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

Viral V. Acharya
NYU-Stern, CEPR and NBER

Ouarda Merrouche
The World Bank

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Abstract: We study the liquidity demand of large settlement 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. 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 more so for weaker banks. We establish that the liquidity demand by settlement banks caused overnight inter-bank rates to rise, 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, the effect was experienced by *all* settlement banks, regardless of their credit risk, suggestive of an interest-rate contagion from weaker to stronger banks operating through the inter-bank markets.

JEL: G21, G28, E42, E58
Keywords: cash hoarding, contagion, systemic risk, counterparty risk

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Abstract: We study the liquidity demand of large settlement 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. 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 more so for weaker banks. We establish that the liquidity demand by settlement banks caused overnight inter-bank rates to rise, 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, the effect was experienced by *all* settlement banks, regardless of their credit risk, suggestive of an interest-rate contagion from weaker to stronger banks operating through the inter-bank markets.

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1 Introduction

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 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 – perhaps at overly attractive terms, against risky collateral, and to parts of the banking sector not generally accommodated in its 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). While such an outcome can substantially contribute to ex-ante moral hazard in bank risk-taking, it is also accompanied by the misfortune of laying the burden of monitoring and (at least some) credit-risk management, away from peer-based inter-bank system on to central bank balance-sheets.

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[2] and investigate its causal effect on inter-bank rates. Our broad conclusion is that events unfolding since August 9, 2007 had the effect of increasing the funding risk of banks,

[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).

[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".

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 and regardless of counterparty risk of borrowing banks, 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 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 withdraws from ATM or a corporation deposits into a money market fund) involves a "debit" from some bank's reserve balance and "credit" into another. 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 and the total financial activity in the economy ends up being a large multiplier on the quantity of circulating reserves.

While the aggregate reserves in the economy stay constant (unless altered by the central bank), by and large a few banks – typically the large ones – play a bigger role in these transactions and determine the price at which reserves are exchanged in the inter-bank market. Banks have access to the central bank's discount window to borrow reserves overnight at a penalty, but such borrowing is 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

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

[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.

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.

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 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). Based on econometric tests for structural breaks, it experienced a 25% increase in the period immediately starting 9th August, 2007, and a further 15% increase around 13th March, 2008 (the revelation of severe funding problems and ultimately collapse of Bear Stearns).[7]

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 aggregate volume of payments activity, argued to be days with greater uncertainty in the activity at individual banks (Furfine, 2000). Such response of settlement

[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 also study "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* be used to borrow overnight on the market. Our results are qualitatively similar for overnight liquidity as well as total liquidity.

[7] While 9th August, 2007 is recognized by most as a crucial breakpoint that initiated the crisis, anecdotal evidence also supports the second breakpoint of 13th March, 2008. See, for example, FT 9 April 2008: "UK banks seek higher borrowing facilities", and FT 10 April 2008: "UK banks seek more BoE borrowing", which noted that "UK banks asked to increase sharply the reserves they hold on deposit at the Bank this month to the highest ever level amid concerns that the instability of the banking system could suddenly leave them desperate for cash. They fear another bank crisis - akin to the collapse of US investment bank Bear Stearns - could see the market seize up. Banks have asked to keep total reserves of £23.54bn on deposit that they can borrow to meet short-term financing needs if they cannot borrow in the interbank market. This is up from the nearly £20bn they had on deposit until yesterday. This is money the banks keep on deposit at the Bank, earning interest, but that they can access when the cost of borrowing from other banks becomes too high."

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, and economic health during the crisis. We find that banks that during the crisis made greater losses (in terms of write-offs, equity price declines and widening of credit default swap spreads), hoarded more liquidity. Further, these banks also held more liquidity in response to payment uncertainty.

In our third piece of evidence, we study the effect of settlement bank liquidity on market-wide overnight inter-bank rates. 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 (with the UK government's GILT as collateral), and unsecured rates from the British Bankers' Association and Wholesale Markets Brokers' Association. 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 induces a negative relationship between settlement bank liquidity and inter-bank spreads. We call this the "arbitrage" effect. Our crucial observation is that when the rise in liquidity of settlement banks is endogenous, in particular, a precautionary response to heightened risks and funding concerns, then this relation may be reversed as they need to be compensated more for releasing liquidity to others. We call this the "liquidity" effect.

We attempt to separate this differential effect on inter-bank rates of exogenous and endogenous components of settlement bank liquidity. We show that the aggregate payment activity is driven by calendar day effects (for instance, lower on bank holidays in the United States), and is essentially uncorrelated over time. Thus, a *lagged* measure of such activity is a potential instrument for settlement bank liquidity while studying its effect on inter-bank rates. Formally, inter-bank rates on a given day depend on the liquidity reserves of settlement banks on that day (measured at 5 am), which we naturally assume includes a component of reserves adjusted to previous day's payment activity (the instrument) and a component adjusted in anticipation of today's payment activity (the endogenous component). We conduct a three-stage least squares estimation linking liquidity to rates and verify the econometric validity of our instrument.

The results reveal a strong causal effect of settlement bank liquidity on inter-bank rates, but in a manner that differs sharply between pre-crisis and post-crisis periods. When evaluated at the breakpoints of settlement bank liquidity (August 9, 2007 and March 13, 2008), we find evidence supportive of the liquidity effect: the effect of (instrumented) liquidity is to raise overnight inter-bank rates in the period during the crisis. In contrast, this relationship 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.

Finally, we ask if this effect of the endogenous rise in settlement bank liquidity on inter-bank rates is uniform for all borrowing banks or limited to those that were affected most adversely during the crisis. We exploit bank-level variation in the inter-bank unsecured borrowing rates (using the Furfine, 2000 algorithm on the payment flows data) and study whether it is determined by bank's own liquidity as well as that of other banks.[8] We find that it is other banks' liquidity that determines a bank's borrowing rate rather than its own liquidity. And importantly, the group of stronger banks during the crisis is as exposed to rate rises (in response to other banks' liquidity) as the group of weaker banks.

We interpret these findings to imply that while the access to capital markets and wholesale borrowing in commercial paper markets might have been impaired for banks depending upon their credit risk, overnight Sterling inter-bank rates in the first year of the crisis do not seem to have been driven by counterparty risk concerns of lending banks about the borrowing banks. Instead, the credit risk of banks appears to have manifested in inter-bank rates through greater lending rates by weaker banks for all borrowing banks. Put another way, our findings suggest that the stress in Sterling money markets was at least partly due to weaker banks engaging in liquidity hoarding as a precautionary response to their own credit risk and in turn their heightened opportunity cost of funds. Such hoarding raised borrowing rates for safer banks too, suggestive of a contagion-style systemic risk operating through inter-bank markets.

Overall, our evidence suggests that regulatory attempts to thaw the money market stress and reduce variability of inter-bank rates, if successful, can have salubrious effects on healthier parts of banking (and possibly, the real 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.

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, 2010). 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. Nevertheless, this remains an important extension that we plan to pursue in future research.

Section 2 provides the relevant institutional details of the UK payment system and

[8] Such data are not available for secured borrowing rates. However, the simple time-series plots of the overnight secured and unsecured rates relative to BoE policy rate track each other rather well (see Figure 2).

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 causal effect of liquidity hoardings on inter-bank rates and the contagion-style results. Section 7 relates our paper to literature and Section 8 concludes.

2 Institutional Background

This section provides some important background information. Section 2.2 provides an overview of the Bank of England (BoE) monetary policy framework. Section 2.1 describes the structure of the payment system and money markets in the UK and institutional and operational boundaries within which banks are able to manage the liquidity requirements arising from their daily payment activity. Section 6 summarizing the range of adjustments to the framework the BoE undertook since August 2007 to restore orderly conditions in money markets is discussed after presenting our main analysis.

2.1 The Monetary Policy Framework[9]

In May 2007 the BoE was given independence and 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. 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.*

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), that 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

[9]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.

accounts, and so 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 keeps 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.[10] 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 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).

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

[10] 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."

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; by solicitors/licensed conveyancers to transfer the purchase price of a house between the bank accounts of those involved; 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. This explains why the amount of activity in CHAPS has not fluctuated much during the crisis (see Figure 4).

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. Hence, even within our sample of ten settlement banks, we will sometimes study the top four clearers and compare them with the rest, as the top clearers are subject to most of the payment uncertainty.

Besides the interbank markets banks manage short-term liquidity needs via their reserves balances held at the central bank. Subject to meeting the monthly target balance and avoiding overnight overdrafts, reserves balances can be varied freely to meet day-to-day liquidity needs. For example, funds can be moved on and off reserves accounts up to the close of the payments system 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 by (i) holding balances on their reserves account at the BoE, as discussed above; (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, emergency) lending facility. We discuss (ii) and (iii) next.

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 holdings 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. Their *total liquidity* is the sum of their *overnight liquidity* and their *intra-day liquidity*. The *intra-day liquidity* is the maximum total collateral that these settlement banks post during a day to obtain intra-day credit from the central bank, including the collateral held overnight in fulfillment of BoE's regulatory liquidity requirement. 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 two rows of Table 1 report various descriptive statistics (mean, standard deviation, minimum, maximum, quantiles) of the overnight and total 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 the overnight liquidity is 27 per cent higher post August 9th and the total liquidity 24 per cent higher. These differences are also seen in Figure 1 (logarithm of total liquidity) and Figure 3 (overnight liquidity) 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 total and overnight settlement bank liquidity in order to mute the effect of outliers (and in subsequent tests to allow interpretation of coefficients in terms of elasticities).

3.2.1 Total Liquidity

Table 2a reports the test results for total liquidity. The first column reports the break dates. The second column gives the 95% confidence interval for each break point. The third column provides the estimated mean of the (log) liquidity series considered for each window. The fourth column details headlines on dates over the period 1 May 2007 to 30 June 2008 falling within the 95% confidence interval for any break point shown in bold.

The total liquidity (in logarithm) and estimated breaks are also plotted in Figure 1. The test identifies two upward breaks in the total liquidity. A first 7.2% increase in the total liquidity occurred on March 27th 2007 and a further 20% increase on August 8th 2007. The first break is modest in comparison to the second and does not coincide with any key market event. In contrast, the second break precedes immediately August 9th 2007, widely believed to be the date of money market "freeze" in the UK, European and US money markets, and coincides exactly with the first negative news announcement by a major European bank (BNP Paribas) in Bloomberg headlines which led to a freeze in the asset-backed commercial paper market.[11]

This is preliminary evidence that the most significant break point in total settlement bank liquidity series might have been a response to the heightened funding risk as banks suddenly faced high costs in raising wholesale funding, for example, issuing short-term asset-backed commercial paper. Instead, banks would now have to tap into other forms of financing such as relying more on reserves balances with the central bank or through

[11] For two weeks in August BNP Paribas suspended redemptions from three money market funds because they did not feel they could fairly value their positions. Before BNP's announcement, loss announcements and other negative news in the headlines were concentrated in the United States, primarily Bear Stearns' hedge funds and also some monoline insurers. A cascade of loss announcements, primarily unscheduled, from US and European banks followed immediately after BNP's announcement as many banks were forced to honor the liquidity and credit enhancements they had sold to asset-backed special purpose vehicles or in some cases take these assets back on balance sheets.

inter-bank markets or do external capital-raising (which is however especially costly in a crisis both in terms of adverse selection costs, as argued by Myers and Majluf, 1984, and dilution costs due to debt overhang, as argued by Myers, 1977).

3.2.2 Overnight Liquidity

Table 2b reports results for the overnight liquidity. 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 the major break in the total liquidity. This break is delayed because banks are allowed to revise their reserves targets only from one Monetary Policy Committee meeting to the next. Figure 3 shows that the first increase in the aggregate reserves target occurred on September 6th 2007, the date the first MPC meeting took place after the sub-prime crisis took hold. One can observe in Table 2b 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 (as described in Section 6). For the October maintenance period, banks chose a higher target – around 20% higher than the aggregate target for the August maintenance period.

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 in the US. Bear Stearns episode reflected yet another 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 in their liquidity stress tests that the worst case scenario was simply the drying up of unsecured funding, but that secured funding may dry up too. This further intensified the funding needs and risks faced by banks and the liquidity response of banks is thus again consistent with a precautionary motive. Note that in contrast to the delayed response following August 9th 2007, the liquidity demand of banks in this case 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 Section 6).[12]

4 Evidence of the Precautionary Motive

While the higher reserves targets may have reflected anticipation of heightened funding needs and risks, one needs to consider also the fact that banks had access to BoE's standing

[12]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.

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 having to use the standing facilities (SF) following an unexpected payment shock in late trading. The expected cost of using 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 the explanatory power of aggregate payment shock uncertainty for settlement bank liquidity and explore its interaction with bank-level funding risk and balance-sheet condition. That is, we now investigate the cross-sectional variation in liquidity demand of settlement banks. From now on our analysis focuses only on overnight liquidity (reserves balances) which is the settlement liquidity remunerated by the central bank and exchanged in the interbank market. The results are similar for total liquidity that includes maximum intraday borrowing from the Bank of England (but repaid by end of the same day).

