DISCUSSION PAPER SERIES

No. 8859

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FINANCIAL ECONOMICS

Centre for Economic Policy Research

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ISSN 0265-8003

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Discussion Paper No. 8859
February 2012

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CEPR Discussion Paper No. 8859

February 2012

ABSTRACT

Precautionary hoarding of liquidity and inter-bank markets: Evidence from the sub-prime crisis*

We study the liquidity demand of large settlement (first-tier) banks in the UK and its effect on the Sterling Money Markets before and during the sub-prime crisis of 2007-08. Liquidity holdings of large settlement banks experienced on average a 30% increase in the period immediately following 9th August, 2007, the day when money markets froze, igniting the crisis. In the UK, unlike in the US until October 2008, the remuneration of reserves accounts provides strong incentives for banks to park liquidity at the central bank rather than lend in the market. We show that following this structural break, settlement bank liquidity had a precautionary nature in that it rose on calendar days with a large amount of payment activity and for banks with greater credit risk. We establish that the liquidity demand by settlement banks caused overnight inter-bank rates to rise and volumes to decline, an effect virtually absent in the pre-crisis period. This liquidity effect on inter-bank rates occurred in both unsecured borrowing as well as borrowing secured by UK government bonds. Further, using bilateral data we show that the effect was more strongly linked to lender risk than to borrower risk.

JEL Classification: E42, E58, G21 and G28
Keywords: cash, contagion, counterparty risk, funding risk, money markets, rollover risk and systemic risk

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* A part of this paper was completed while Acharya was a Senior Houblon-Norman Fellow at the Bank of England (BoE) and a Professor of Finance at London Business School, and Ouarda Merrouche was an Economist at the BoE's Financial Stability Directorate. This paper reflects the authors' own opinion and not necessarily those of the BoE. Acharya is grateful for the support of BSI Gamma Foundation and Europlace de Finance. Authors are grateful to seminar participants at the Bangor Business School, Bank of England, BSI Gamma Foundation's September 2008 Conference in Zurich, the CREDIT Conference 2008 in Venice, De Paul University, the Euronext conference in Amsterdam 2009, the European Central Bank, Europlace de Finance conference 2009, FIRS Conference 2010, Goethe University, the Kansas Fed, the NBER Summer Institute 2009, University of Waterloo, Unicredit Conference 2009, the World Bank, the paper's discussants (Morten Bech, Catharine Casamatta, Hans Degryse, Arvind Krishnamurthy, David Lando, Loriana Pelizzon and Enrichetta Ravina), Jose Liberti, Kjell Nyborg, Raghuram Rajan, Amit Seru, Vikrant Vig, and especially Roger Clews and Simon Wells (for helpful discussions and insights concerning BoE's monetary policy framework and Sterling money markets). We thank Rachel Bracken and Liz Tregear for help with collecting the data and Rustom Irani for research assistance. All errors remain our own.

Submitted 1 January 2012

1 Introduction

1.1 Motivation

The financial crisis of 2007–2009 has highlighted the important role played by money markets (short-term borrowing and lending markets between banks and bank-like institutions) in shuffling liquidity around the financial system. Globally, these markets experienced severe stress starting with the 9th of August, 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 (ABCP), which caused rollover problems for structured investment vehicles (SIV's) 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 took the risk of assets from SIV's and conduits back on their balance sheets.[1] In the period that followed, inter-bank markets for borrowing and lending also seemed to get adversely affected.

Inter-bank markets are generally the private lender-of-last-resort for banks' short-term liquidity needs. Lack of adequate liquidity flow through these markets is considered to have 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. Also, central banks' transmission mechanism for monetary policy could be rendered less effective if its liquidity

[1]This was either due to reputational reasons or due to liquidity and credit guarantees that sponsoring banks had contractually provided to the SIV's and conduits. See Acharya, Schnabl and Suarez (2009).

provision gets trapped on balance-sheets of some banks instead of lubricating the flow of credit amongst banks. In turn, central banks may be forced to resort to emergency lending operations (as has been witnessed through a series of liquidity facilities created by the New York Federal Reserve, the Bank of England, the European Central Bank, 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 inter-bank 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 inter-bank rates.[2] Our broad conclusion is that events unfolding since August 9, 2007 had the effect of increasing the funding risk 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, inter-bank rates rose in *both* secured and unsecured markets, suggestive of an interest-rate contagion through the inter-bank 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 the settlement banks since they can be considered as 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

[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 (FT) 12 August 2007: "Scramble for cash reflects fears for system"; FT 26 March 2008: "Hoarding by banks stokes fear over crisis"; FT 19 May 2008: "Loans to banks limited despite market thawing".

they face and how this demand affects market-wide and bank-specific inter-bank rates provides a natural setting for the questions we wish to answer. We examine bank liquidity in terms of their reserve balances with the central bank and the price of this liquidity in terms of the overnight inter-bank rates.

The reserve balances held by banks at a central bank can be understood as their "checking accounts."[3] 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 payment; or, to have illiquid claims by extending own reserves to others in the economy in the form of loans to households and corporations, to other banks through inter-bank markets, purchase assets such as mortgage-backed securities, etc. Each financial transaction taking place in the economy (for example, a retail depositor withdrawing from 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 reserves to meet all of their payment activity. Hence, they use the inter-bank market to exchange reserves. In turn, the total financial activity in the economy ends up being a large multiplier on the quantity of circulating reserves. For instance, aggregate reserves of 20 billion £ can support over 1 trillion £ of transaction activity, and conversely, reduction in 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

[3]We are grateful to one of our discussants, Arvind Krishnamurthy, for providing this analogy.

in these transactions and determine the price at which reserves are exchanged in the inter-bank market. Banks have access to the central bank's discount window to borrow reserves overnight but at a penalty. However, generally such borrowing is also associated with the "stigma" that if borrowing in isolation, a bank might be perceived to be riskier than others, triggering a run on the bank.[4]

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 got significantly impaired. We investigate how this affected the portfolio decision 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 inter-bank market.

1.2 Empirical setting and results

Our choice of the Sterling money markets is driven primarily by the fact that the Bank of England (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 2, the remuneration offered by the BoE on these reserves (within a band) implies that it was

[4] Armantier, Ghysels, Sarkar and Shrader (2010) provide compelling evidence of such a stigma attached to borrowing from the discount window during the financial crisis of 2007-08.

optimal for banks to park their liquidity in the form of these reserves.[5]

Further, under the BoE monetary policy framework, banks are allowed to determine their own reserves 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 as their "overnight liquidity"), allowing for its separation from fluctuations in bank reserves induced due to *supply* of reserves by the central bank.[6] Finally, since we focus on reserves held by settlement banks, which form a subset of banks that hold total reserves of the economy, there are daily shifts in our measure of settlement bank liquidity even when there is no change affected by the BoE in 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 payments activity; funding needs arising from idiosyncratic payments fluctuations are more easily met through borrowing from other

[5]In contrast, the Federal Reserve in the United States did not pay interest on reserves until October 2008 so that bank liquidity over and above the reserves requirement would typically not be parked at the Federal Reserve.

[6]We have also studied "total liquidity" that includes the bank collateral as 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 total liquidity.

banks in the overnight market.[7] Such response of settlement bank liquidity to payment activity is non-existent in the pre-crisis period.

Next, we employ the bank-level variation 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 risk or rollover risk, and higher solvency risk hoarded more liquidity. Further, these banks also held more liquidity in response to increases in payment activity. Even though, on average, there is 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 i.e. financial constraint driving precautionary demand rather than factors internal to the payment system (increase in variability of payment activity).

In our third piece of evidence, we study the effect of settlement bank liquidity on market-wide overnight inter-bank rates and volumes. In order to subsume any step-variations induced by policy changes, we look at spreads of the inter-bank rates to BoE's policy rate. We obtain overnight secured rates and volumes (with the UK government's GILT as collateral), and unsecured rates and volumes from the British Bankers' Associa-

[7]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 as even though no individual bank knows its own exact activity for next day ahead of time (and at any rate, it is difficult for an econometrician to estimate this well), it is generally known in advance if some days are likely to be more or low activity in the aggregate (for instance, due to holidays in the United States or upcoming holidays in the United Kingdom, and so on).

tion and Wholesale Markets Brokers' Association, and the Bank of England, respectively. In normal times, the "arbitrage" hypothesis in money markets postulates that if inter-bank rates become higher than the BoE policy rate, then banks that experience exogenous rise in their liquidity that day release the liquidity to other needy banks in order to capture the spread. This should induce a negative relationship between settlement bank liquidity and inter-bank spreads. We call this the "arbitrage" effect. Our crucial observation is that this relation may be reversed when the rise in liquidity of settlement banks is *endogenous*, in particular, a precautionary response to heightened risks and funding concerns. In this case, settlements 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 inter-bank rates and volumes, 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 inter-bank rates and reduce volumes in the period *during* the crisis. In contrast, the relationship between liquidity and interbank rates is significantly negative in the period *prior* to the crisis, consistent with the *arbitrage* effect of settlement bank liquidity on inter-bank rates. What is striking is 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, suggestive of a contagion-style systemic risk operating through inter-bank markets. In particular, the overnight Sterling inter-bank rates in the first year of the crisis do not seem to have been driven purely by counterparty risk concerns of lending banks about the borrowing banks. And, since smaller, second-tier banks borrow mainly from large, settlement banks in the secured interbank market, the latter market was also substantially affected from liquidity hoarding by 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, we find further supportive evidence for our interpretation. The rate charged by one bank to another bank (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 observed in the aggregate data during the crisis contains a precautionary demand effect.

