to the Monetary Policy Framework during the Crisis

The current monetary policy framework of the BoE is designed to enable it to continue achieving its primary rate-setting objective while responding to any sudden or pronounced shifts in demand for central bank money.

During the market turbulence of 2007-2008 the BoE undertook a range of adjustments to its framework giving leeway for banks to build up larger liquidity buffers. By and large, all of the changes were a response to stress in inter-bank markets and thus should be viewed as endogenous, rather than being "natural experiments."

(1) On September 13 and 18, 2007, the BoE offered an extra (i.e., above the aggregate target) £4.4 billion (each time) in its regular weekly OMOs, amounting to 25% of the aggregate reserves target for the current maintenance period. This was accommodated by an increase in the reserves band around the target from 1% to 37.5%. These actions were taken to help offset the disturbance to conditions in the short-term money markets following the announcement of lender of last resort assistance to Northern Rock on September 14, 2007. In particular, it was a recognition that reserves banks might need extra reserves over and above their announced targets at the beginning of the current maintenance period.

(2) The BoE further announced on September 19, 2007 that to alleviate strains in longer-maturity money markets it would conduct auctions to provide funds at three-month maturity against a wider range of collateral (including mortgage collateral) than in the BoE's weekly OMOs. While this change may have indirectly affected bank demand for liquidity, it does not directly affect our analysis since we focus on overnight inter-bank markets.

(3) For the maintenance period beginning on October 4, 2007, the ranges around reserves banks' targets within which reserves are remunerated were widened from +/-1% to +/-30%. The target ranges remained at this level until July 10, 2008, when they were reduced to +/-20%. Further, in view of the increase in the reserves targets set by reserves scheme members and the potential for future increase, with effect from the maintenance period starting on May 8, 2008, the BoE more than doubled the reserves target ceiling it sets for each reserves scheme member. Both of these changes allowed banks a greater response to perceived risks through their reserves balances at the BoE.

(4) On April 21, 2008, the BoE introduced the SLS to deal with the overhang of existing assets on banks' balance sheets. The scheme allows banks and building societies to swap for up to three years some of their illiquid assets for liquid Treasury Bills. In other words, the purpose of the scheme is to finance part of the overhang of currently illiquid assets by temporarily exchanging them with more easily tradable assets. The banks can then use these assets to finance themselves more normally. All of the banks and building societies that are eligible to sign up for the standing deposit and lending facilities within the bank's sterling monetary framework can take part in the scheme. It was widely perceived that, like the Federal Reserve's Primary Dealer Credit Facility in the US, this liquidity scheme played a significant role in easing concerns of funding against illiquid collateral and diffused funding risks (at least temporarily).

Appendix B. Calendar Effects on the Aggregate Level of Payment Activity

This table reports the OLS estimates of a regression of payment activity (the aggregate logarithm of the payments value between all UK banks) on various calendar effects. Here UK holidays is a dummy that takes value one on days immediately preceding and following bank holidays, US holidays takes value one on US holidays, and so forth. "Quarter 1" takes value one on each day of the last week of the first quarter, and so on so forth. Robust standard errors are reported in parentheses.

Calendar Dummies	(1)
United Kingdom Holidays [-1;+1]	0.073*
	(0.039)
United States Holidays [0]	-0.575***
	(0.032)
First 5 days of the month	0.002
	(0.018)
Last 5 days of the month	-0.009
	(0.022)
Tuesday	-0.110***
	(0.022)
Wednesday	-0.092***
	(0.020)
Thursday	-0.059***
	(0.019)
Friday	-0.002
	(0.021)
Quarter 1	0.081
	(0.064)
Quarter 2	0.035
	(0.06)
Quarter 3	0.138
	(0.107)
Quarter 4	-0.111***
	(0.031)
Constant	5.497***
	(0.015)
R-Squared	0.38
Number of observations	376

Note: The superscripts *, and **** indicate significance at the 10% and 1% levels, respectively.