4.1 Benchmark specification

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 interbank loans activity. We use two measures of aggregate payment activity that are also typically employed in analysis of money markets: *Payment value* measuring the Sterling amount and *Payment volume* measuring the number of transactions. A higher payment value controlling for number of transactions implies greater payment risk; conversely, higher payment volume controlling for payment value implies small size transactions and lower payment risk.[13]

Table 1 shows the summary statistics for payment value and volume 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 any differential response of settlement bank liquidity to payment activity must thus arise from a rise in the perceived cost of managing payment shocks through means other than central bank reserves. Figure 4 plots the payment activity in value and volume (in logarithm). At first sight, these series appear to be white noise processes. A Portmanteau test reported in Table 3 confirms this observation. For both series the lag-one autoregressive coefficients are small (not reported). The Portmanteau test for lag-one has p-value of 0.29 for the aggregate payment value and 0.12 for the aggregate payment volume rejecting the null hypothesis that the first lag autocorrelation is different from zero.

Importantly though, payment risk measured as daily changes in aggregate payment activity is in fact predictable by banks due to calendar effects. In fact, APACS, the UK payments association, claim to be able to forecast close to 100 per cent of the fluctuations in aggregate payment flows (not their distribution across banks). Table 3 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 75 per cent of the variation in the payment volume and 40 per cent of the variation in payment value. 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 also.

To investigate how banks adjusted their liquidity reserves at the start of the day in response to payment activity measured at the end of 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:[14]

$$OLiq_{it} \quad = \quad \omega_i + \sum_{s=1}^{3} \delta^s \cdot break_t^s + \alpha \cdot P_t + \sum_{s=2}^{3} \beta^s \cdot P_t * break_t^s$$

[13]Note that the two are correlated, but not highly so (around 0.5) with not much difference in the pre- and during crisis periods.

[14]For most of the remaining analysis, we focus on the reserves liquidity because only reserves can be lent overnight in the market. Collateral that may be used for intraday borrowing (under the regime double-duty) must be held overnight on balance-sheet in fulfillment of regulatory liquidity requirements.

$$+ \quad \mu \cdot X_{i(t-1)} + \sum_{s=2}^{3} \gamma^s \cdot X_{i(t-1)} * break_t^s + \varepsilon_t \ , \qquad (1)$$

where i stands for a bank subscript, ω_i is a bank fixed effect, $OLiq_{it}$ is the overnight liquidity of settlement banks, and P is a vector of measures of aggregate payment activity (the volume and the value). Payment activity is in logarithm and liquidity is in percentage of a standard deviation variation from the first half of 2007 average (capturing abnormal variations in bank liquidity demand). The breaks are based on estimations in Table 2: $break_t^1$ is a post August 8th 2007 dummy; $break_t^2$ is a post September 11th 2007 dummy; $break_t^3$ is a post March 13th 2008 dummy.[15]

Hence, the first line of the specification allows for a structural break in settlement bank liquidity at these break points, tests for its sensitivity to aggregate payment activity, and whether this sensitivity changed around the break points. The second line of the specification allows for a test of whether settlement bank liquidity was higher for some banks and more so following the break points. We employ five specifications with different bank characteristics X_i (lagged, wherever applicable), that capture the bank's payment exposure, funding risk and realized health during the crisis:

1. A dummy variable for whether the bank is one of the top 4 settlement banks in terms of payment activity.

2. Cumulative write-offs scaled by total assets (quarterly series).

3. The % fall in equity market capitalization relative to the average capitalization in 2006 (daily series).

4. The cumulative change in the 5-year senior unsecured (Modified Restructuring clause) credit default swap (CDS) premium collected from MarkIt (daily series).

5. The cumulative change in the ratio of total assets to retail deposits (monthly series).

The rationale for picking these bank characteristics is as follows. Bigger settlement banks are exposed to greater risk of payment shocks because of their larger customer banking activity (settling payment on behalf of other banks) which they cannot predict as well as their own payment activity. 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 and CDS changes) should incorporate better public information available on the financial condition of a bank, including anticipation of losses and not just realized losses. Finally, fall in retail deposits relative to

[15] We exclude $break_t^1$ for the interaction effect as there is only one month between that break and $break_t^2$ and thus little statistical power for its identification.

assets accounts for the fact that while some banks were directly threatened by the meltdown of the ABCP market, they were rendered especially fragile if they also experienced a flight of retail deposits to safer banks.[16]

Table 1 reports descriptive statistics of these variables. There is significant variability across banks in the measures of bank health and funding risk. About 50 per cent of the banks in our sample did not report any losses as of March 2008, but all did between then and end of our sample period (with an average of 6% write-offs relative to assets). Equity and CDS prices experienced dramatic swings over the sample period for many banks. While CDS spreads increased 20 basis points (bps) on average, the maximum widening was as high as 200 bps. Similarly, while average equity price decline was small, the worst decline was over 70%. And while some banks gained retail deposits relative to assets (a fall in the assets to deposits ratio), others experienced significant losses[17].

The overall results for estimation of the benchmark specification are reported in Table 4. The results in columns (1) through (7) suggest that following events unfolding since 9 August 2007, banks (especially riskier banks) hoarded liquidity.

Column (1) shows that the settlement banks react to an (expected) increase in payment value on day t by holding more liquidity at the start of the day. Controlling for the aggregate payment value a decline in the aggregate payment volume, i.e., an increase in the average payment size, also causes settlement banks to hold larger buffers at the start of the day. Interestingly, column (2) shows that the relationship between settlement bank liquidity demand and payment value is significant statistically only during the crisis, that is, following September 11th 2007 ($break_t^2$), the first MPC date after the onset of the crisis. In other words, reserves held by settlement banks rose with higher value of payment activity, during the crisis but not before. While there is a response in settlement bank liquidity to more payment transactions even before the crisis, the response is magnified following $break_t^2$. The p-values of the total effects of payment activity on liquidity demand in each phase of the crisis (reported at the bottom of Panel A) vary around 1 per cent statistical significance. Further, the relationship is economically meaningful: a one percentage change in the value of payment activity post September 11th 2007 is associated with a 2.59 percent of a standard deviation increase in the liquidity buffer of settlement banks relative to pre-crisis average.

In columns (3) through (6), we find that higher bank risk is associated with increased liquidity demand during the crisis. Higher losses (measured by write-offs, equity price

[16]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.

[17]The summary statistics reported are for the whole sample period. The top 5% of the distribution of losses gives an idea of how the variables look like during the crisis.

decline, and widening of CDS spreads) and higher funding risk (captured by the top 4 settlement bank dummy) are both associated with higher demand for liquidity during the crisis, with the widening of CDS spreads showing the effect on liquidity only following $break_t^3$ (13th March 2008). In terms of magnitude, the four largest settlement banks increased their buffer by an additional 29 percent of a standard deviation (relative to pre-crisis levels) compared to smaller banks (column 3). Unlike the other risk metrics, declines in retail deposits are not associated with a statistically significant change in liquidity demand (column 7) during the crisis, even though the coefficients have the expected positive sign.

Figures 5 and 6 depict this effect graphically. They show a dramatic rise in liquidity demand among high risk banks relative to low risk banks as the crisis unfolds, the risk measures being respectively whether the bank is a top four settlement bank or has above median rise in assets to retail deposits during the crisis. The figures look similar with other risk measures. Note that in the figures, we focus on revisions to reserves targets by settlement banks in the two groups on MPC dates. Changes in these target are pure variation in demand since banks *choose* their reserves target. The figures underscore results of Table 4 Panel A that high risk banks revised their reserves targets soon after inception of the crisis in August/September 2007, whereas low risk banks did so only in 2008 (and less strongly at that).

4.2 Heterogeneity in the Precautionary Reaction of Banks

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 payment activity. We split the sample in high risk and low risk banks using the median of the risk metrics as threshold (except in the case of top four settlement bank classification where the partition is simply top banks and others).

The estimation results are reported in Table 5 Panel A and confirm a more pronounced precautionary reaction to payment activity (especially, in terms of payment value) among banks with troubled balance-sheet conditions. It is easier to gauge the significance of the results by looking at Panel B which reports the p-values for the significance of the total effects in each phase of the crisis and p-values for the significance of the difference in coefficients between high risk banks and low risk banks. We see that the relationship between aggregate payment activity and liquidity demand is stronger during the crisis and more so for weaker banks. Importantly, the difference between high risk and low risk banks is significant statistically when risk is measured by write-offs, widening of the CDS premium, and loss of retail deposits.

To sum up, the findings in this section confirm our hypothesis that the increase in the settlement bank liquidity witnessed during the crisis was (at least in part) precautionary. 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 weaker banks and banks characterized by greater balance-sheet funding risk.

5 Effect of Liquidity Hoarding on Money Market Rates

In the second half of the paper, 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 before and during the crisis.

5.1 Revised "Arbitrage" Condition in Stressed Money Markets

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, however, 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 now 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 excess precautionary liquidity only if the return on liquidity exceeds the high private benefit, causing interbank 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.

5.2 An Instrumental Variables Approach

To isolate the exogenous and endogenous components of settlement bank liquidity, we once again exploit variations in payment activity. Section 2.1 highlighted mechanisms whereby aggregate payment activity correlates with the settlement banks' overnight liquidity and Section 4.1 provided supporting empirical evidence. We take advantage of this relationship in our econometric approach.

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

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

where the precautionary demand for liquidity is captured by the dependence of l_t on P_t, the payment activity on day t (assuming banks are able to make a reasonable forecast of the aggregate payment activity). Then, equation (2) can be rewritten as:

$$l_t = \alpha^2 l_{t-2} + \alpha\beta P_{t-1} + \beta P_t + \varepsilon_t^l \ . \tag{3}$$

Note that such an autoregressive structure would be natural when a bank chooses reserves subject to a target it committed to at the previous target-setting day.[18] Thus, within a maintenance period, bank liquidity at time t is a function of all the past history of payment activity.

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

$$r_t = \gamma l_t + \delta P_t + \varepsilon_t^r \ . \tag{5}$$

That the market rate on a given day is a direct function of the payment activity on that day follows from Furfine (2000). The argument goes as follows. Payment flows on any given day are positively correlated with reserves balance uncertainty. As uncertainty generates a precautionary demand for reserves, days with higher payment flows are associated with upward pressure on the market rate. In other words, on busier days, banks

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

$$\Delta_t \equiv l_t - l_{t-1} = \theta\left(\bar{l} - l_{t-1}\right) + \beta P_t + \varepsilon_t^l, \tag{4}$$

where $\bar{l}$ is the reserves target of the bank. Then, up to a constant (the reserves target), bank liquidity l_t follows an autoregressive structure as proposed.

desire to hold a larger cushion of reserves to protect against penalties for overnight overdrafts. In equilibrium, this generates a positive relationship between payments activity and the market rate.

If this Furfine (2000) argument holds P_t is not a valid instrumental variable for l_t, in studying the effect of liquidity l_t on interbank rate r_t. However, because P_t is a white noise process (based on evidence presented in Section 4.1 and Figure 4), P_{t-1} is potentially a valid instrument for l_t. In other words, inter-bank rates on a given day depend on the liquidity reserves of settlement banks on that day (measured at 5 am), which we naturally assume includes a component of reserves adjusted to previous day's payment activity (the instrument) and a component adjusted in anticipation of today's payment uncertainty (the endogenous component).

The use of this instrument also helps address another issue, that of omitted variable bias. It is plausible that during the crisis period, there were day to day fluctuations in counterparty risk in the inter-bank markets. Such risk would simultaneously raise inter-bank rates and generate a precautionary demand for liquidity at banks. Since payment activity P_t is a white noise process, P_{t-1} is uncorrelated with counterparty risk on day t which is more likely to determine, or be a function of, P_t. Thus, instrumenting bank liquidity l_t with P_{t-1} also helps isolate the effect of liquidity on inter-bank rate r_t which is unrelated to a counterparty risk factor.

5.3 Estimating the *Liquidity* Effect

5.3.1 Regression Specification

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

$$\begin{cases} Y_t = \alpha_y \cdot OLiq_t + \sum_{s=2}^{3} \beta_y^s \cdot OLiq_t * break_t^s + \sum_{s=1}^{3} \gamma_y^s \cdot break_t^s + \varepsilon_t^y \ , \\ OLiq_t = \alpha_o \cdot P_{t-1} + \sum_{s=2}^{3} \beta_o^s \cdot P_{t-1} * break_t^s + \sum_{s=1}^{3} \gamma_o^s \cdot break_t^s + \varepsilon_t^o \ , \end{cases} \tag{6}$$

where Y_t is a vector of two variables: the secured and the unsecured inter-bank rate spread to the policy rate (in bps). All other variables are as in specification (1). The system is estimated using three-stage-least squares (3SLS) employing lagged payment activity as an instrument.[19] We also report results of estimation using the ordinary least squares (OLS) for sake of comparison.

[19]Three stage least squares is a combination of multivariate seemingly-unrelated regressions (SURE) and two stage least squares. It obtains instrumental variable estimates, also taking into account the covariances across equation disturbances. If the error terms of the different equations are correlated across equations, then joint estimation of the equations is able to exploit this cross equations correlation to obtain more efficient estimates.

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).

5.3.2 Money Markets Data

To estimate this specification, we use daily market-wide interest rates 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.[20] Table 6 reports descriptive statistics of the rates data as well as overall volumes (which we analyze at market-wide and at bank level in case of unsecured volumes in the Appendix). 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 2 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 announcements and bailouts (see the timeline of news in Table 2).[21]

It might seem a puzzling observation in that the secured rate has increased more than the unsecured rate, even if by a small margin. Note that 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). Coincidentally, Table 6 shows that in terms of aggregates, both the secured volume and the unsecured volume have increased post-August 9th 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. We entertain this possibility in the Appendix where we analyze unsecured volumes in overnight inter-bank markets.