Our paper is most closely related to Ashcraft, McAndrews, and Skeie (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 which involves factors that are not specific to the interbank market (payment uncertainty). We focus in particular on tightening of financial constraints for banks that induces in them precautionary demand for liquidity, which anecdotally appears to have affected many markets besides the interbank market. Hence, in contrast to 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 in end of June 2008 (when this paper was initiated). It is no doubt interesting to examine the period post-June 2008, especially around the collapse of Lehman Brothers. On the one hand, counterparty risk concerns in inter-bank 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, Kovner and Schoar, 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 9 August 2007 provides a more attractive "event."

Section 2 provides the relevant institutional details of the UK payment system and money markets. Section 3 documents the regime switch in liquidity reserves of banks and Section 4 shows that liquidity hoardings of banks have a precautionary aspect to them. Section 5 establishes the effect of liquidity hoardings on inter-bank rates at aggregate and bilateral level. Section 6 relates our paper to additional literature and Section 7 concludes.

2 Institutional Background

This section provides some important background information. Section 2.1 provides an overview of the Bank of England (BoE) monetary policy framework. Section 2.2 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 1 summarizes the range of adjustments to the framework the BoE undertook since August 2007 to restore orderly conditions in money markets.

2.1 The Monetary Policy Framework[8]

In May 2007 the BoE assigned operational responsibility of monetary policy to its newly created Monetary Policy Committee (MPC). The MPC meets at least once a month to set the rate of interest. The MPC is responsible for setting the appropriate rate to meet the set inflation target (based on the Consumer Price Index) by the Chancellor of the Exchequer. The inflation target is 2 per cent, with a 1 per cent 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.

[8] This section relies heavily on "The framework for the Bank of England's operations in the sterling money markets (The 'Red Book')" available at http://www.bankofengland.co.uk/publications/news/2006/054.htm, Clews (2005), various issues of the Bank of England's Quarterly Bulletin (Q3 2007–Q4 2008), and unpublished notes by Bank of England staff.

A combination of *reserves 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.

37 UK banks and building societies that are members of the reserves scheme set their "target" balances at the beginning of each maintenance period (Monetary Policy Committee's decision date until the next) and undertake to hold balances, remunerated at the official Bank 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 first-tier, or in other words, the settlement banks, which join the scheme automatically because their role in the payments system entails them having reserves 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 would be remunerated at the official Bank rate.

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

Open Market Operations (OMOs) are used by the BoE to provide the amount of money needed to enable reserves banks, in 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.[9] OMOs comprise short-term repos at the official Bank rate, long-term repos at market rates determined in variable-rate tenders, and outright purchases of high-quality bonds. The BoE accepts as counterparties in its open market operations (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 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 Bank rate, of +/- 25 basis points (bps) on the final day of the monthly reserves maintenance period, and of +/- 100 basis points on all other days. Their usage, however, is subject to the "stigma" problem, especially during a crisis, as explained in the introduction (Section 1).

[9]The Bank of England *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."

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 few (larger) first-tier banks also referred to as the settlement banks or clearers. 15 banks are direct participants in the large-value payment system called CHAPS. Two of the direct participants are foreign owned banks with a narrow retail activity in the UK. In our sample of large, settlement banks, we exclude these two foreign banks since their liquidity kept in the form of the BoE reserves underestimates their overall liquidity, possibly substantially. We also exclude the BoE and the CLS bank (the clearing bank) and the one bank which became a settlement bank only in October 2008 (outside of our sample period). Hence, we are left with ten large, settlement banks.

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. Importantly however, financial transactions are not settled through CHAPS but through the securities settlement system.

Money markets or inter-bank 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 market 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 and instead are more likely to pass it vertically up the system. So below the top tier, horizontal movement is very limited.

Besides the inter-bank 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 in order 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 reserves target from month to month in response to, for example, variations in the size or uncertainty of their payments 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 payments system, ensuring that settlement banks are able to make payments in advance of expected receipts later in the day. Intra-day 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 Bank of England'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 by (i) holding balances on their reserves account at the BoE; (ii) keeping high-quality assets that can be exchanged for central bank money in the open market operations (OMOs); and, (iii) through the Bank's standing (or semantically what is the same as, emergency) lending facility.

3 Regime Shifts in Settlement Bank Liquidity

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

3.1 Descriptive Statistics

We measure the settlement banks' *overnight liquidity* as the sum of the reserves accounts held by the ten 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) cumulative borrowing from the central bank in weekly open market operations 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 Bank of England remain constant for the economy, except when changed by the Bank of England, the reserves with the large, settlement banks fluctuate on a daily basis based on their transactions with the other banks in the money market system and directly with their own corporate and household borrowers.

The data are obtained from the Bank of England. All data are daily and cover the period 02 January 2007 to 30 June 2008. The first row of Table 1 (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 (pre- and post-August 9th 2007). We see from the difference that liquidity held by first-tier banks is 27 per cent higher post August 9th. 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 banks' 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 the Bai and Perron (1998) test which 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 in order to mute the effect of outliers (and in subsequent tests to allow interpretation of coefficients in terms of elasticities).

Table 2 reports results. The test identifies two breaks in the overnight liquidity. The first break, a 24% increase in overnight liquidity, occurred around September 11th 2007. This is one month later than ignition of the sub-prime crisis on 9th August 2007. This is because banks are allowed to revise their reserves targets only from one Monetary Policy Committee meeting to the next. The first increase in the aggregate reserves target therefore occurred on September 6th 2007, the date the first MPC meeting took place after the sub-prime crisis took hold.[10]

At the second break, March 13th 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

[10]One can observe further increases in the overnight liquidity from mid-September onwards following the BoE decisions to inject extra liquidity in its regular weekly open market operations (see Appendix 1 for details on the adjustments to the monetary policy framework undertaken during the crisis).

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 13th, 2008 is also consistent with a precautionary motive. Note that in contrast to the delayed response following August 9th 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 4th 2007 to widen the band around target within which reserves are remunerated from +/-1% to +/-30% (as described in Appendix 1).[11]

4 Evidence of the Precautionary Motive

While the higher reserves targets may have reflected anticipation of heightened funding needs and rollover risks, one needs to consider also 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 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 (SF) following an unexpected payment shock in late trading. The expected cost of using

[11] 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.

the SF is a function of the direct penalty in using it (which remained constant or in fact 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 policy rate and the overnight (secured) market rate.

Across maintenance periods, i.e., from one MPC meeting to another, 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 that too only at monthly frequency. No data on asset sales are easily available. And lending volumes can be reasonably imputed at 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 variation in bank demand for liquidity.

In order to tease the tradeoff faced by banks in building up reserves, we examine how uncertainty in aggregate payment shock affects settlement bank liquidity and explore interaction of this uncertainty with bank-level funding risk and balance-sheet condition. That is, we investigate the time-series variation of total settlement bank liquidity and also the cross-sectional variation in liquidity demand of individual settlement banks on a day to day basis.

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 might 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 Bank of England payment database. The daily payment activity is measured as the sum of all transactions that flow through the large-value payment system (CHAPS), net of inter-bank loans activity.

Table 1 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 as it suggests that any differential response of settlement bank liquidity to payment activity likely arises from bank-level differences in the perceived cost of managing payment shocks through means other than central bank reserves. Figure 2 plots the payment activity (in logarithm). At first sight, these series appear to be white noise processes.[12]

Importantly though, a significant fraction of payment activity is predictable by banks due to calendar effects. Appendix 2 reports the effects on aggregate payment activity of a non-exhaustive set of calendar dummies, which includes holidays in United States and the United Kingdom, and fixed effects for day of the week, quarter, and beginning and end of each month. With these few dummies we are able to predict 40 per cent of the variation in payment value.