Appendix C. Relationship between Intraday Liquidity Demand, Payment Activity, and Bank Risk

We estimate an individual bank's studentized demand for intraday liquidity as a function of predicted payment activity interacted with alternative risk rankings. See Table I for a definition of liquidity and payment activity. Intraday (collateralized) liquidity usage (measured by the amount of collateral posted by settlement banks every morning at the central bank) is normalized by subtracting the mean and dividing by the standard deviation, both calculated over the first 12 sample months. In column (1) risk is measured by the ratio of loan assets to retail deposits (Mismatch I), in column (2) risk is total assets divided by retail deposits (Mismatch II), in column (3) risk is the ratio of sight deposits to time deposits (deposit fragility), in column (4) risk is the cumulative equity price fall, in column (5) risk is the ratio of risk-weighted assets to total assets. We split the sample of 10 banks in three groups according to the value of the risk metric used: high risk for top three banks (HR dummy), medium risk for middle four banks (MR dummy), and low risk for bottom three banks (LR dummy). The regressions are run on data covering the 10 UK settlement banks in the period January 2, 2007 to June 30, 2008. The variable Break3 is a dummy that takes value one post August 8, 2007, the Bai-Perron structural break date in the intraday liquidity time series. We report robust standard errors in parentheses.

	Mismatch I	Mismatch II	Deposit Fragility	Equity Price Fall	Risk-Weighted Assets
	(1)	(2)	(3)	(4)	(5)
Predicted payment activity*LR	3.136	2.214	-4.602*	-1.654	-4.717*
	(2.247)	(2.193)	(2.267)	(1.593)	(2.467)
Predicted payment activity*MR	-5.601*	3.534	-3.350	-2.396	-2.521
	(2.434)	(3.945)	(2.261)	(2.431)	(2.846)
Predicted payment activity*HR	6.337	-4.068	2.562	1.202	5.540
	(4.810)	(2.442)	(2.310)	(2.876)	(3.239)
Predicted payment activity*Break3*LR	-7.073**	-9.093***	3.590	1.113	4.386*
	(2.338)	(2.034)	(2.374)	(2.051)	(2.038)
Predicted payment activity*Break3*MR	5.146**	2.572	4.832*	2.717	1.792
	(1.800)	(3.465)	(2.231)	(2.148)	(2.646)
Predicted payment activity*Break3*HR	3.905	3.907*	-0.293	0.652	-1.253
	(3.978)	(1.932)	(2.638)	(3.595)	(4.131)
Break3	-0.153	-0.153	-0.210	-0.00348	-0.155
	(0.323)	(0.323)	(0.261)	(0.255)	(0.285)
Tests p-values X=Payment activity					
X*HR*Break3=X*LR*Break3	0.02	0.00	0.33	0.93	0.05
R-Squared					
Maintenance period fixed effect	yes	yes	yes	yes	yes
Bank fixed effect	yes	yes	yes	yes	yes
Number of observations	3008	3008	3760	2632	3384

Note: The superscripts *, **, and **** indicate significance at the 10%, 5% and 1% levels, respectively.

Appendix D. Robustness Check: Measuring the "Liquidity Effect" using Liquidity Holdings in Percentage Deviation from Target

We report 2SLS estimates of the liquidity effect on the secured and unsecured rates spread to the policy rate and the volumes (in logarithm) where lagged agregate payment activity measures (volume and value) are used as instruments for liquidity demand. The markets data are aggregated daily data for the period January 2, 2007 to June 30, 2008. Liquidity is the sum of the 10 first-tier UK settlement banks' reserve balances held at the central bank in percentage deviation from their aggregate target. The variable Break1 is a dummy that takes value one post September 11, 2007. All variables are defined and sources reported in Table I. We report robust standard errors in parentheses.

	(1)	(2)	(3)	(4)
	Secured Spread	Unsecured Spread	Secured Volume	Unsecured Volume
Liquidity	-0.652**	-0.402	-0.003	-0.003
	(0.265)	(0.279)	(0.009)	(0.003)
Liquidity*Break1	0.825**	0.618*	0.011	0.005
	(0.344)	(0.370)	(0.013)	(0.004)
Break1	-23.830***	-22.130**	0.164	-0.053
	(9.078)	(9.994)	(0.308)	(0.104)
Constant	-8.922	-63.500	2.179	2.432***
	(72.810)	(58.820)	(2.286)	(0.861)
First stage F-statistic	14.65	14.65	14.65	14.65
Underidentification test p-value	0.00	0.01	0.02	0.03
Hansen-Sargan test p-value	0.29	0.22	0.95	0.08
Number of observations	295	295	295	295

Note: The superscripts *, **, and **** indicate significance at the 10%, 5% and 1% levels, respectively.