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

[21]We explain in Section 6 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.

5.3.3 Effect of Liquidity Hoarding on Rates

The results of estimating specification (6) are reported in Table 7 where the dependent variable is either the secured or the unsecured rate spread to policy rate (in bps). In the set of columns labeled (1) and (2), we report OLS estimates, and in (3) and (4) the 3SLS estimates. Set of columns (1) and (3) employ log of total settlement bank overnight liquidity, whereas in (2) and (4), we measure the total liquidity of settlement banks in percentage deviation from their aggregate target. The first measure would reflect changes in liquidity from one maintenance period to another also due to revision in targets (which induce central bank injections or draw downs of reserves), whereas the second measure focuses exclusively on deviations from these targets (that is, fluctuations that are unmet by central bank injections).

Consider first the OLS results. We find that for both secured and unsecured rates, while before the crisis a higher level of liquidity held by settlement banks is associated with a significant decline in overnight spreads (the arbitrage effect), during the crisis the incremental effect is positive (the liquidity effect), starting with $break_t^2$ (13th September 2007). The total effect of liquidity on rate spreads during the crisis is in fact not statistically significant, as shown in tests at bottom of the table. The OLS specification, however, suffers from potential endogeneity and omitted variable biases discussed above.

Next, Table 7 shows that in terms of our instrument (lagged payment activity), for all 3SLS specifications the over-identification test lead to non-rejection of the instrument. The instruments are also strong predictors of liquidity demand with the F-statistics at the first stage being largely above 10, ruling out issues of weak instrumentation. More substantively, we find that all the OLS effects are qualitatively present in the 3SLS specifications too, but the magnitude of both arbitrage and liquidity effects is about three times as large (comparing (1) and (3) for log of overnight liquidity) or four to six times as large (comparing (2) and (4) for percentage deviation of reserves from targets). This effect, combined with statistical significance of the instrument, suggest that lagged payment activity indeed helps isolate the effect of bank liquidity on inter-bank rates that is not driven by common factors such as counterparty risk concerns.

In terms of economic magnitude (column (1)), a 10 per cent pre-crisis increase in the overnight liquidity buffer is associated with a 5.53 bps *decline* in the secured spread; post-crisis, however, there is a correction of 6.89 bps in the direction of an *increase* in the secured spread. 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 secured rate. The reason is that activity in the unsecured market is concentrated among the settlement banks. As highlighted in Section 2 settlement banks participate in the unsecured market to manage the liquidity needs that arise from their daily payment activity. It follows that the unsecured rate is the rate at which settlement banks borrow. Relating settlement bank liquidity and the unsecured (settlement bank borrowing) rate therefore is a weak test of the market-wide externality created by hoarding behavior at settlement banks.

Interestingly, there is no significant incremental effect post 13th March 2008. The coefficient on $OLiq_t * break_t^3$ is not significant statistically nor robust in its sign and relatively small in magnitude. We conjecture that apart from the two weeks following the Bear Stearns collapse, further stress in inter-bank markets was contained for the period going from end-March to the end of our sample period (June 2008). In particular, on April 21st 2008, the BoE introduced the special liquidity scheme to deal with the overhang of assets on bank balance sheets, allowing banks and building societies to swap for up to three years some of their illiquid assets for liquid Gilts. The introduction of this scheme might have gone some way towards calming the inter-bank markets but (as our results show) did not reverse the liquidity effect that initiated in September 2007.

These results confirm our hypotheses: in stressed conditions banks release their (precautionary) excess liquidity only at a liquidity premium that exceeds 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. In other words, when the rise in liquidity of settlement banks is a precautionary response to heightened risks and funding concerns, banks require to be compensated more for releasing liquidity to others. 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 adverse funding conditions. Such hoarding raised the lending rates charged in secured as well as unsecured inter-bank markets.

5.4 Contagion Effect

We showed so far that the regime shifts in settlement bank liquidity can be explained by a precautionary reaction at weaker banks. We also showed that the rise in this liquidity raised average interbank rates during the crisis. This latter effect could be due to counterparty risk, that is, due to a rise in the borrowing cost of weaker banks, and/or due to the liquidity effect, that is, due to a rise in the lending rates of weaker banks. We employed an instrument to get around the counterparty risk effect, but so far only employed the average inter-bank rate. In our final test, we try to separate these two effects using the liquidity response of an individual bank and its contagious effect of causing interbank rates to rise for *all* other banks (borrowing from it).

We estimate the regression:

$$Spread_{it} = \omega_i^s + \alpha^s * OLiq_{it} + \beta^s * OLiq_{i-t} + \varepsilon_{it}^s \ , \tag{7}$$

where *Spread* is the (transaction-value weighted) unsecured spread to policy rate paid on overnight borrowing by bank i on day t. Note that only unsecured market data are available at bank level (extracted from CHAPS, the large value payment system, using the algorithm of Furfine, 2000). $OLiq_{it}$ is the overnight liquidity held by bank i; and $OLiq_{i-t}$ is the aggregate overnight liquidity held by all banks other than bank i. Descriptive statistics of the main variables used in the analysis are reported in the second half of Table 6. Note that the bank-level unsecured rate spread is clearly more variable than the average or market-wide rate spread. The mean spread is also lower for our bank-level spread data and this is because the bank-level analysis is confined to the ten large settlement banks, whereas the market-wide spread is based on inter-bank borrowing for a much larger set of financial players. Also, as before, the quantity variables (liquidity and payment activity) are normalized due to large differences in size across banks, as the number of standard deviation changes from the mean, both calculated over the first 12 months of our sample period.

We estimate the equation using OLS and also by 2SLS using P_{it-1}(own payment activity) and P_{i-t-1} (aggregate payment activity of all other banks) as instruments for $OLiq_{it}$ and $OLiq_{i-t}$, where P is a vector of lagged payment activity measures (volume and value). We thus have four instrumental variables for two endogenous variables. We also estimate the specification where α and β are interacted with the two break dummies. The instrumental variables are interacted similarly. The contagion hypothesis requires that each bank's borrowing rate depends (positively) on the precautionary liquidity of other banks ($\beta > 0$), and more so following the crisis.

In Table 8, we report estimates of the contagion effect. Columns (1) and (2) we show the OLS estimates whereas in (3) and (4) we report the 2SLS estimates along with the Hansen-Sargan test of over-identification. The dependent variable is the bank borrowing spread to policy rate (in bps). We use two alternative measures of liquidity demand: (1) abnormal variations from pre-crisis levels (columns 1 and 3); and (2) liquidity in percentage deviation from the target to isolate demand that is not (yet) met by the central bank (columns 2 and 4).

In all columns, the estimates show that the rate at which a bank borrows varies significantly with the liquidity held by other banks in the system but not with its own endowment. Further, there is a significant difference between pre-crisis and crisis times. While pre-crisis, increase in liquidity with other banks causes a bank's borrowing rate to go down, in crisis, as other banks in the system hoard liquidity for precautionary reasons, the bank's borrowing rate goes up. The differential crisis effect is statistically significant in columns (1), (2) and (4), but not in (3), even though the signs are consistent throughout. As in Table 7, the 2SLS effects for both arbitrage and liquidity channels are stronger than the ones identified in the OLS.[22]

[22]Note that coefficients on the current payment activity confirm that higher payment uncertainty causes significant rises in interbank rates, as we postulated earlier (equation 5).

To investigate whether counterparty risk played a substantial role in affecting bank borrowing rates during our sample period, we augment specification (7) with interactions of bank's own liquidity and other banks' liquidity with dummies for high risk and low risk groups (as employed in Table 5). The results are reported for 2SLS estimations in Table 9 Panel A for the borrowing spread with liquidity demand measured as deviations from the pre-crisis levels (we report just one measure for sake of parsimony).

As in Table 8, the contagion effect is statistically and economically significant: A bank's borrowing spread is significantly altered by the total liquidity of other banks (negative arbitrage effect pre-crisis and an incremental and positive liquidity effect post-crisis, and statistically significantly so when risk groupings are based on top settlement banks, equity price declines and retail deposit losses), but is overall independent of the bank's own liquidity buffer. Interestingly though, these effects are virtually identical between high risk and low risk banks. Panel B reports p-values for the significance of the effects in each phase of the crisis and for the significance of the difference in coefficients between high and low risk banks. The contagion effects compared between the high risk and the low risk groups (HR = LR tests) are by and large never rejected at conventional significance levels.

To summarize, our analysis shows significant evidence for one sufficient condition for contagion in the form of an individual bank's borrowing cost being determined by other banks' liquidity. Since the effects are present both pre- and during crisis, the critical determinant of whether there is significant contagion or not is whether there is a significant rise in bank liquidity hoardings. The latter was the case since the inception of the crisis as we documented in Table 4.

6 Robustness to Calendar Effects and Policy Changes

In this section, we first consider robustness of our results to augmenting our baseline specifications with calendar effects and policy changes. We note at the outset that in our view, the policy reforms to the monetary policy framework were not natural experiments but were in fact endogenous to economic variables of interest, such as, bank liquidity and inter-bank rates. Thus, controlling for the timing of adjustments to the monetary policy framework in our analysis is at one level, taking the conservative position that these reforms were fully supply driven rather than demand driven, but at another level, raises the caution that any results be interpreted with a grain of salt since in the process we are introducing endogenous actions of the central bank as explanatory variables.

An important event in Sterling money markets prior to the onset of the crisis 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 potentially lead eventually to an "uncovered" OMO, as happened in June 2007, before the turmoil, which means that reserves were eventually undersupplied and interbank rates went up dramatically due to lack of reserves relative to banks' targets. The Money Market Liaison Group at BoE thought that the reaction to the uncovered OMO in end of June 2007 may have reflected some money market participants not fully appreciating how the Bank's sterling monetary framework was supposed to work.[23]

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). We will check robustness of our results by controlling for the uncovered OMO episode through a dummy variable.

Also, there were important adjustments made to the monetary policy framework in the UK during the period of the crisis giving leeway for banks to build up larger liquidity buffers. We describe them below and also control for them in some of our analysis to understand which policy changes coincided with important demand shifts. 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

[23]Bindseil, Nyborg and Strebulaev (2004, 2009) discuss how repo auctions at the European Central Bank, which were also fixed-rate tenders, experienced uncovered operations in early 2000's.

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 temporarily easing concerns of funding against illiquid collateral.

We examine the robustness of our results by controlling for policy variables in Tables 4 and 5 (precautionary demand for liquidity in the aggregate and in the cross-section of banks, respectively) and Table 7 (arbitrage versus liquidity effect of precautionary liquidity on inter-bank rates). In Table 10 Panel A, we augment specification (1) with variables Z_t that include a full set of dummies to control for exogenous calendar effects: (1) A dummy for days in the last week of June 2007 when the uncovered OMO occurred; (2) A dummy that takes value one on days when the regular weekly open market operations take place (every Thursday); and (3) Maintenance days' fixed effects to control for regular within maintenance patterns in liquidity holdings. In Table 10 Panel B we further augment specification (1) with: (4) Dummies marking two periods when alternative adjustments to the monetary policy framework were in place: (a) the widening of bands around target between October 5th 2007 and May 1st 2008, and (b) the higher ceiling set on reserves targets from May 2nd 2008 onwards, including which helps control for shifts that one-time adjustments to the monetary policy framework might have caused on the aggregate liquidity; and, (5) A dummy for days when the BoE injected liquidity in excess of the aggregate target chosen by banks: 13 September 2007 to 3 October 2007 and 17 March 2008 to 9 April 2008.

In Panel A we find in columns (1)–(7) the total effects *during the crisis* remain significant at the five percent to one percent level (as shown by p-values at the bottom). As before, the precautionary liquidity reaction of an individual bank to fluctuations in payment activity is significant during the crisis but not before the crisis. In Panel B, controlling for policy changes does not have a substantial effect on the total effects (in particular after break3, i.e., 13th March 2008); the precautionary liquidity reaction of banks to fluctuations in payment activity remains strong during crisis and insignificant before crisis. And the effect during crisis ($\alpha+\beta^2$ and $\alpha+\beta^2+\beta^3$) is statistically significantly different from the pre-crisis effect (α). In particular, we cannot reject the hypothesis that $\alpha \neq \alpha + \beta^2 + \beta^3$ at the 5 per cent level (test not reported). Importantly, in both panels the coefficients capturing the sensitivity of liquidity demand to bank risk characteristics remain strong. During the crisis, weaker banks and banks exposed to greater payment uncertainty exhibit substantially greater overnight liquidity even controlling for various policy changes, and in particular, not just across reserves maintenance periods but also within maintenance periods.

It is also instructive to study the coefficients on policy variables. First, it is noteworthy that the introduction of a higher ceiling set on reserves target is associated with settlement banks increasing their liquidity buffer by 40% to 50% of a standard deviation relative to pre-crisis average. It was made possible by the central bank for banks to maintain higher reserves and they did so. Second, excess (above aggregate target) supplies of liquidity by the central bank are associated with a substantial increase in the stock of liquidity held by settlement banks. Third, the widening of the bands around target gave banks greater flexibility to manage the liquidity needs arising from their daily payment activity. This too coincided with settlement banks raising their liquidity though the effect is not robust in terms of statistical significance. Finally, the effect of the uncovered OMO dummy is negative, but not statistically significant.