[12] A Portmanteau test reported in Appendix 2 confirms this observation. The lag-one autoregressive coefficient is small (not reported). The Portmanteau test for lag-one has p-value of 0.29 rejecting the null hypothesis that the first lag autocorrelation is different from zero.

Economically important calendar effects are (i) United States holidays which are associated with a 58 per cent drop in the value of payments activity, (ii) days around the United Kingdom holidays when there are, for instance, higher than usual deposit withdrawals; and (iii) fourth quarter effect which is negative.

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

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

where i stands for a bank subscript, t for 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 2: $break_t^1$ is a post September 11th 2007 dummy; $break_t^2$ is a post March 13th 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 as even though no individual bank knows its own exact activity for next day ahead of time (and at any rate, it is difficult for an econometrician to estimate this well), it is generally known in advance if some days are likely to be more or low activity in the aggregate (for instance, due to holidays in the United States or upcoming holidays in the United Kingdom, and so on). A maybe more important reason to focus on aggregate payment activity rather than individual bank payment activity is that funding needs arising from idiosyncratic payments fluctuations are more easily met through borrowing from other banks in the overnight market rather than *self-insurance*.

The overall results for estimation of the benchmark specification are reported in Table 3. 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) 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 11th September, 2007 ($break_t^1$), there is a significant positive incremental relationship between the reserve balances of settlement banks and payment activity, which is economically large: 24% of a standard deviation shift in liquidity demand for a 1 standard deviation increase in predictable payment activity. In other words, reserves held by settlement banks rose with 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 13th, 2008 ($break_t^2$). Column (4) shows that the results are robust to controlling for lagged deviation of the banks' reserves balance from target which controls for the fact that calendar effects might 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 within maintenance period variations in payment activity allows 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).[13] In columns (4) through

[13] 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 BoE Rate. This fixed-rate bidding has one potential undesirable consequence that given the amount of reserves each counterparty actually desires, the size of their bid is determined by their expectation (or guess) as to how much other counterparties will bid for. That can set up a dynamic where, from week to week, the extent to which a short-term repo OMO is "covered" (that is, reserves required by banks to meet their targets are supplied through the OMO) is on a rising or falling trend. If, for example, a counterparty thinks its peers will bid for much more than they in fact desire, then it too must do the same in order to be allotted roughly what it actually wants. If the cover ratio is on a declining dynamic, that can lead eventually to an "uncovered" OMO, as happened in June 2007, before the turmoil, reserves were eventually undersupplied and inter-bank rates went up dramatically due to 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 pre- and during the crisis might be due to this June/July 2007 episode, which precedes the most interesting period of our analysis (August 2007 onward). Hence we check robustness of our results by controlling for

(6) the results are stable.

In column (7) we redefine the break dummies, we do this to check whether the change in bank behaviour is temporary. i.e. 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 11 September 2007 until the last day of the September 2007 maintenance period and $break_t^2$ to be a dummy that takes value one from 13 March 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 temporary shift in UK banks' liquidity management strategy.

In Table 4 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[14] , 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

the uncovered OMO episode through a dummy variable.

[14]"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.

Fall in retail deposits could help account for the fact that while some banks were directly threatened by the meltdown of the ABCP 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.[15] 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 anticipation of future losses and not just realized losses.

Table 1 reports 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.[16]

[15] 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.

[16] 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 Equity price fall and RWA) 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. It 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 three or bottom three in loans to retail deposits during the crisis. The figure looks similar with other risk measures. The figures underscore results of Table 4 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 in high risk, medium risk and low risk banks based on top three, middle four, or bottom three, respectively of the risk measure.

The estimation results are reported in Table 5. 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-risk and medium-

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

risk banks relative to the low-risk banks). For the high-risk banks the shift in liquidity demand is about twice larger than the average effect we estimated in Table 3. And the difference between strong and weak banks is statistically significant at the 5% level for all risk metrics we employ except for deposit fragility.[17]

To sum up, the findings in Tables 3-5 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.

[17] In Appendix 3 we report corrobarating (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 8 August 2007. We estimated the regressions in Table 5 with intraday liquidity as a dependent variable and 8 August 2007 as the break date instead of 11 September 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 11 September 2007 is kept as the break date.

5 Effect of Liquidity Hoarding on Money Market Rates and Volumes

In the second half of our empirical analysis, we explore what were the consequences of the increase in hoarding of liquidity by settlement banks for inter-bank markets. In particular, we document how movements in liquidity demand by banks altered inter-bank 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 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 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 inter-bank rates to be higher. We call this the "liquidity" effect.

In our empirical work, we aim to identify both these effects: first, the arbitrage effect that *exogenous* increases in settlement bank liquidity would drive inter-bank rates toward the policy rate, and the liquidity effect that *endogenous* (in our case, precautionary) increases in settlement bank liquidity would drive inter-bank rates above the policy rate.

5.1 Regression Specification

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

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

where Y_t is either the inter-bank rate spread to the policy rate (in bps) or the logarithm of the volume of interbank activity in billion £. $OLiq_t$ is overnight liquidity aggregated across all UK settlement banks and expressed in logarithm. $break_t^1$ is a post September 11th 2007 dummy.

Our hypothesis is that in the pre-crisis period, the effect of settlement bank liquidity on inter-bank 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 Money Markets Data

To estimate specification (2), we use daily market-wide interest rates and volume data from the British Bankers' Association and Wholesale Markets Brokers' Association. The secured rate is the Gilt Collateral (GC) rate. The unsecured overnight rate is the SONIA rate.[18] Table 1 also reports descriptive statistics of the rates and volume data. The secured rate spread to the policy rate is 6.25bps on average with a large standard deviation of 12.65bps, whereas the unsecured rate spread to the policy rate is 11.47bps with a variability of 13.31bps.

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 30 to 35 bps), have coincided with negative market news, e.g., loss

[18] SONIA stands for Sterling Over Night Index Average. It tracks actual Sterling overnight funding rates experienced by market participants.

announcements and bailouts (see the timeline of news in Table 2).[19] Figures 5 and 6 show that both secured and unsecured volume trend upward, but that there is an increase in the volatility of interbank volumes from August 2007. In what follows we will show that this is the consequence of volumes becoming more sensitive to liquidity demand pressures, i.e. greater and more frequent recourse to rationing during the crisis.

In the last two columns of Table 1, we also report the differences in rates, volumes, and liquidity between the pre-crisis and the post-crisis period, and in parentheses we report these differences excluding the week of the uncovered OMO. It might seem a puzzling observation that the secured rate has increased more than the unsecured rate, even if by a small margin; + 2.4 basis points on average for the secured rate and + 0.66 basis points for the unsecured rate.

A deterioration in the quality of collateral pledged cannot be an explanation for why secured rates have increased more from before crisis to during the crisis, compared to unsecured rates, because we focus on the UK Gilt rate where 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) Table 1 and Bank for International Settlements (2010) Table 1).

[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 too only 2.41 bps higher during the crisis than pre-crisis.

Coincidentally, both the secured volume and the unsecured volume have increased post-9 August 2007, but the increase has also been more than twice larger 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 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 that 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

Estimations of specification (2) are reported in Table 6 panel A where the dependent variable is either the secured or the unsecured rate spread to policy rate (in bps). We find that for both secured and unsecured spreads, a higher level of liquidity held 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). This is true whether aggregate bank liquidity is measured as (logarithm of) total reserves balances of settlement banks (columns under (1)) on a day, or as percentage deviation of total reserves balances on a day from aggregate target of reserves set by settlement banks (in a given maintenance period). It is important to note that our estimates of the liquidity effect tend to be of similar magnitude for the secured rate and the unsecured rate, and in fact somewhat stronger for the unsecured rate.

In panel B we report results where the dependent variable is either the secured volume or the unsecured volume. The effect of an increase in liquidity demand of settlement banks on volume is negative during the crisis but not before the crisis and statistically significant for the secured volume and for both measures of liquidity demand: a one percentage point increase in liquidity demand is associated with a 0.46 percentage point decline in secured volume and a one percent increase in the deviation of liquidity demand from target ("excess reserves") is associated with a 0.33 percentage decline in volume. This suggests that second-tier banks which are present only in the secured market are more affected than first-tier banks. A one standard deviation increase in liquidity demand of settlement bank is associated with 25% of a standard deviation decline in secured interbank activity during the crisis.

But these effects are likely temporary, as shown in Figures 5 and 6 in the long run, including during the crisis, interbank volumes (both secured and unsecured) trend upwards. In other words, these estimations we attempt to explain the cycle (short term fluctuations) in interbank volumes rather than the trend.