Appendix E. Selection Equation

This table reports the logit estimates of the probability of two banks (*i* and *j*) being counterparties in the interbank market as a function of the amount of their bilateral payment activity (net of interbank loan activity). Payment activity *ij* is the payment flow from bank *i* to bank *j*. See Table I for a definition of payment activity. The sample covers 10 UK settlement banks over 22 maintenance periods from January 2007 to June 2008. Both specifications include maintenance period fixed effects.

	(1)
Payment activity *ij*	0.377**
	(0.161)
Payment activity *ji*	0.352**
	(0.179)
Nber. of observations	1694

Note: The superscripts *, **, and **** indicate significance at the 10%, 5% and 1% levels, respectively.

Appendix F. Reduced-Form Effect of Lender and Borrower Risk on Bilateral Spreads and Volumes

The dependent variable is the bilateral spread or the bilateral volume. The specification for the spread corrects for sample selection (using the Heckman model) where the probability of a positive trade is predicted in the first stage by the amount of bilateral payments (net of interbank loans). The selection equation is reported in Appendix E. The volume equation is estimated from a Tobit model. The sample covers 10 UK settlement banks over 22 maintenance periods from January 2007 to June 2008. All specifications include maintenance period fixed effects. The reserves target of a bank is scaled by its payment activity. The volume lent is scaled by the lender payment activity. In column (1) risk is measured by the ratio of loan assets to retail deposits (Mismatch I), in column (2) risk is total assets divided by retail deposits (Mismatch II), in column (3) risk is the ratio of sight deposits to time deposits (deposit fragility), in column (4) risk is the cumulative equity price fall, in column (5) risk is the ratio of risk-weighted assets to total assets. Standard errors clustered by bank-pair are reported in parentheses. See Table VIII for a definition of the spread, the volumes, and reserves target and see Table I for descriptive statistics of the various risk metrics.

Panel A. Dependent variable: Bilateral spread

	Mismatch I	Mismatch II	Deposit Fragility	Equity Price Fall	Risk-Weighted Assets
	(1)	(2)	(3)	(4)	(5)
Borrower risk	0.126	0.006	0.567	-5.541	0.247
	(0.265)	(0.011)	(4.211)	(5.556)	(1.019)
Lender risk	-0.592**	-0.022*	1.804	0.890	-0.807
	(0.272)	(0.012)	(3.552)	(9.533)	(1.489)
Borrower risk*crisis	0.341	0.024	0.024	3.696	0.577
	(0.412)	(0.017)	(4.621)	(5.582)	(1.282)
Lender risk *crisis	1.053**	0.0297*	-6.226	0.219	3.235*
	(0.435)	(0.018)	(4.239)	(9.550)	(1.725)
Maintenance period fixed effects	yes	yes	yes	yes	yes
Uncensored observations	827	827	1146	811	859

Note: The superscripts *, ** indicate significance at the 10% and 5% levels, respectively.

Panel B. Dependent variable: Bilateral volume

	Mismatch I	Mismatch II	Deposit Fragility	Equity Price Fall	Risk-Weighted Assets
	(1)	(2)	(3)	(4)	(5)
Borrower risk	-0.011***	-0.040***	0.170***	0.116*	-0.088***
	(0.001)	(0.003)	(0.035)	(0.069)	(0.014)
Lender risk	-0.003**	-0.017**	-0.077**	0.076	-0.110***
	(0.001)	(0.007)	(0.032)	(0.055)	(0.025)
Borrower risk*crisis	-0.004**	0.006	-0.023	-0.111	0.017
	(0.002)	(0.006)	(0.043)	(0.069)	(0.018)
Lender risk *crisis	-0.001	0.004	0.063	-0.072	0.051*
	(0.002)	(0.009)	(0.039)	(0.055)	(0.029)
Maintenance period fixed effects	yes	yes	yes	yes	yes
Nber of observations	1048	1048	1609	974	1180

Note: The superscripts *, **, and **** indicate significance at the 10%, 5% and 1% levels, respectively.