In Table 10 Panel C, we augment specification of equation (6) with calendar effects and policy variables Z_t described above. Controlling in addition for maintenance period fixed effects is an alternative way of capturing variations in liquidity demand that are not met by the central bank. We only report the 3SLS results. The broad conclusion is that statistical significance of both the arbitrage effect (negative coefficient on settlement bank liquidity in explaining inter-bank rates in the pre-crisis period) and the liquidity effect (positive coefficient for incremental effect in the post-crisis period) remains strong when the dependent variable is the secured rate (the market-wide rate), and their magnitudes are similar when compared to sets of columns (3) and (4) in Table 7.

7 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 micro-structure of inter-bank markets in terms of reserves requirements by central banks and the monetary policy, (iv) the transmission of bank-level stress as contagion in the financial sector.

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. Holmstrom and Tirole (1998) argue that in the presence of aggregate liquidity shocks asset sales cannot provide sufficient liquidity for an efficient functioning of markets. Allen and Gale (2000) build a model of co-insurance against uncertain liquidity shocks through bank cross-holdings. Coinsurance works well against idiosyncratic shocks: banks with surpluses provide liquidity to banks with shortages. However the whole liquidity of the banking system is bounded by the aggregate liquid assets in the banks' portfolio. Hence while the cross-holdings work perfectly in normal times and help reallocate liquidity across banks, they cannot create additional liquidity. Diamond and Rajan (2001) develop a model where a bank failure can spread to the whole system through a reduction in the common pool of available liquidity. In Allen, Carletti and Gale (2008) liquidity hoarding by banks is driven by an increase in aggregate uncertainty which causes banks to stop using the interbank market to trade with each other. The banks hoard liquidity because they may need it to meet high *aggregate* demand.

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.

While we do not study bilateral inter-bank market data required to investigate strategic behavior, our findings suggest that the stress in inter-markets witnessed during the sub-prime crisis is unlikely to have been due (entirely) to counterparty risk concerns. We find almost identical effects in the Sterling money markets for overnight lending in secured as well as unsecured transactions. While our results on transmission of an individual bank's funding risk, and its precautionary hoardings, to other banks do not find a direct parallel in the literature, this form of contagion is similar in its overall spirit to that considered in models of aggregate liquidity shortages. These include 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.[24]

Our paper also relates to the small literature exploring 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. While we control for open market operations in our tests, 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 using lagged payment flows as an instrument to isolate the effect of that component of reserves on interest rates that arises as a precaution against *unobserved* funding risk faced by banks in capital or inter-bank markets. Fecht, Nyborg and Rocholl (2010) study the German banks' behavior in ECB's repo auctions during June 2000 to December 2001, a period of high global corporate default rates even if not a banking crisis. They examine the effect of bank-specific and market-wide factors on prices that banks pay for liquidity, measured as their borrowing rates in repos with the ECB, and find (as we do) that the rate a bank pays for liquidity depends on other banks' liquidity and not just its own.

Ashcraft and Duffie (2007) also provide evidence consistent with 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 overconcentration of reserves does not arise in some banks. The authors hint at the possibility that precautionary targeting of reserves by banks, anticipating the heightened risk of hoarding by other banks, can lead to a "gridlock", high interest rates and systemic risk, on days when some large institutions end up with high reserves (by chance or by design). It is possible that precautionary hoardings we identify capture such a phenomenon, but the fact that they increase in our data for weaker banks leads us to conclude that they are potentially also a response to funding needs during adverse conditions.[25]

Finally, Ashcraft, McAndres and Skeie (2010) provide a theoretical model and empirical evidence for the Federal Funds market showing that banks hold excess reserves intra-day as well as overnight, are reluctant to lend, and intra-day fed funds rate becomes highly volatile due to precautionary behavior of banks in response to heightened payment

[24]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 may be worthy of pursuit in future (see Acharya and Skeie, 2010, for some early work along these dimensions).

[25]In contrast to the crisis of 2007-2009, 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.

uncertainty (during the crisis of 2007-08). These results corroborate our findings for the UK inter-bank markets. Our bank-level findings shed further light by explaining that the precautionary response is mainly due to weaker banks but its effects are felt by all banks.

8 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 interbank market rates, we uncovered an important precautionary demand 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.

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 interbank markets (as suggested theoretically by Acharya, Gromb and Yorulmazer, 2008, and supported empirically by Fecht, Nyborg and Rocholl, 2010). This would require bilateral analysis of interbank markets and relationships. The second is the strategic behavior due to adversely affected banks not disclosing their losses early enough and delaying asset sales (Diamond and Rajan, 2009), and safer banks hoarding cash with the motive to acquire these assets at deep discounts in future (Acharya, Shin and Yorulmazer, 2007 and Diamond and Rajan, 2009). 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 strategies rose sky-high and an overall freeze resulted in the global financial system. This too remains a feasible exercise in a bilateral analysis of interbank markets.

Finally, volatility in inter-bank rates can also induce volatility in bank lending rates to the real economy, which is worthy of investigation as an additional spillover effect due the liquidity hoarding by weaker banks. In some unreported tests for only five UK banks, we find that the monthly household and corporate lending rates (fixed and floating) as well as lending volumes respond to the variability in inter-bank rates. Overall, as inter-bank rate faced by a bank rises, its lending rates to households and corporates rise and volumes shrink, and the effect exists mostly during the crisis but not before.[26]

[26]Descriptive evidence in the BoE *Credit Conditions Survey* in 2007 Q4 show that lenders had revised

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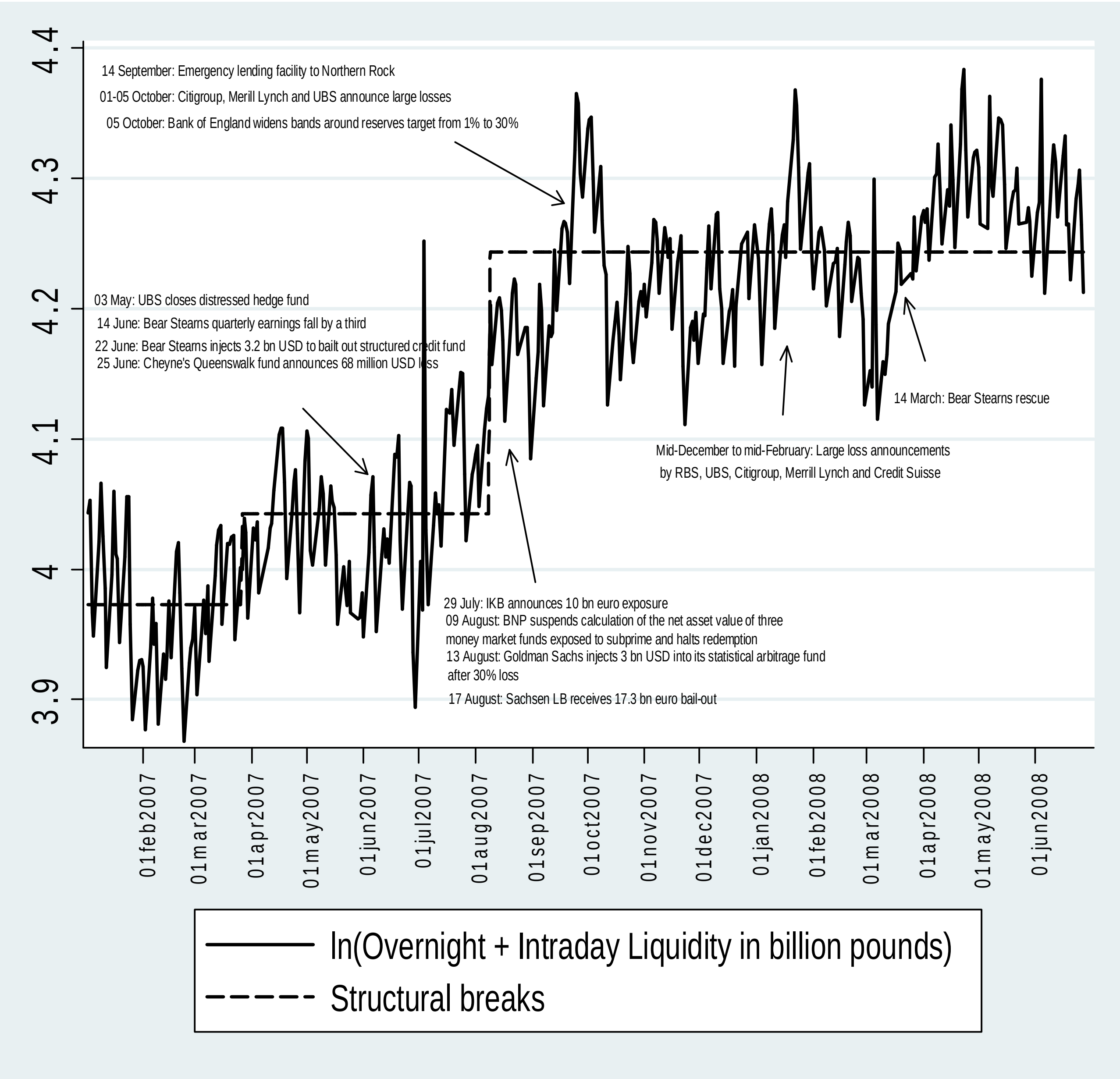


Figure 1. Total settlement bank liquidity (overnight plus intraday) and key market events

Note: The overnight liquidity is the sum of the reserves accounts of all 10 UK settlement banks balances measured at 5 am each day. The intraday liquidity is the maximum collateralized intraday-credit that can be obtained from the central bank each day. The structural breaks (broken line) were estimated using the Bai-Perron algorithm for multiple breaks.

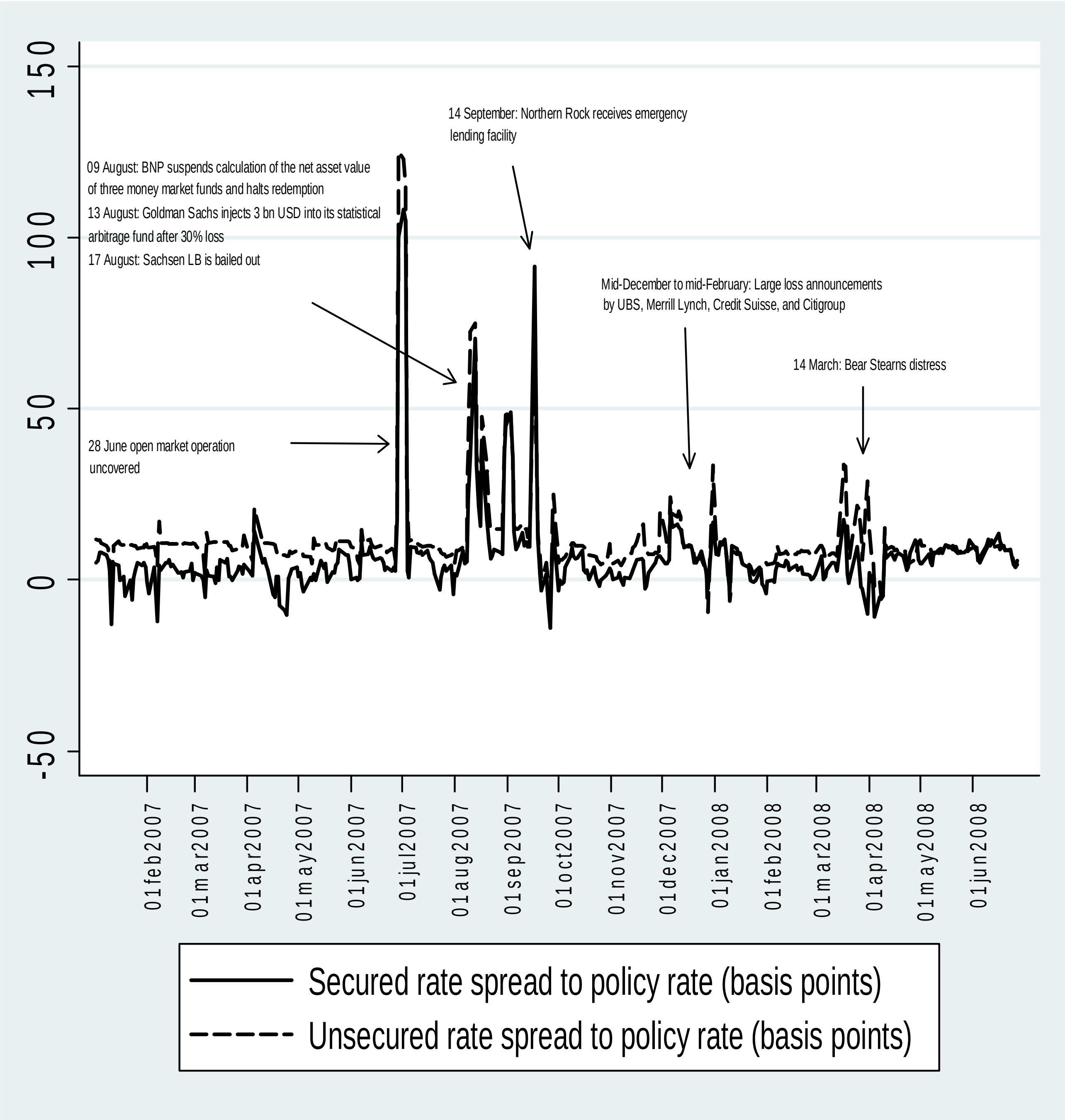


Figure 2. Overnight money market spreads (basis points) and key market events

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.