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 inter-bank rates are similar for secured and unsecured inter-bank lending – to imply that Sterling money markets experienced stress during the crisis not necessarily (or 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 due to their own credit risk and funding risk. Such hoarding raised the lending rates charged in secured as well as unsecured inter-bank 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 inter-bank market, after employing the Furfine (1999) algorithm to identify inter-bank borrowing and repayment transactions. Note that such data are unavailable for the secured market as it works largely through a third-party broker arrangement. The sample covers 10 UK banks over 22 maintenance periods in the period January 2007 to June 2008. 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 7 reports descriptive statistics of the data. There is considerably more variability in the bilateral data than reflected in the aggregate data. For example, the unsecured inter-bank spread (transaction rate minus the policy rate) charged by one bank to another varies between −87 basis points and 110 basis points. Variability in volume is also important. The proportion of non-active bilateral trades (zero volumes) in our sample has 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 also matters in affecting 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 just by 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 inter-bank loans. Since UK banks have recourse to the overnight inter-bank 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 3.

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

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

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 lender and borrower reserve targets respectively (scaled by their respective payment activities to control for size), *crisis* is a post August 2007 dummy, and m_r are maintenance periods fixed effects. *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 Appendix4. 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:

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

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 (3).

Columns (1) and (2) of Table 8 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 charge 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 basis points increase in the spread charged.

Further, an important concern that the aggregate relationship is the result of a positive correlation between borrower credit quality, borrower liquidity hoarding, and borrowing rate does not find support in 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 consider simultaneously the volumes of bilateral activity. Tobit estimates for inter-bank activity in columns (3) and (4) of Table 8 show that bilateral activity in inter-bank markets tends to be negatively related with both borrower and lender liquidity. During the crisis, the inter-bank activity becomes somewhat less negatively associated with lender liquidity, but the overall effect remains 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 in order to reduce their costs of borrowing in the inter-bank market (potentially leaving the market altogether) and when they do so they also charge more for lending in the inter-bank market (again, potentially not lending in the market at all).

To summarize, we find that the positive aggregate relationship between inter-bank rate and bank liquidity during the crisis is driven by a positive relationship between the liquidity balances of lenders and the rate they charge on the loans they extend during the crisis. This is consistent with a precautionary demand effect: lenders who have a higher ”demand” for liquidity during the crisis charge a higher rate to release it.

6 Related Literature

Our paper cuts across a number of different strands of literature, in particular, on (i) reasons why firms hoard cash, (ii) the function played by inter-bank markets and the reasons why they may experience stress, (iii) the transmission of bank-level stress as contagion in the financial sector, and (iv) the micro-structure of inter-bank 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 for precaution against funding risk finds parallel in the corporate finance literature on financial constraints. In this literature (see, for example, Almeida, Campello and Weisbach, 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 them to hoard more cash. The rationale for banks to hoard liquidity against *aggregate* financing shocks has also been modeled in several papers.[20]

The theory of inter-bank markets generally agrees on its role as being one of liquidity insurance and peer monitoring. The reasons why these markets may fail sometimes or experience severe stress differ across studies. Allen, Carletti and Gale (2008) and Freixas, Martin and Skeie (2008) focus on incompleteness of contracting on liquidity shocks; Bhattacharyya and Gale (1987), Flannery (1996), Bhattacharyya and Fulghieri (1994), Freixas and Jorge (2007), and Heider, Hoerova and Holthausen (2008) focus on asymmetric information and/or counterparty risk and related inefficiencies; finally, Acharya, Gromb and Yorulmazer (2008) focus on issues arising due to market power and strategic behavior of liquidity-surplus banks. Our findings suggest that the stress in inter-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

[20] See, for example, Holmstrom and Tirole (1998), Allen and Gale (2000), Diamond and Rajan (2001), and Allen, Carletti and Gale (2008), among others.

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 models due to Freixas and Rochet (1996), Allen and Gale (2000), Freixas, Parigi and Rochet (2000), Caballero and Krishnamurthy (2001), Diamond and Rajan (2005), and Acharya (2009) wherein banks are reliant on a common pool of liquidity and one bank's adversity reduces the available pool for others due to fire sales of assets, deadweight losses from bad assets, or drawdowns of inter-bank 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 inter-bank 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, Nyborg and Rocholl (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, not just its own.

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

7 Conclusion

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

On policy front, our evidence suggests that regulatory attempts to thaw such money market stress and reduce variability of inter-bank rates, if successful, can have salubrious effects on healthier parts of banking sector. Our results, however, suggest that to the extent a part of the stress emanates from liquidity hoardings of banks with troubled funding and balance-sheet conditions, such thawing should involve addressing insolvency concerns (for example, early supervision and stress tests, and 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 (3-month) and overnight borrowing seems an intriguing issue to investigate. Further, our study focused 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 market power of some large players in the inter-bank markets (as suggested theoretically by Acharya, Gromb and Yorulmazer, 2008, and supported empirically by Fecht, Nyborg and Rocholl, 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, Shin and Yorulmazer, 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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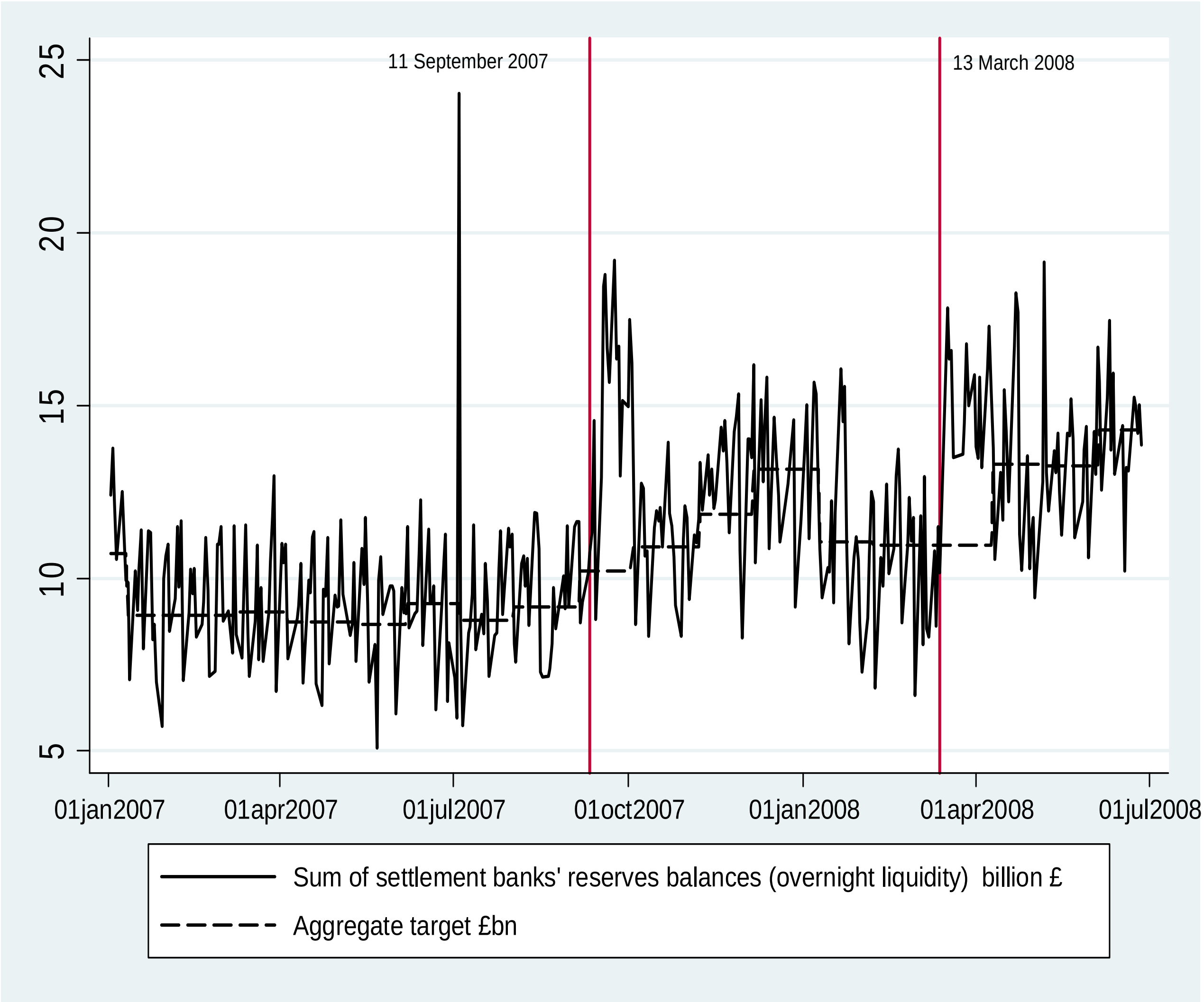

Figure 1. Overnight liquidity held by settlement banks and their aggregate target

Note: The overnight liquidity is the sum of the reserves accounts of all settlement banks balances measured at 5 am each day. Under the current monetary policy framework UK settlement banks *choose* a reserves target which they are required to achieve on average within maintenance period. They reset their reserves targets at the start of each maintenance period. The data are for 10 UK settlement banks (foreign banks and subsidiaries are omitted).