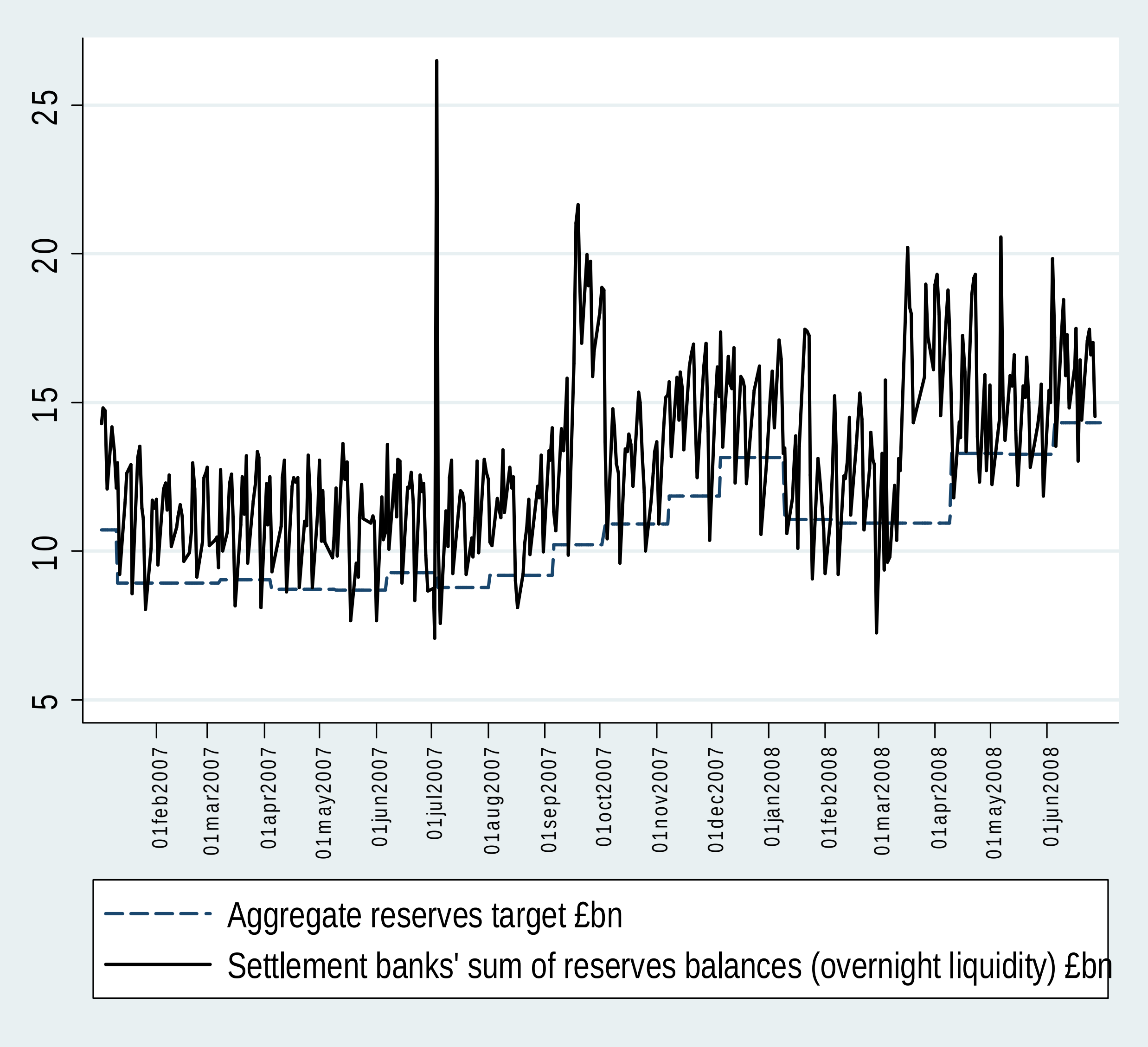
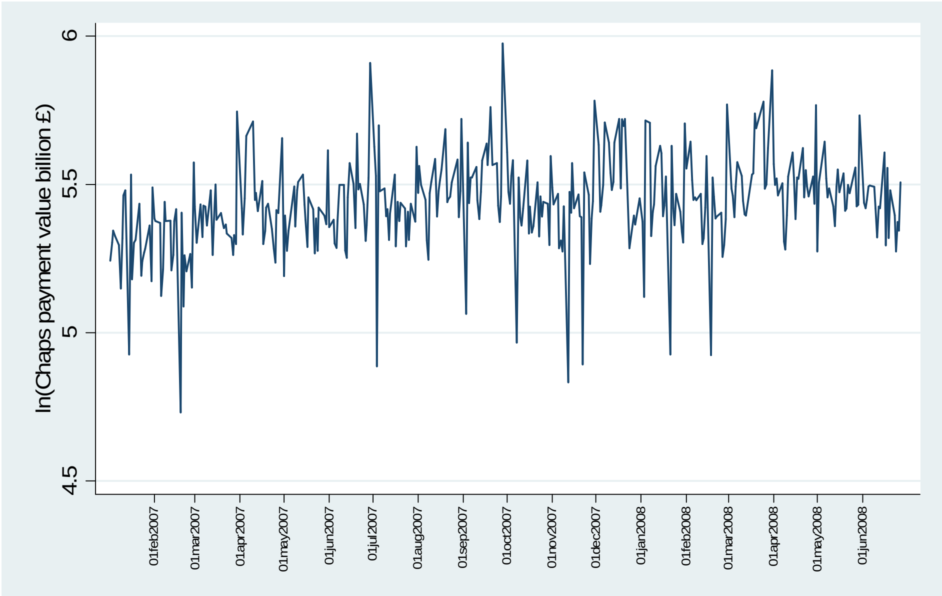
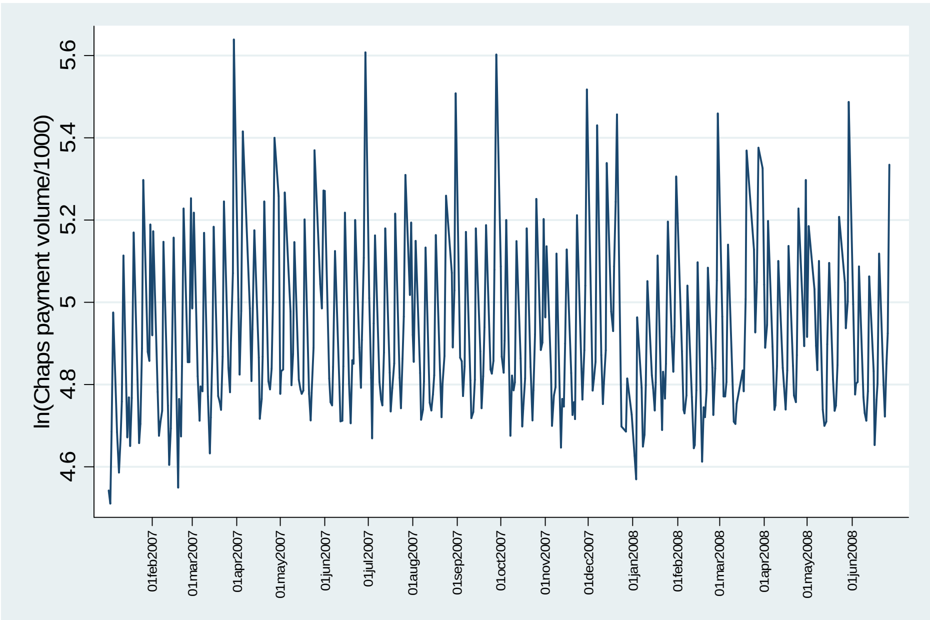


Figure 3. Overnight liquidity held by settlement banks and their aggregate target

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).



Panel A. Value



Panel B. Volume

Figure 4. CHAPS payments activity (logarithm)

Note: Payment activity (value and volume) 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). Both the aggregate value and the aggregate volume of payments are net of overnight interbank loans activity.

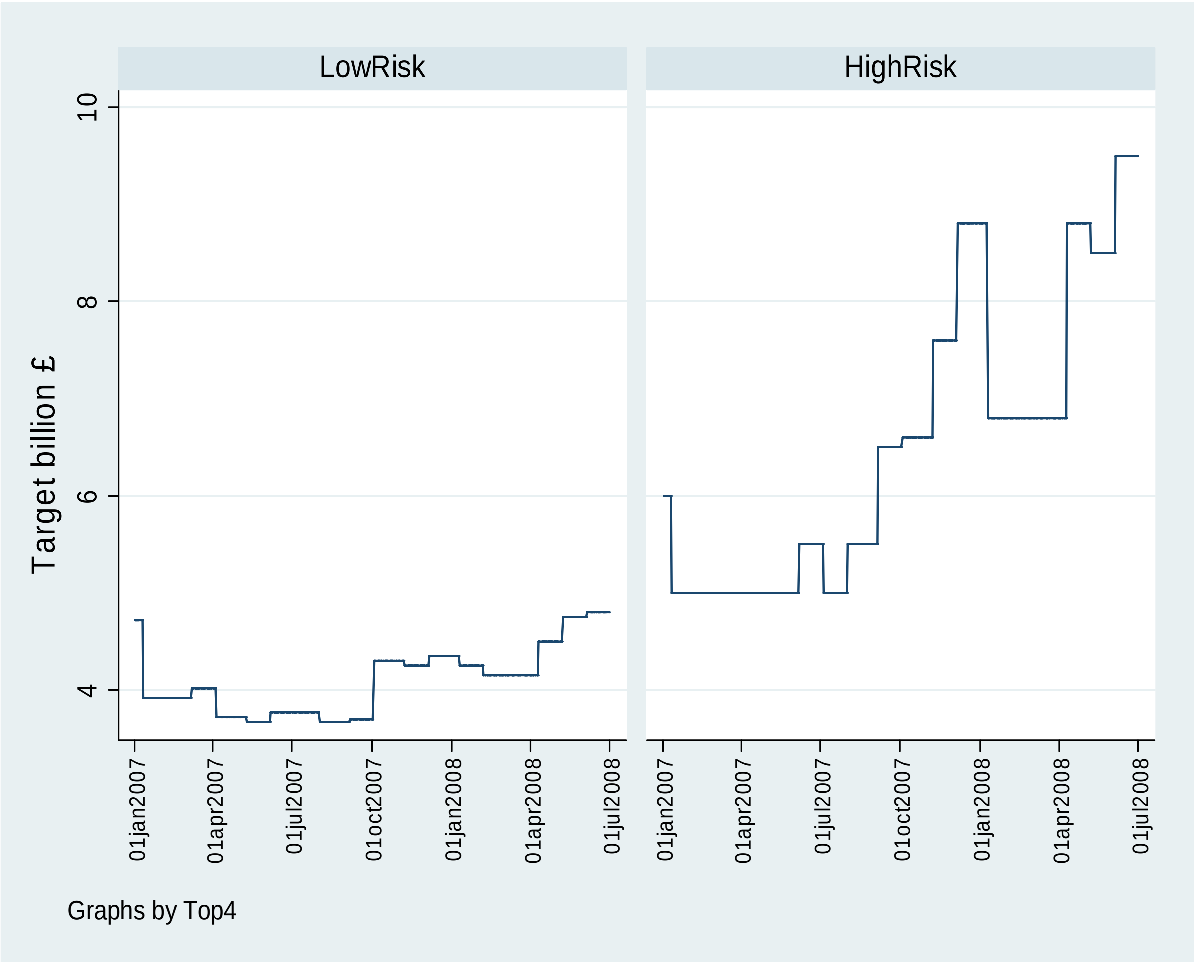


Figure 5. Reserves target of high risk (top 4 settlement banks in terms of payment activity) and low risk (other) settlement banks in billion pounds

Note: The frequency is one maintenance period. The data cover 10 UK settlement banks. Under the current monetary policy framework UK settlement banks *choose* a reserves target at the start of each maintenance period which they are required to achieve on average within the maintenance period.