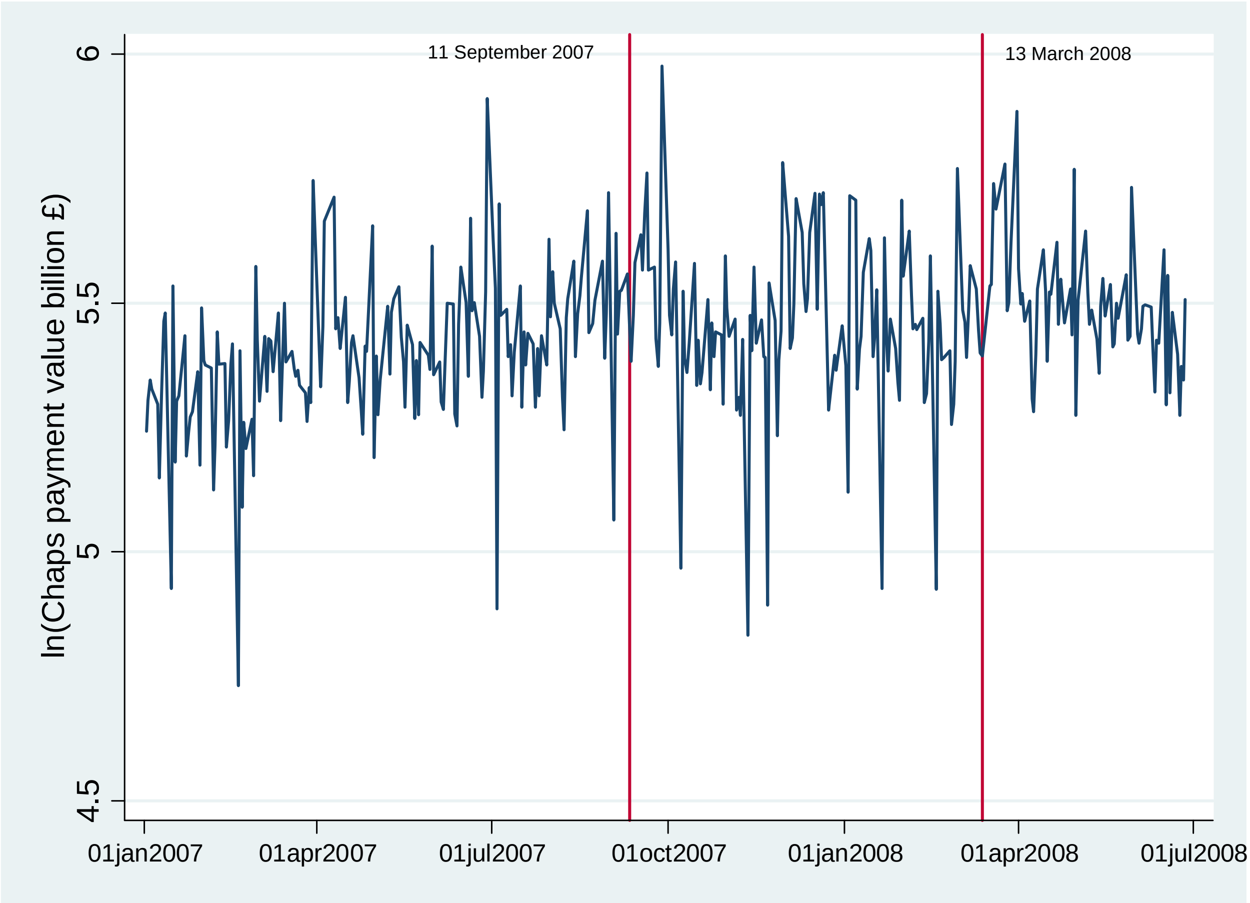

Figure 2. CHAPS payments activity (logarithm)

Note: Payment activity (value) is the sum of all transactions that flow through CHAPS, the UK large-value payment system (real-time-gross settlement system operated by the Bank of England). It is net of overnight interbank loans activity.

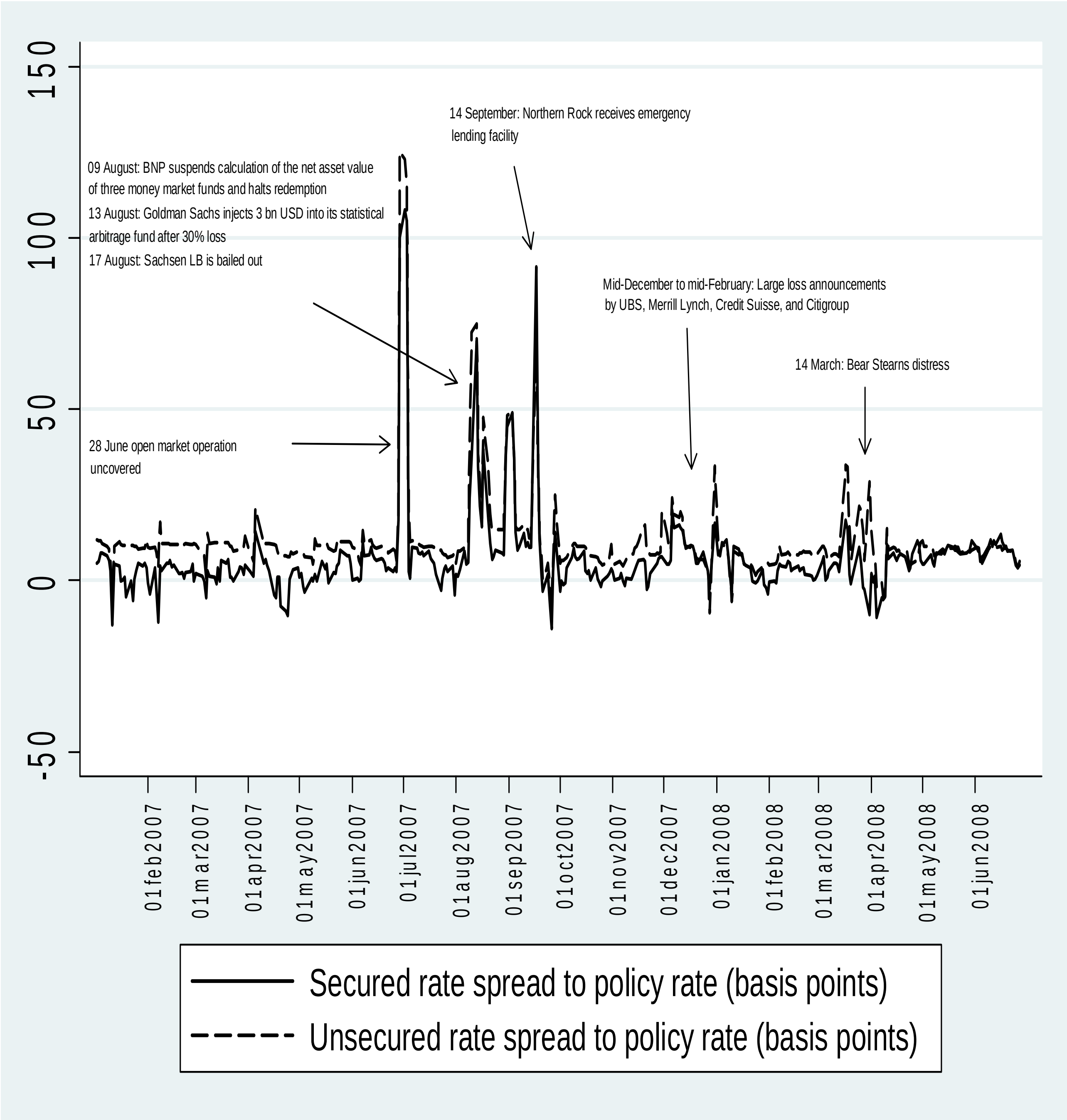

Figure 3. Overnight money market spreads (basis points) and key market events

Note: The data are daily and cover the whole market. The secured rate is the Gilt Collateral (GC) rate. The unsecured overnight rate is the Sterling Overnight Index Average (SONIA) rate.