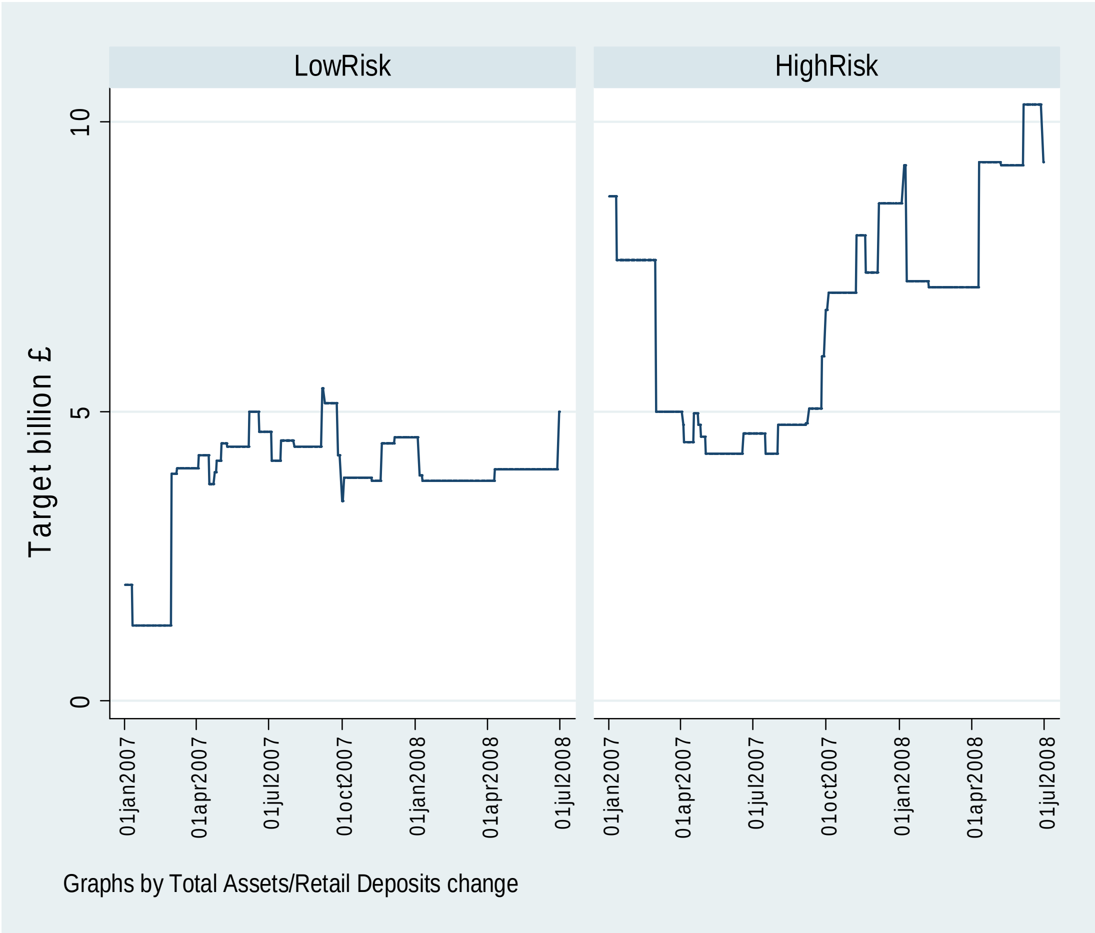


Figure 6. Reserves target of high risk (higher than median decline in deposits) and low risk (lower than median decline in deposits) settlement banks in billion British pounds

Note: The threshold to categorize settlement banks into high or low risk is the median of the (cumulative) change in total assets retail deposits ratio. See table 1 for a definition of the equity price decline. The data cover 10 UK settlement banks (foreign banks are omitted). See figure 2 for a definition of the target.

Table 1. DESCRIPTIVE STATISTICS: Settlement bank Liquidity, Payment Activity and Indicators of Bank Risk

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. The total liquidity includes the overnight and the intraday liquidity. The intraday liquidity is the maximum collateralized intraday-credit that banks can obtained from the central bank each day. Payment activity (value and volume) 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). Both the aggregate value and the aggregate volume of payments are net of interbank loans activity. Equity price data are from Bloomberg and credit default swap (CDS) premiums from MarkIT. We use the 5-years MR senior tranche premium.

Variables	Mean	Standard Deviation	Min	Max	5th percentile	50th percentile	95th percentile	(pre-August 9th) - (post August 9th)	
Aggregate variables								Difference	P-value
ln(Settlement banks overnight liquidity billion £)	2.39	0.25	1.62	3.18	1.96	2.40	2.79	0.27	0.00
ln(Settlement banks total liquidity billion £)	4.12	0.13	3.82	4.36	3.91	4.15	4.30	0.24	0.00
ln(Payment volume/1000)	4.91	0.21	4.51	5.64	4.67	4.84	5.31	0.00	0.67
ln(Payment value billion £)	5.44	0.16	4.73	5.98	5.21	5.43	5.71	0.09	0.00
Total settlemnt banks overnight liquidity in % deviation from aggregate target	25.00	23.35	-33.90	185.57	-10.19	23.36	63.82		
Variables used in bank-level regressions									
Settlement bank overnight liquidity (1)	0.10	1.07	-3.32	7.76	-1.18	-0.12	2.15		
Log(Aggregate Payment Value (trillion £))	0.26	0.04	0.13	0.43	0.21	0.26	0.34		
Log(Aggregate Payment Volume (million))	0.14	0.03	0.09	0.28	0.11	0.13	0.20		
Risk metrics (*)									
Write-offs/Total Assets (quarterly)	0.06	0.06	0.00	0.39	0.00	0.04	0.16		
Cumulative change in Total Assets/Retail Deposits (monthly)	-0.32	4.38	-28.39	17.71	-1.85	0.00	1.55		
Equity Price Decline % (2)	-0.64	28.21	-69.71	70.92	-60.046	-0.395	45.005		
Cumulative change in CDS premium (basis points)	26.65	29.57	-1.12	199.85	-0.50	18.37	82.79		

(1) Normalized by subtracting the mean and dividing by the standard deviation both calculated over the first 12 sample months.
(2) Cumulative from 2006 mean. The source is Bloomberg.
(*) In the analysis all risk metrics are lagged by one period.

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 settlemnt bank liquidity series (overnight and total). 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 the intraday and overnight liquidity.

Panel 2a. Dependent Variable: Ln(Overnight Liquidity+Intraday Liquidity)

Break Dates	95 % Interval	Estimates	Key Market News	Date
1/2/2007		3.937***	**Sample Starts**	
		(0.007)	**Early Phase**	
3/27/2007	[27/02/07;19/04/07]	4.009***	UBS to close Dillon Read hedge fund unit. The unit suffers large losses in US-sub prime	03 May 2007
		(0.006)	Bear stearns announces quarterly earnings fall by a third as trading revenues were impacted by	14 June 2007
8/8/2007	[30/07/07;09/08/07]	4.213***	problems in the US mortgage market. Fixed income sales and trading revenue fall by 21 per cent.	
		(0.004)	Bear Stearns provides 3.2 bn dollars financing to bail out structured credit fund	22 June 2007
			Cheyne's Queenswalk fund announces 68 million dollars losses	25 June 2007
UDmax	*SupLRt(2/1)*	*SupLRt(3/2)*	IKB announces surprise 10 billion € exposure to US sub-prime mortgages through it ABCP-funded vehicles	30 July 2007
234.469***	23.425***	8.535		
			Main Phase	
			BNP Paribas suspends the calculation of the net asset value of three money market funds exposed to sub-prime and halts redemption	**09 August 2007**
			Goldman Sachs injects $3bn ($2bn of its own capital) into its statistical arbitrage fund	13 August 2007
			Sachsen LB receives a €17.3bn bailout by German state	17 August 2007
			Bank of England announces emergency lending facility to Northern Rock	**14 September 2007**
			Bank of England supplies additional reserves to the banking system +25% (one week maturity)	**13 September 2007**
			UBS says it would make write downs of $3.4bn to its fixed income portfolio	01 October 2007
			Citigroup says Q3 earnings will fall 60% on a year ago	01 October 2007
			Merrill Lynch announces it will make a loss in Q3 due to a $5.5bn write-down	05 October 2007
			Merrill Lynch reports write-downs of $7.9 bn on sub-prime mortgages and asset-backed securities	24 October 2007
			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

Panel 2b. Dependent Variable: Ln(Overnight Liquidity)

Break Dates	95 % Interval	Estimates	Timeline of Events (continued)	
1/2/2007		2.236***	Bank of America's CEO pre-announces writedowns of $3bn in Q4.	13 November 2007
		(0.015)	Bear Stearns announces an expected write down of $1.2bn in Q4	14 November 2007
9/11/2007	[23/08/07;18/09/07]	2.474***	Freddia Mac announces a Q3 loss of $2bn	20 November 2007
		(0.017)	UBS announces further write downs of $10bn (dated to end November)	10 December 2007
3/13/2008	[04/03/08;08/04/08]	2.629***	Bank of America announces it may have to record more than its initial $3.3 billion losses and write-downs	12 December 2007
		(0.023)	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
UDmax	*SupLRt(2/1)*	*SupLRt(3/2)*	Credit Suisse announces additional $2.85 billion losses	19 February 2008
112.673***	17.392***	8.936	**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. Calendar Effects on the Aggregate level of Payments Activity

This table reports ordinary least squares (OLS) estimates of a regression of the aggregate log payments value and volume 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.

	OLS (1)	OLS (2)
Calendar Dummies	ln(Payments Value)	ln(Payments Volume)
United Kingdom Holidays [-1;+1]	0.073*	0.115**
	(0.039)	(0.048)
United States Holidays [0]	-0.575***	-0.146***
	(0.032)	(0.024)
First 5 days of the month	0.002	0.044**
	(0.018)	(0.018)
Last 5 days of the month	-0.009	0.184***
	(0.022)	(0.021)
Tuesday	-0.110***	-0.085***
	(0.022)	(0.017)
Wednesday	-0.092***	-0.054***
	(0.020)	(0.018)
Thursday	-0.059***	0.036**
	(0.019)	(0.017)
Friday	-0.002	0.347***
	(0.021)	(0.017)
Quarter 1	0.081	0.044
	(0.064)	(0.052)
Quarter 2	0.035	-0.019
	(0.06)	(0.048)
Quarter 3	0.138	0.030
	(0.107)	(0.074)
Quarter 4	-0.111***	-0.462***
	(0.031)	(0.049)
constant	5.497***	4.815***
	(0.015)	(0.012)
Portmanteau Test for White Noise at Lag-1 P-value	0.29	0.12
R-squared	0.38	0.75
Number of Observ.	376	376

Note: The portmenteau test is run on the residuals from regressions that exclude the constant term.
Monday is the omitted day.

Table 4. Evidence on Settlement Banks' Precautionary Liquidity Reaction during the Crisis

This table reports estimates of equation (1). We express an individual bank demand for liquidity as a function of the aggregate level of payment activity and balance sheet measures of its credit and liquidity risk, allowing for a shift in this relationship during the crisis. See Table 1 for a definition of liquidity and payment activity. Overnight liquidity is normalized by subtracting the mean and dividing by the standard deviation both calculated over the first 12 sample months. We use four alternative risk metrics described in table 1. The regressions are run on data covering the 10 UK settlement banks in the period January 2 2007 to June 30 2008. Here we report the results for the overnight liquidity as it is our main focus. Break1 takes value one from 08/08/07 onwards; Break2 takes value one post 11/09/07; and Break3 takes value one post 13/03/2008. We report robust standard errors in brackets.

Dependent variable: Individual settlement bank overnight liquidity

			Risk=Top 4 banks	Risk=Write-offs/TA	Risk=Equity Price Decline	Risk=ΔCDS	Risk=ΔTA/Retail deposits
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
ln(Payment value)(t)	3.547***	-0.059	-0.057	-0.069	-0.554	-1.068	0.119
	[0.529]	[0.810]	[0.808]	[0.808]	[0.949]	[1.158]	[0.904]
ln(Payment value)(t)*Break2		2.590**	2.589**	2.414**	2.717**	4.541***	2.841**
		[1.054]	[1.052]	[1.049]	[1.263]	[1.564]	[1.179]
ln(Payment value)(t)*Break3		1.119	1.114	1.037	0.867	-1.302	2.037*
		[1.088]	[1.085]	[1.078]	[1.437]	[1.740]	[1.223]
ln(Payment volume)(t)	-5.629***	-3.549***	-3.549***	-3.537***	-2.191**	-2.801***	-3.578***
	[0.624]	[0.807]	[0.805]	[0.805]	[0.944]	[0.972]	[0.898]
ln(Payment volume)(t)*Break2		-2.120*	-2.122*	-1.972*	-2.067	-2.497*	-2.725**
		[1.169]	[1.166]	[1.162]	[1.410]	[1.453]	[1.306]
ln(Payment volume)(t)*Break3		0.483	0.490	0.355	0.465	1.758	-0.176
		[1.275]	[1.272]	[1.261]	[1.672]	[1.607]	[1.436]
Risk			0.052	0.275	-0.014***	0.005	-0.018*
			[0.081]	[0.504]	[0.002]	[0.007]	[0.010]
Risk*Break2			0.291***	1.312***	0.013***	-0.007	0.010
			[0.065]	[0.499]	[0.002]	[0.007]	[0.014]
Risk*Break3			0.074	1.516*	0.001	0.004**	0.008
			[0.063]	[0.854]	[0.001]	[0.002]	[0.007]
Break1		0.221***	0.222***	0.230***	0.297***	0.099	0.228***
		[0.060]	[0.060]	[0.060]	[0.075]	[0.146]	[0.067]
Break2		-0.247	-0.364	-0.298	-0.16	-0.558	-0.125
		[0.251]	[0.252]	[0.252]	[0.301]	[0.365]	[0.281]
Break3		-0.312	-0.342	-0.337	-0.201	-0.025	-0.455*
		[0.238]	[0.239]	[0.237]	[0.318]	[0.370]	[0.268]
Constant	0.111	0.437**	0.381**	0.483***	-0.149	0.696***	0.360*
	[0.130]	[0.184]	[0.184]	[0.184]	[0.234]	[0.245]	[0.207]
Tests p-values X=ln(Payment value)							
X+X*Break2=0		**0.001**	**0.001**	**0.002**	**0.018**	**0.002**	**0.001**
X+X*Break2+X*Break3=0		**0.001**	**0.001**	**0.001**	**0.025**	0.194	**0.000**
Tests p-values X=ln(Payment volume)							
X+X*Break2=0		**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
X+X*Break2+X*Break3=0		**0.000**	**0.000**	**0.000**	**0.014**	**0.017**	**0.000**
Risk+Risk*Break2=0			**0.000**	**0.001**	0.487	0.292	0.250
Risk+Risk*Break2+Risk*Break3=0			**0.000**	**0.002**	0.991	**0.078**	0.907
R-squared	0.03	0.06	0.07	0.06	0.09	0.06	0.10
Bank fixed effects	x	x	x	x	x	x	x
Number Observ.	3780	3780	3780	3780	2582	2368	3016

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

Table 5. Precautionary Liquidity Reaction to Fluctuations in Payment Activity and Bank Risk

In this table we report estimates of equation (1) extended to allow the slope of the liquidity reaction to aggregate payment fluctuations to depend on whether the bank is classified as high risk (HR) or low risk (LR). Bank risk is measured by the same indicators as in Table 4 using the median as threshold. Except in column (1) where the dummy takes value one if the bank is one of the top 4 clearers in terms of payment activity. The sample covers the 10 UK settlement banks in the period January 2 2007 to June 20 2008. We report robust standard errors in brackets, pvalues for the significance of the total effect in each phase of the crisis, and pvalues for the statistical difference between HR and LR banks (null hypotheses are listed). See Table 1 for a definition of the dependent and explanatory variables. See Table 4 for a definition of the Break points. Note that the dummy variables HR*Break, LR*Break, HR, LR are perfectly collinear with the Break dummies and bank fixed effects.