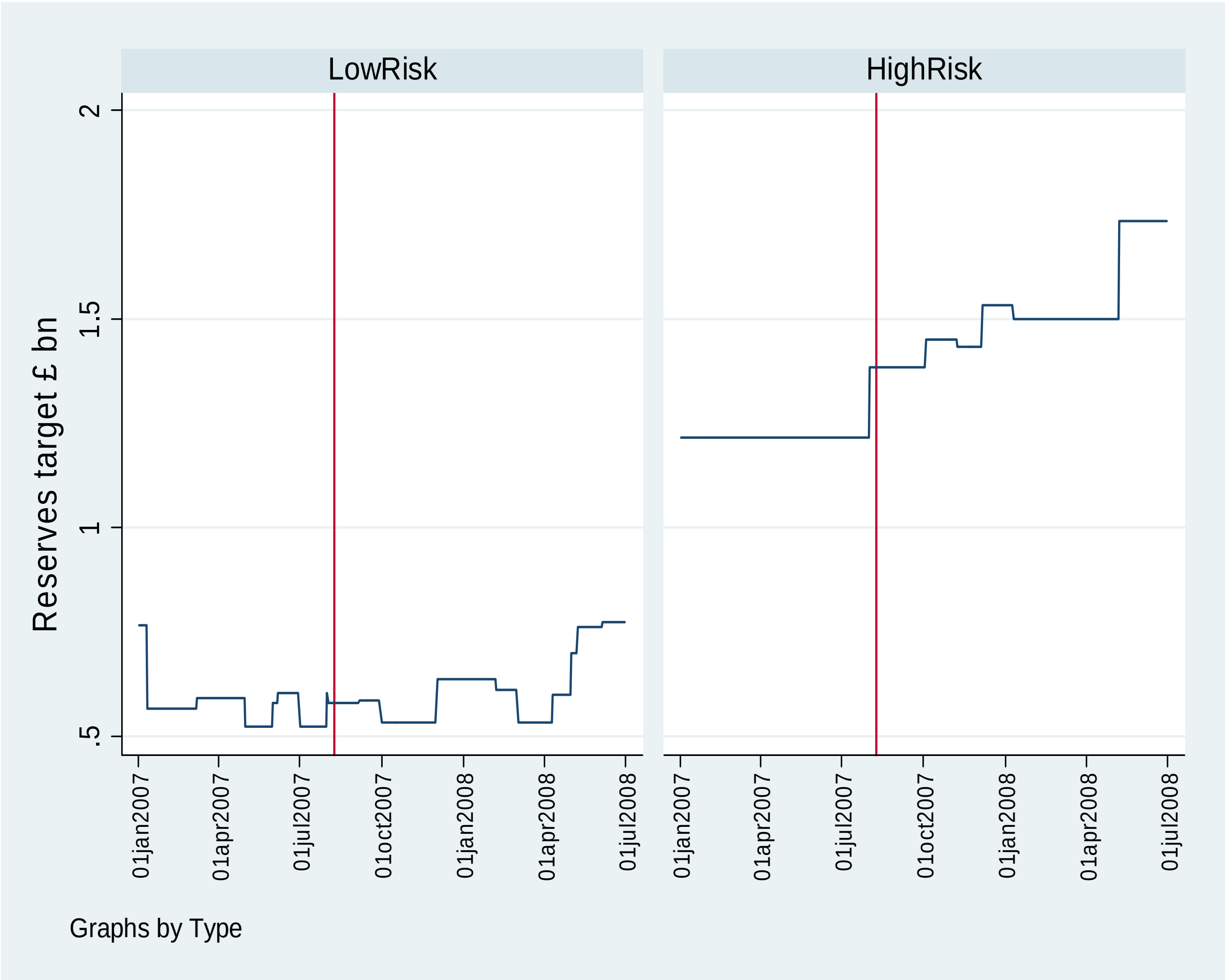

Figure 4. Reserves target of high risk banks (three banks with highest loan to retail deposits ratio), and low risk banks (three banks with lowest loan to retail deposits ratio) in billion British pounds

Note: The data cover 10 UK settlement banks (foreign banks are omitted). See figure 1 and table 1 for a definition of the reserves target. The red vertical line indicates the start of the crisis.

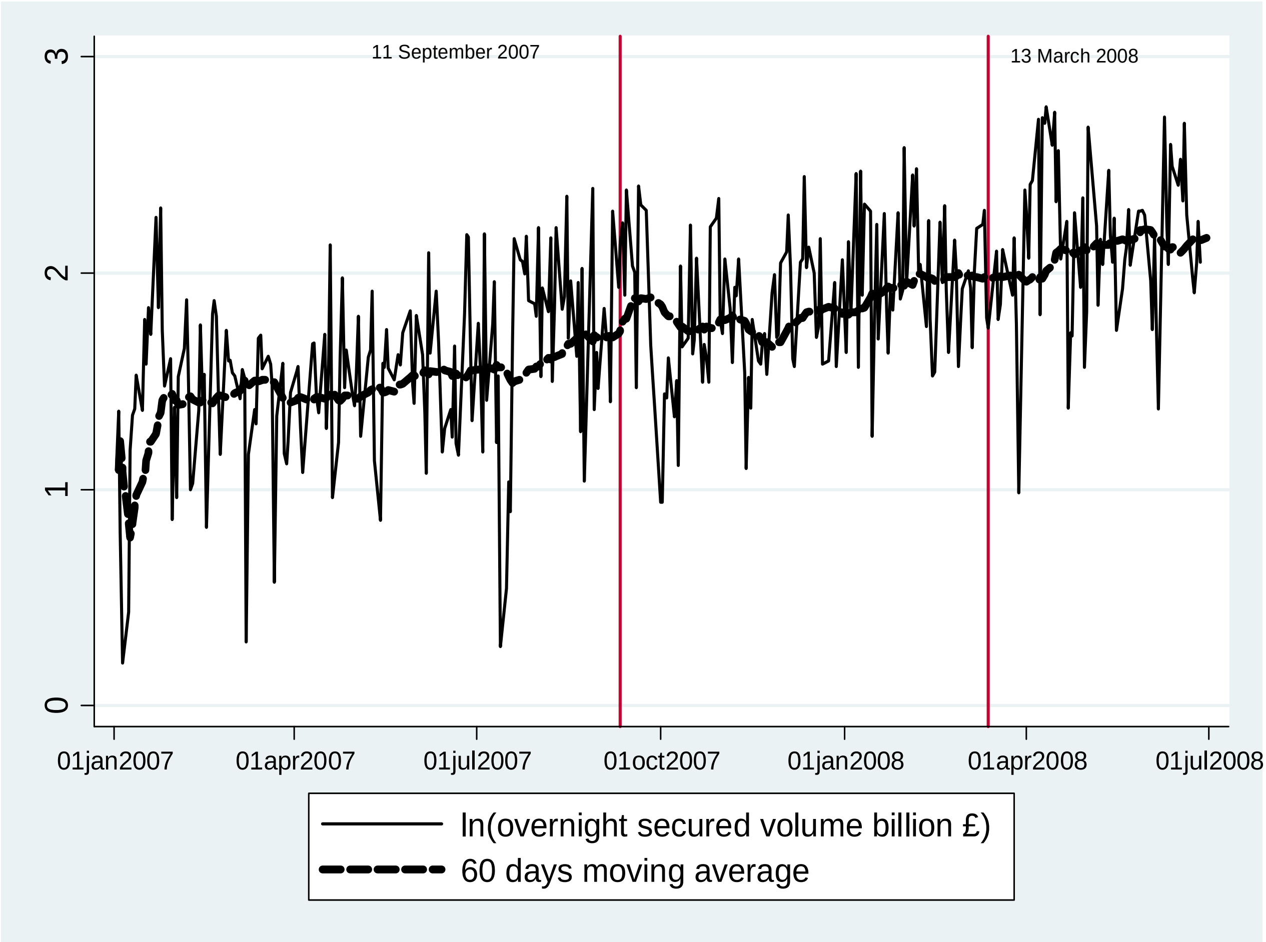

Figure 5. Secured overnight market volume

Note: The data are from the British Bankers' Association and the Wholesale Markets Brokers' Association. The volumes reported are for activity secured by gilts (government bonds) collateral.