Dependent variable: Individual settlement bank overnight liquidity

Panel A. Estimation results

	Risk=Top 4 banks	Risk=Write-offs/TA	Risk=Equity Price Decline	Risk=ΔCDS	Risk=ΔTA/Retail deposits
	(1)	(2)	(3)	(4)	(5)
ln(Payment value)(t)*HR	-1.479	0.747	-1.238	-1.346	0.007
	[1.103]	[0.924]	[1.049]	[1.265]	[0.989]
ln(Payment value)(t)*LR	0.89	-0.854	0.305	-0.504	0.384
	[0.950]	[0.924]	[1.122]	[1.265]	[1.086]
ln(Payment value)(t)*Break2*HR	4.486***	3.067**	4.004***	5.359***	3.403**
	[1.293]	[1.210]	[1.415]	[1.736]	[1.343]
ln(Payment value)(t)*Break2*LR	1.323	2.110*	1.053	3.550**	2.046
	[1.164]	[1.210]	[1.524]	[1.736]	[1.398]
ln(Payment value)(t)*Break3*HR	0.47	0.648	-0.200	0.097	3.180**
	[1.356]	[1.255]	[1.618]	[1.900]	[1.439]
ln(Payment value)(t)*Break3*LR	1.545	1.550	2.320	-2.151	0.971
	[1.213]	[1.255]	[1.732]	[1.900]	[1.439]
ln(Payment volume)(t)*HR	-0.616	-4.507***	-2.258*	-2.474*	-3.031***
	[1.258]	[1.125]	[1.237]	[1.356]	[1.151]
ln(Payment volume)(t)*LR	-5.504***	-2.588**	-2.220	-3.224**	-4.301***
	[1.031]	[1.125]	[1.424]	[1.356]	[1.388]
ln(Payment volume)(t)*Break2*HR	-4.423**	-3.270**	-3.094*	-3.649*	-3.118*
	[1.833]	[1.631]	[1.855]	[2.031]	[1.789]
ln(Payment volume)(t)*Break2*LR	-0.588	-0.991	-0.394	-0.916	-2.143
	[1.499]	[1.631]	[2.136]	[2.031]	[1.908]
ln(Payment volume)(t)*Break3*HR	2.061	1.455	1.761	-0.942	-2.57
	[2.010]	[1.774]	[2.222]	[2.249]	[2.038]
ln(Payment volume)(t)*Break3*LR	-0.559	-0.429	-1.529	3.789*	2.185
	[1.641]	[1.774]	[2.492]	[2.249]	[2.038]
Break1	0.221***	0.224***	0.237***	0.233***	0.237***
	[0.060]	[0.059]	[0.072]	[0.076]	[0.067]
Break2	-0.247	-0.248	-0.266	-0.754**	-0.085
	[0.251]	[0.250]	[0.299]	[0.349]	[0.281]
Break3	-0.312	-0.314	-0.210	0.125	-0.472*
	[0.237]	[0.234]	[0.314]	[0.366]	[0.269]
Constant	0.386*	0.423**	0.541**	0.559**	0.349*
	[0.234]	[0.186]	[0.214]	[0.243]	[0.205]
R-squared	0.07	0.07	0.09	0.06	0.10
Bank fixed effect	x	x	x	x	x
Number Observ.	3780	3780	2589	2368	3016

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

Panel B. Significance of Total Effects

Tests p-values X=ln(Payment value)					
X*HR =X*LR	**0.059**	**0.077**	0.140	0.440	0.707
(1): X*HR+X*HR*Break2=0	**0.007**	**0.000**	**0.009**	**0.002**	**0.001**
(2): X*LR+X*LR*Break2=0	**0.018**	0.165	0.232	**0.018**	**0.018**
HR=LR: (1)=(2)	0.550	**0.012**	0.248	0.438	0.377
(3): (1)+X*HR*Break3=0	**0.013**	**0.000**	**0.093**	**0.023**	**0.000**
(4): (2)+X*LR*Break3=0	**0.002**	**0.021**	**0.024**	0.623	**0.013**
HR=LR: (3)=(4)	0.855	0.189	0.486	**0.041**	**0.024**
Tests p-values X=ln(Payment volume)					
X*HR =X*LR	**0.002**	0.227	0.986	0.692	0.477
(1): X*HR+X*HR*Break2=0	**0.001**	**0.000**	**0.000**	**0.000**	**0.000**
(2): X*LR+X*LR*Break2=0	**0.000**	**0.008**	0.135	**0.012**	**0.000**
HR=LR: (1)=(2)	0.581	**0.030**	0.240	0.394	0.890
(3): (1)+X*HR*Break3=0	0.132	**0.000**	**0.089**	**0.000**	**0.000**
(4): (2)+X*LR*Break3=0	**0.000**	**0.021**	**0.075**	0.865	**0.025**
HR=LR: (3)=(4)	0.131	0.329	0.850	**0.021**	**0.097**

Table 6. DESCRIPTIVE STATISTICS: Money Markets Rates

Aggregate (meaning covering the entire markets) interest rates and volume data are from the British Bankers'Association and t he 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. Bank -level unsecured market data are from the Bank of England extracted from the payments database using the Furfine algorithm. Repo volume data are from the monthly balance sheet reports collected by the B ank of England statistics division. See Table 1 for a definition of liquidity.

Variables	Mean	Standard Deviation	Min	Max	5th percentile	50th percentile	95th percentile	(pre-August 9th) - (post August 9th) Difference	P-value
Aggregate variables									
Secured overnight rate %	5.47	0.31	5.03	6.66	5.06	5.47	5.89	0.06	0.00
Unsecured overnight rate %	5.52	0.32	5.04	6.75	5.08	5.52	5.94	0.05	0.13
Secured overnight rate spread to policy rate (basis points)	6.25	12.65	-14.17	108.33	-3.88	4.50	17.50	2.41	0.05
Unsecured overnight rate spread to policy rate (basis points)	11.47	13.31	-9.37	125.38	3.98	9.38	29.22	-0.66	0.61
ln(Secured overnight volume billion £)	1.77	0.44	0.19	2.77	1.03	1.76	2.46	0.45	0.00
ln(Unsecured overnight volume billion £)	3.12	0.16	2.58	3.59	2.85	3.12	3.39	0.13	0.00
Bank level variables									
Unsecured borrowing spread to policy rate (basis points)	4.43	11.21	-210.00	201.00	-5.00	3.29	17.42		
Own overnight liquidity (1)	0.00	1.00	-3.55	6.49	-1.22	-0.21	1.90		
Others overnight liquidity (1)	2.39	0.39	-0.68	3.27	-1.59	0.15	1.15		
Own overnight liquidity in % deviation from target	3.72	34.21	-100.00	273.00	-51.33	3.15	56.49		
Others overnight liquidity in % deviation from target	-74.17	5.30	-106.18	-58.40	-80.95	-73.43	-67.66		

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

Table 7. The Impact of Settlement Banks Precautionary Liquidity Hoarding on Overnight Money Market Spreads

We report ordinary least squares (OLS) and three stage least squares (3SLS) estimates of the liquidity effect on overnight secured and unsecured rates. All spreads are in basis points. See Table 4 for a definition of the Break points. The 3SLS model is in calendar days time rather than in working days time i.e. Mondays are excluded to avoid the distortion from Friday being both a day of particularly high payments activity and the day following the regular weekly open market operation (OMO). The model in calendar days time is preferred because the model in working days time is not well identified; payments activity on day t-1 is a weak instrument for overnight liquidity holding on day t. All variables are defined in Table 6 and sources reported. The market data are aggregate (i.e. cover the entire market) daily data for the period January 2 2007 to June 30 2008. Liquidity is the liquidity help by the ten first-tier UK settlement bank. We report in brackets robust standard errors. Pvalues for the significance of total effects in each phase of the crisis also reported.

Dependent variables: Whole market secured and unsecured rates spread to policy rate

	Liquidity=ln(Total settlement bank reserves balances)		**Liquidity=Total settlement bank reserves balances in % deviation from aggregate target**		**Liquidity=ln(Total settlement bank reserves balances)**		**Liquidity=Total settlement bank reserves balances in % deviation from aggregate target**	
	(1)		**(2)**		**(3)**		**(4)**	
	OLS				**3SLS**			
	secured spread	unsecured spread	secured spread	unsecured spread	secured spread	unsecured spread	secured spread	unsecured spread
Liquidity	-19.262***	-21.104***	-0.140***	-0.135***	-55.329***	-60.967***	-0.656**	-0.732**
	[5.470]	[5.670]	[0.043]	[0.044]	[18.255]	[20.506]	[0.268]	[0.303]
Liquidity*Break2	26.686***	28.114***	0.182***	0.181***	68.930***	58.714**	0.788**	0.725*
	[7.619]	[7.897]	[0.058]	[0.061]	[25.533]	[28.681]	[0.327]	[0.370]
Liquidity*Break3	-13.48	-1.539	-0.134*	0.014	-18.609	37.798	-0.236	0.149
	[11.353]	[11.768]	[0.070]	[0.073]	[46.046]	[51.722]	[0.272]	[0.307]
Break2	-83.801***	-90.529***	-21.648***	-24.960***	-185.589***	-161.271**	-33.657***	-35.655***
	[19.480]	[20.191]	[2.968]	[3.093]	[64.380]	[72.316]	[8.133]	[9.197]
Break3	37.456	3.971	4.430*	0.271	51.161	-102.835	7.191	-2.772
	[31.002]	[32.134]	[2.401]	[2.502]	[125.506]	[140.977]	[6.518]	[7.370]
Break1	17.897***	18.027***	17.126***	17.214***	16.259***	16.652***	13.169***	13.217***
	[2.573]	[2.667]	[2.573]	[2.681]	[2.676]	[3.006]	[3.299]	[3.730]
Constant	51.372***	62.885***	8.528***	15.459***	137.810***	158.586***	21.530***	30.701***
	[13.256]	[13.740]	[1.474]	[1.536]	[44.053]	[49.484]	[7.118]	[8.049]
Tests p-values X=Liquidity								
X+X*Break2=0	0.162	0.202	0.292	0.269	0.446	0.911	0.483	0.974
X+X*Break2+X*Break3=0	0.546	0.599	0.110	0.313	0.906	0.456	0.598	0.521
Hansen-Sargan								
Overidentification statistic=					16.877		9.250	
P-value=					(0.154)		(0.682)	
Number Observ.	376	376	375	375	296	296	295	295

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

Table 8. Settlement banks liquidity and contagion effect: bank level analysis

In this table we report estimates of the liquidity effect using bank-level data. We let the spread paid by a bank depend on both its own liquidity and the liquidity held by other banks in the system. The sample covers the 10 UK banks in the period January 2 2007 to June 30 2008. We report robust standard errors in brackets and pvalues for the statistical significance of the total effects in each phase of the crisis in parentheses. Significant effects are highlighted in bold. We report OLS and 2SLS estimates using lagged payment activity (own and others, value and volumes) as instruments, in total four instruments for two endogenous variables. And control for current aggregate payment activity.