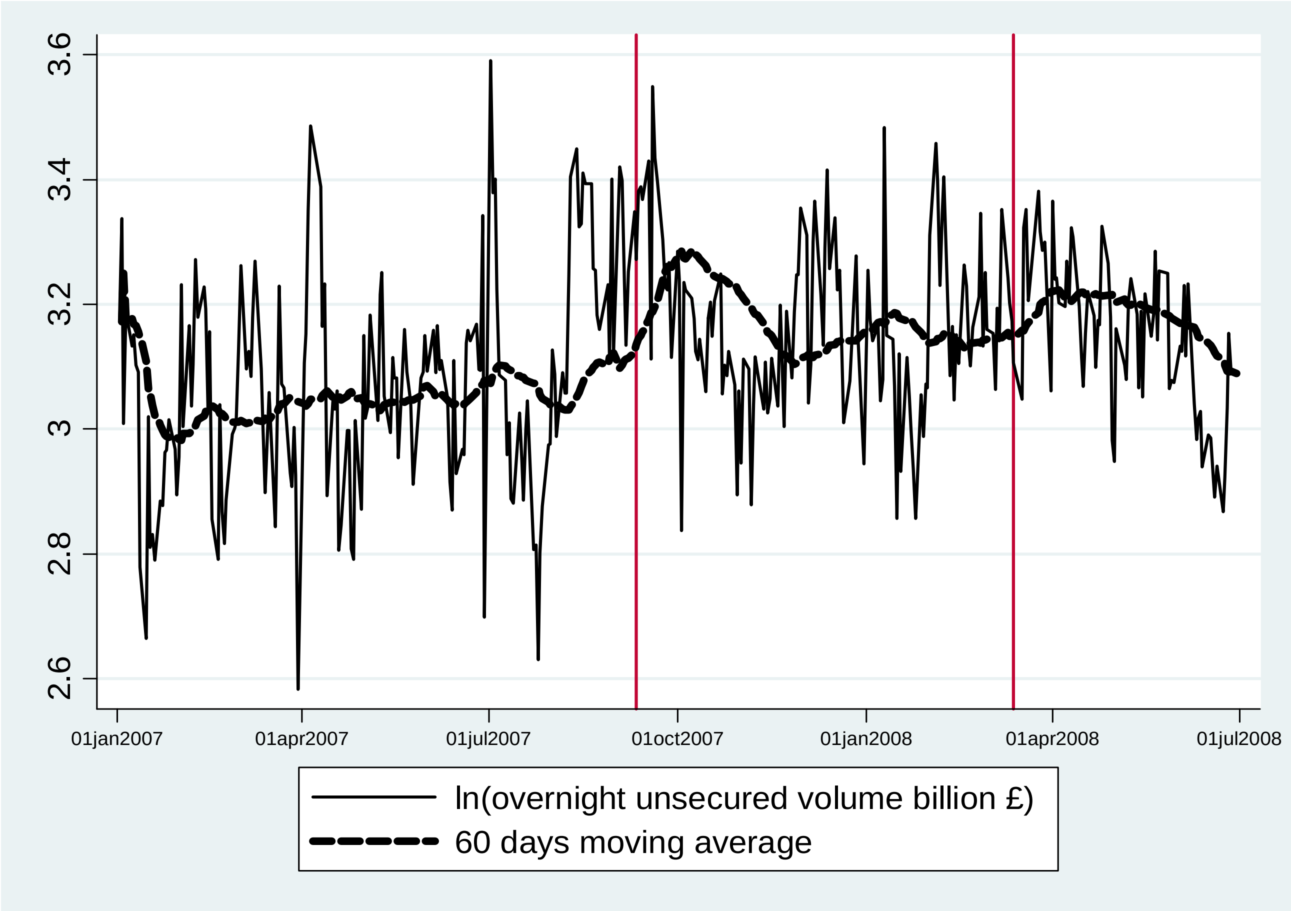

Figure 6. Unsecured overnight market volume

Note: The data are from the Bank of England statistics department. The data cover all activity settled by first-tier banks that are direct participants in the large value payment system.

Table 1. Descriptive statistics

The data are from the Bank of England statistics division (when not specified otherwise) and most cover the period 02/01/07 to 30/06/08. Settlement (First-Tier) banks are the ten UK banks that settle their payments activity directly at the central bank. Overnight liquidity is the sum of the reserves accounts balances of those ten 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(trillion £), the UK large-value payment system (real-time-gross settlement system operated by the Bank of England). 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 2. 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 (GC) 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 02/01/2007 to 30/06/2008. 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; 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	2.435	0.322
								(3.34)	(0.17)
Secured overnight spread (c)	6.25	12.65	-14.17	108.33	-3.88	4.50	17.50	-2.41	0.045
								(-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)

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 1. Continued

Variables	Mean	Standard Deviation	Min	Max	5th percentile	50th percentile	95th percentile	(pre-August 9th) - (post August 9th) Difference	P-value
Log(secured volume billion £)	1.77	0.44	0.20	2.77	1.034	1.764	2.456	-0.448	0.000
								(-0.451)	(0.000)
Log(unsecured volume billion £)	3.12	0.16	2.58	3.59	2.846	3.115	3.394	-0.132	0.000
								(-0.138)	(0.000)
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		

Table 2. Bai-Perron Multiple Level Break Tests on Settlement Bank Liquidity

The Bai and Perron (1998) sequential algorithm is used to estimate the timing of (lasting) level shifts in the settlement bank 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 for 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 2 months. The test results are reported in this table together with a timeline of relevant events put together using Bloomberg. See Table 1 for a definition of overnight liquidity.

Break Dates	95 % Interval	Estimates	Key Market News	Date
			Bank of England announces emergency lending facility to Northern Rock	**14 September 2007**
11/09/2007	[23/08/07;18/09/07]	2.474***	**Bank of England supplies additional reserves to the banking system +25% (one week maturity)**	**13 September 2007**
		(0.017)	UBS says it would make write downs of $3.4bn to its fixed income portfolio	01 October 2007
13/03/2008	[04/03/08;08/04/08]	2.629***	Citigroup says Q3 earnings will fall 60% on a year ago	01 October 2007
		(0.023)	Merrill Lynch announces it will make a loss in Q3 due to a $5.5bn write-down	05 October 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	24 October 2007
112.673***	17.392***	8.936	Morgan Stanley announces a $3.7bn loss on sub-prime structured credit	08 November 2007
			Rumours of a $10bn write-down by Barclays relating to securities backed by sub-prime mortgages	09 November 2007
			Bank of America's CEO pre-announces writedowns of $3bn in Q4.	13 November 2007
			Bear Stearns announces an expected write down of $1.2bn in Q4	14 November 2007
			Freddia Mac announces a Q3 loss of $2bn	20 November 2007
			UBS announces further write downs of $10bn (dated to end November)	10 December 2007
			Bank of America announces it may have to record more than its initial $3.3 billion losses and write-downs	12 December 2007
			Citigroup announces it is to raise at least $14.5 billion in new capital	15 January 2008
			Merrill Lynch reports $ 10.3 billion loss	17 January 2008
			Ambac announces Q4 net loss of $3.225 billion	22 January 2008
			XL capital Ltd expects Q4 net loss of up to $1.2 billion	23 January 2008
			Credit Suisse announces additional $2.85 billion losses	19 February 2008
			JP Morgan agrees to provide secured lending to Bear Stearns	**14 March 2008**
			JP Morgan agrees to purchase Bear Stearns for $2 per share	**16 March 2008**
			Fed gives primary dealers effective access to the discount window through a new credit facility	16 March 2008
			HBOS equity price falls sharply on rumours of liquidity problems. HBOS denies any problem.	19 March 2008

Note: (***) stands for significant at the 1 per cent level. Standard errors in parenthesis. Liquidity is measured as the sum of reserves accounts held at the central bank.

Table 3. Precautionary liquidity demand

This table reports estimates of equation (1). We express an individual bank demand for overnight liquidity as a function of the predictable aggregate level of payment activity, allowing for a shift in this relationship during the crisis. See Table 1 for a definition of liquidity and payment activity. Predicted payment activity is payment activity predicted by calendar effects as detailed in appendix 2. 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. Break1 is a dummy variable that takes value one post 11/09/07; and Break2 takes value one post 13/03/2008. We report robust standard errors in brackets. In column (7) Break1 is a dummy variable that takes value one from 11/09/07 to the end of the September 2007 maintenance period; and Break2 takes value one from 13/03/2008 to the end of the March 2008 maintenance period.

Dependent variable: studentized individual settlement bank overnight liquidity

	(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]			
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			1.290				-0.777
			[1.144]				(1.226)
						-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	0.020
Maintenance days fixed effects					x	x	
Bank fixed effects	x	x	x	x	x	x	x
Nber of Observations	3760	3760	3760	2950	3760	3760	3760

Note: (*), (**), (****) stands for statistically significant at the 10 per cent, 5 per cent and 1 per cent level, respectively.

Table 4. Relationship between liquidity demand and bank risk

We estimate an individual bank studentized demand for liquidity as a function of alternative risk metrics. See Table 1 for a definition of overnight liquidity. Overnight 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; 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. Break1 is a dummy variable that takes value one post 11/09/07. We report robust standard errors in brackets.

	Mismatch I	Mismatch II	Deposit fragility	Equity price fall	Risk-weighted assets
	(1)	(2)	(3)	(4)	(5)
Risk	-0.0624	0.00311	-1.584	-0.877***	-1.228***
	(0.0464)	(0.313)	(1.723)	(0.0164)	(0.255)
Risk*Break1	0.164***	0.766***	-0.858	0.734***	0.764***
	(0.0322)	(0.164)	(1.162)	(0.0130)	(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	0.0781	0.357	-0.0760	0.0403
	(0.159)	(0.144)	(0.889)	(0.143)	(0.254)
R-squared	0.093	0.093	0.060	0.085	0.079
Maintenance period fixed effects	x	x	x	x	x
Bank fixed effects	x	x	x	x	x
Nber of Observations	3016	3016	3770	2582	3329

Note: (*), (**), (****) stands for statistically significant at the 10 per cent, 5 per cent and 1 per cent level, respectively.

Table 5. Relationship between overnight liquidity demand, payment activity, and bank risk

We estimate an individual bank studentized demand for overnight liquidity as a function of predicted payment activity interacted with alternative risk rankings. See Table 1 for a definition of liquidity and (predict) 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; in column (5) risk is the ratio of risk-weighted assets to total assets. We split the sample of ten banks in three groups according to the value of the risk metric used: high risk for top 3 banks (HR dummy), medium risk for middle 4 banks (MR dummy), and low risk for bottom 3 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. Break1 is a dummy variable that takes value one post 11/09/07. We report robust standard errors in brackets.

	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	-0.0186	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	0.110	0.110	0.069	0.090	0.102
Maintenance period fixed effect	x	x	x	x	x
Bank fixed effect	x	x	x	x	x
Nber of Observations	3008	3008	3760	2632	3384

Note: (*), (**), (****) stands for statistically significant at the 10 per cent, 5 per cent and 1 per cent level, respectively.

Table 6. The impact of settlement banks precautionary liquidity hoarding on overnight money market spreads

We report ordinary least squares (OLS) estimates of the liquidity effect on market-wide overnight secured and unsecured rate spread in panel A and market-wide secured and unsecured volumes in panel B. The rates spreads from policy rate are in basis points. All variables are defined in Table 1 and sources reported. The market data are aggregated daily data for the period January 2 2007 to June 30 2008. Liquidity is the sum of the ten first-tier UK settlement banks' reserves balances held at the central bank. Break1 is a dummy variable that takes value one post 11/09/07. We report in brackets robust standard errors.

Panel A. Money market rates

	Liquidity=ln(reserves balances)		**Liquidity=reserves balances in % deviation from aggregate target**	
	(1)		**(2)**	
	secured spread	unsecured spread	secured spread	unsecured spread
Liquidity	-21.52***	-22.49***	-0.142***	-0.138***
	(5.238)	(5.576)	(0.0395)	(0.0422)
Liquidity*Break1	20.48***	24.80***	0.129**	0.156***
	(7.124)	(7.583)	(0.0563)	(0.0601)
Break1	-51.68***	-65.00***	-2.020	-5.719
	(19.97)	(21.26)	(6.791)	(7.251)
Constant	62.32***	67.56***	11.02	14.51*
	(14.27)	(15.63)	(7.091)	(7.513)
Maintenance period fixed effects	x	x	x	x
R-squared	0.27	0.26	0.268	0.246
Nber of Observations	376	376	375	375

Note: (**), (****) stands for statistically significant at the 10 per cent, 5 per cent and 1 per cent level, respectively.

Panel B. Money market volumes

	Liquidity=ln(reserves balances)		Liquidity=reserves balances in % deviation from aggregate target	
	(1)		(2)	
	secured volume	unsecured volume	secured volume	unsecured volume
Liquidity	0.136	0.064	0.057	0.068
	(0.164)	(0.063)	(0.123)	(0.047)
Liquidity*Break1	-0.457**	-0.112	-0.327*	-0.099
	(0.223)	(0.086)	(0.175)	(0.067)
Break1	1.125*	0.331	0.010	0.100
	(0.625)	(0.241)	(0.211)	(0.080)
Constant	0.561	2.989	2.152***	3.138***
	(0.446)	(0.172)	(0.221)	(0.050)
Maintenance period fixed effects	x	x	x	x
R-squared	376	376	375	375
Nber of Observations	0.405	0.337	0.406	0.356

Note: (**), (****) stands for statistically significant at the 10 per cent, 5 per cent and 1 per cent level, respectively.

Table 7. Descriptive statistics: bilateral money market data

The bilateral data on money market activity are derived from transaction level information extracted from the Bank of England payments database. The data cover 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 the other and volume is the bilateral liquidity flow, the volume lent by one bank to another bank. 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 the 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 reserves target of a bank is scaled by the bank payment activity, as a proxy for bank size. The volume lent is scaled by the 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 8. 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 (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 3. The sample covers 10 UK banks over 22 maintenance periods in the period January 2007 to June 2008. All specifications include maintenance period fixed effects. Standard errors clustered by bank-pair are reported in brackets. See table 7 for a definition of the spread, the volumes, and reserves. A bank reserves target of a bank is scaled by its payment activity. The volume is scaled by the lender payment activity.

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

Robust standard errors in brackets
* significant at 10%; ** significant at 5%; *** significant at 1%

Appendix 1. Adjustments to the monetary policy framework during the crisis

The current monetary policy framework of the Bank of England (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 13th and 18th 2007, the BoE offered an extra (i.e. above aggregate target) £4.4bn(each time) in its regular weekly open market operations, amounting to 25% of the aggregate reserves target for the current maintenance period. This was accommodated by an increase in the reserves band around 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 14th 2007. In particular, it was a recognition that reserves banks might need extra reserves over and above their announced targets at beginning of the current maintenance period.

(2) The BoE further announced on 19th September 2007 that in order to alleviate strains in longer-maturity money markets it would conduct auctions to provide funds at 3 month maturity against a wider range of collateral (including mortgage collateral) than in the BoE's weekly open market operations. While this change may have indirectly affected bank demand for liquidity, it does not directly affect our analysis as we focus on overnight inter-bank markets.

(3) For the maintenance period beginning on October 4th 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 10th 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 8th 2008, the BoE more than doubled the reserves target ceiling it sets for each reserves scheme member. Both of these changes allowed banks to respond more to perceived risks through their reserves balances at the BoE.

(4) On April 21st 2008, the BoE introduced the special liquidity scheme 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 exchanging them temporarily 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 are able to take part in the Scheme. It was widely perceived that like the Federal Reserve's Primary Dealer Credit Facility (PDCF) in the United States, this liquidity scheme played a significant role in easing concerns of funding against illiquid collateral and diffused funding risks (at least temporarily).

Appendix 2. Calendar Effects on the Aggregate level of Payments Activity

This table reports ordinary least squares (OLS) estimates of a regression of payment activity (the aggregate logarithm of the payments value between all UK banks) on various calendar effects. UK holidays is a dummy taking value one on days immediately preceeding and following bank holidays; US holidays takes value one on US holidays and so on 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 in parentheses. (*), (**), (***) indicates significance at 10 per cent, 5 per cent and 1 per cent level, respectively. The results indicate that up to 75 per cent of the variation in payment activity can be explained by few calendar dummies.

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
Nber of Observations	376

Appendix 3. Relationship between overnight liquidity demand, payment activity, and bank risk

We estimate an individual bank studentized demand for intraday liquidity as a function of predicted payment activity interacted with alternative risk rankings. See Table 1 for a definition of liquidity and (predict) payment activity. Intraday (collateralized) liquidity usage (measured by the amount of collateral posted by settlement banks in the 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 ten banks in three groups according to the value of the risk metric used: high risk for top 3 banks (HR dummy), medium risk for middle 4 banks (MR dummy), and low risk for bottom 3 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. Break3 is a dummy variable that takes value one post 08/08/07, the Bai-Perron structural break date in the intraday liquidity time series. We report robust standard errors in brackets.

	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	x	x	x	x	x
Bank fixed effect	x	x	x	x	x
Nber of Observations	3008	3008	3760	2632	3384

Note: (*), (**), (****) stands for statistically significant at the 10 per cent, 5 per cent and 1 per cent level, respectively.

Appendix 4. Selection equation

This table reports 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 1 for a definition of payment activity. The sample covers 10 UK banks over 22 maintenance periods in the period 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

Robust standard errors in brackets

* significant at 10%; ** significant at 5%; *** significant at 1%