Dependent variable: Unsecured borrowing rate spread to policy rate (in basis points)

	Using abnormal variations in liquidity	**Liquidity in % deviation from target**	**Using abnormal variations in liquidity**	**Liquidity in % deviation from target**
	OLS		**2SLS**	
	(1)	(2)	(3)	(4)
Own liquidity	-0.528	-0.003	-0.383	0.244
	[0.329]	[0.010]	[5.767]	[0.167]
Others liquidity	-10.916***	-0.026*	-49.413***	-0.467**
	[1.589]	[0.013]	[18.563]	[0.208]
Own liquidity *Break2	1.031	0.64	23.313	14.179
	[0.607]	[0.477]	[21.247]	[18.061]
Others liquidity*Break2	12.261***	3.978***	21.755	-15.967
	[1.297]	[0.974]	[21.279]	[20.022]
Own liquidity *Break3	-0.844	-0.883	-16.309	-0.32
	[0.550]	[0.566]	[19.806]	[24.589]
Others liquidity*Break3	0.891	-1.04	15.203	1.15
	[1.246]	[1.178]	[21.627]	[23.857]
Break1	12.606***	12.290***	12.208***	8.059***
	[1.068]	[1.142]	[1.710]	[2.561]
Break2	-1.146	-26.428***	-64.909	24.718
	[2.967]	[2.944]	[50.940]	[49.119]
Break3	-45.474***	3.195	-39.734	-15.691
	[3.278]	[2.863]	[51.942]	[56.334]
ln(Payment value)(t)	18.500***	18.017***	18.100***	17.190***
	[1.350]	[1.369]	[5.296]	[4.957]
ln(Payment volume)(t)	-1.489**	1.414**	-10.321*	2.669
	[0.518]	[0.528]	[5.529]	[3.159]
Bank fixed effect	x	x	x	x
X=Own liquidity				
X+X*Break2=0	0.324	0.214	0.223	0.425
X+X*Break2+X*Break3=0	0.370	0.529	0.326	0.343
X=Others liquidity				
X+X*Break2=0	0.249	0.003	0.193	0.414
X+X*Break2+X*Break3=0	0.000	0.000	0.127	0.307
Hansen-Sargan				
Overidentification statistic=			7.265	5.259
P-value=			0.297	0.511
Number Observ.	3421	3411	2677	2667

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

Table 9. Contagion effects by risk type

In this table we report estimates of the liquidity effect using bank-level data and letting the estimates vary between high risk (HR) and low risk (LR) banks. See Table 5 for a definition of risk types. And Table 4 for a definition of the Break points. In this specification we allow the spread paid and charged by a bank to depend on both its own liquidity and the liquidity held by other banks in the system. The sample covers the 10 UK banks in the period January 2 2007 to June 30 2008. We report robust standard errors in brackets, pvalues for the statistical significance of the total effects in each phase of the crisis, and pvalues for the statistical significance of the difference between bank types. See Tables 1 and 6 for a definition of all explanatory and dependent variables. Significant effects are highlighted in bold. We report 2SLS estimates using lagged payment activity (own and others, value and volumes) as instruments, in total four instruments for two endogenous variables by bank type. And we control for current aggregate payment activity. Note that the dummy variables HR*Break, LR*Break, HR, LR are perfectly collinear with the Break dummies and bank fixed effects.

Dependent variable: Overnight settlement bank unsecured borrowing spread

Panel A. Estimation results

	Risk=Top 4 banks	Risk=Write-offs/TA	Risk=Equity Price Decline	Risk=ΔCDS	Risk=ΔTA/Retail deposits
	(1)	(2)	(3)	(4)	(5)
Own Overnight liquidity*HR	-6.058	5.902	-20.168*	-15.137	-10.393**
	[4.182]	[6.648]	[11.152]	[11.634]	[4.375]
Own Overnight liquidity*LR	4.724	-16.692	10.204	1.595	1.928
	[7.114]	[11.557]	[12.166]	[7.017]	[7.275]
Own Overnight liquidity*HR*Break2	11.359	4.311	23.519*	49.793	9.509
	[7.682]	[15.694]	[13.917]	[41.046]	[7.107]
Own Overnight liquidity*LR*Break2	10.252	29.404**	-0.700	-4.989	12.538
	[10.993]	[14.673]	[12.348]	[15.992]	[19.479]
Own Overnight liquidity*HR*Break3	0.938	2.978	2.781	-33.363	4.655
	[5.657]	[17.387]	[5.084]	[38.719]	[7.903]
Own Overnight liquidity*LR*Break3	-14.907	-10.043	-11.206	2.236	14.565
	[9.795]	[11.212]	[6.816]	[16.395]	[50.524]
Others Overnight liquidity*HR	-39.193***	-28.935	-35.674**	-25.648	-49.121***
	[13.431]	[18.225]	[17.846]	[20.527]	[17.144]
Others Overnight liquidity*LR	-45.978***	-26.998	-33.104*	-24.934	-48.946***
	[14.470]	[18.719]	[17.681]	[20.838]	[17.375]
Others Overnight liquidity*HR*Break2	29.273**	15.994	30.391**	19.284	43.389***
	[12.035]	[18.887]	[14.633]	[22.088]	[13.924]
Others Overnight liquidity*LR*Break2	28.384**	17.317	25.868*	21.286	40.030***
	[11.828]	[18.148]	[13.975]	[22.043]	[13.542]
Others Overnight liquidity*HR*Break3	11.748	-1.499	7.379	5.450	-2.593
	[10.130]	[12.669]	[10.520]	[19.783]	[19.107]
Others Overnight liquidity*LR*Break3	11.249	-0.991	8.584	3.548	-2.963
	[10.061]	[12.056]	[10.605]	[20.166]	[23.717]
Break1	12.230***	11.800***	13.425***	12.938***	12.212***
	[1.681]	[1.684]	[2.287]	[1.864]	[1.925]
Break2	-81.838***	-52.661	-80.357**	-63.450	-111.727***
	[28.402]	[44.206]	[34.099]	[53.082]	[31.671]
Break3	-29.243	0.480	-18.092	-9.438	5.209
	[24.862]	[29.109]	[26.027]	[47.973]	[49.634]
ln(Payment value)(t)	18.499***	17.123***	21.058***	13.595*	17.085***
	[3.833]	[4.357]	[5.107]	[7.343]	[6.148]
ln(Payment volume)(t)	-8.348**	-6.219	-9.404*	-3.536	-9.432
	[4.181]	[4.585]	[5.609]	[6.575]	[5.943]
Bank fixed effect	x	x	x	x	x
Hansen-Sargan statistic=	13.772	8.386	10.836	15.846	12.720
P-value=	0.316	0.754	0.543	0.198	0.390
Number Observ.	2677	2677	1927	2215	2127

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

Panel B. Significance of Total Effects

Tests p-values X=Own overnight liquidity					
X*HR =X*LR	0.212	**0.088**	0.114	0.157	0.144
(1): X*HR+X*HR*Break2=0	0.250	0.439	0.395	0.352	0.860
(2): X*LR+X*LR*Break2=0	**0.080**	0.188	0.125	0.822	0.413
HR=LR: (1)=(2)	0.283	0.870	0.415	0.316	0.389
(3): (1)+X*HR*Break3=0	0.262	0.134	0.244	0.768	0.506
(4): (2)+X*LR*Break3=0	0.987	0.679	0.622	0.851	0.461
HR=LR: (3)=(4)	0.422	0.314	0.191	0.731	0.558
Tests p-values X=Others overnight liquidity					
X*HR =X*LR	0.285	0.287	**0.081**	0.395	0.889
(1): X*HR+X*HR*Break2=0	0.288	0.241	0.608	0.742	0.518
(2): X*LR+X*LR*Break2=0	**0.093**	0.322	0.486	0.853	0.357
HR=LR: (1)=(2)	0.195	0.203	**0.090**	0.361	0.123
(3): (1)+X*HR*Break3=0	0.706	0.074	0.518	0.866	0.557
(4): (2)+X*LR*Break3=0	0.206	0.195	0.738	0.987	0.510
HR=LR: (3)=(4)	0.235	**0.092**	0.603	0.544	0.416

Table 10. Controlling for adjustments to the monetary policy framework

See Tables 4 and 5 for details of the specification , definitions of the variables used and and sample covered. In these spec ifications we control for adjustements to the monetary policy framework undertaken during the crisis and calendar effects. Uncovered OMO takes value on e the last week of June 2007. Band-Widening takes value one in the period 05/10/2007 to 01/05/2008 i.e. after the Bank of England widened the band s around reserves targets. Higher-Reserves-Target-Ceiling takes value one from 01/05/2008 onwards i.e. after the Bank of England doubled the reser ves target ceiling. Esupply is a dummy that takes value one on days when the central bank OMO offer was in excess of the aggregate target chosen by banks. See Section 2.3 for a detailed description of the reforms undertaken by the Bank of England during the crisis. Robust standard errors are reported in brackets.

Panel A. Liquidity demand

Dependent variable: Individual settlement bank overnight liquidity

			Risk=Top 4 banks	Risk=Write-offs/TA	Risk=Equity Price Decline	Risk=ΔCDS	Risk=ΔTA/Retail deposits
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
ln(Payment value)(t)	3.911***	0.194	0.195	0.149	-0.849	-1.471	0.474
	[0.573]	[0.896]	[0.894]	[0.893]	[1.050]	[1.362]	[0.992]
ln(Payment value)(t)*Break2		1.982*	1.981*	1.797	2.393*	4.441***	2.194*
		[1.105]	[1.102]	[1.100]	[1.319]	[1.697]	[1.228]
ln(Payment value)(t)*Break3		1.639	1.633	1.547	1.521	-1.111	2.582**
		[1.109]	[1.106]	[1.097]	[1.447]	[1.775]	[1.240]
ln(Payment volume)(t)	-5.250***	-2.757***	-2.756***	-2.689***	-0.737	-1.312	-2.594**
	[0.900]	[1.014]	[1.012]	[1.013]	[1.181]	[1.287]	[1.121]
ln(Payment volume)(t)*Break2		-1.632	-1.635	-1.458	-1.547	-2.013	-2.276*
		[1.189]	[1.186]	[1.183]	[1.427]	[1.507]	[1.321]
ln(Payment volume)(t)*Break3		0.036	0.044	-0.081	-0.209	1.2	-0.948
		[1.295]	[1.291]	[1.280]	[1.676]	[1.619]	[1.447]
Risk			0.054	0.319	-0.086***	0.006	-0.017*
			[0.081]	[0.501]	[0.014]	[0.007]	[0.010]
Risk*Break2			0.291***	1.362***	0.076***	-0.007	0.009
			[0.064]	[0.497]	[0.011]	[0.007]	[0.014]
Risk*Break3			0.073	1.464*	0.005	0.004**	0.008
			[0.064]	[0.864]	[0.008]	[0.002]	[0.007]
Break1		0.182***	0.183***	0.193***	0.288***	0.087	0.172**
		[0.062]	[0.062]	[0.062]	[0.077]	[0.149]	[0.070]
Break2		-0.125	-0.241	-0.18	-0.133	-0.579	0.025
		[0.267]	[0.267]	[0.267]	[0.318]	[0.393]	[0.296]
Break3		-0.385	-0.414*	-0.404*	-0.293	0.03	-0.490*
		[0.245]	[0.245]	[0.243]	[0.323]	[0.382]	[0.274]
Uncovered OMO	-0.596***	-0.239	-0.239	-0.241	-0.152	-0.292	-0.25
	[0.171]	[0.176]	[0.176]	[0.176]	[0.204]	[0.227]	[0.195]
Constant	-0.157	0.336	0.218	0.051	-0.294	0.408	0.331
	[0.264]	[0.264]	[0.300]	[0.276]	[0.360]	[0.397]	[0.290]
Tests p-values X=ln(Payment value)							
X+X*Break2=0		**0.008**	**0.008**	**0.018**	0.111	**0.016**	**0.003**
X+X*Break2+X*Break3=0		**0.001**	**0.001**	**0.002**	**0.030**	0.303	**0.000**
Tests p-values X=ln(Payment volume)							
X+X*Break2=0		**0.000**	**0.000**	**0.001**	0.109	**0.034**	**0.000**
X+X*Break2+X*Break3=0		**0.002**	**0.002**	**0.003**	0.158	0.240	**0.000**
Risk+Risk*Break2=0			**0.000**	**0.005**	0.246	0.334	0.244
Risk+Risk*Break2+Risk*Break3=0			**0.000**	**0.002**	0.572	0.115	0.893
R-squared	0.03	0.09	0.09	0.09	0.11	0.08	0.14
Bank fixed effects	x	x	x	x	x	x	x
Maintenance days effects	x	x	x	x	x	x	x
OMO days fixed effects	x	x	x	x	x	x	x
Number Observ.	3770	3770	3770	3770	2582	2368	3016

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

Panel B. Liquidity demand

Dependent variable: Individual settlement bank overnight liquidity

			Risk=Top 4 banks	Risk=Write-offs/TA	Risk=Equity Price Decline	Risk=ΔCDS	Risk=ΔTA/Retail deposits
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
ln(Payment value)(t)	1.180*	-0.073	-0.072	-0.107	-1.083	-1.631	0.094
	[0.608]	[0.894]	[0.892]	[0.892]	[1.047]	[1.363]	[0.987]
ln(Payment value)(t)*Break2		1.429	1.432	1.377	1.448	3.728**	1.339
		[1.120]	[1.117]	[1.114]	[1.342]	[1.742]	[1.241]
ln(Payment value)(t)*Break3		1.762	1.752	1.655	2.175	0.359	2.301*
		[1.154]	[1.151]	[1.141]	[1.516]	[1.850]	[1.290]
ln(Payment volume)(t)	-3.585***	-2.671***	-2.670***	-2.606***	-0.706	-1.376	-2.446**
	[0.894]	[1.010]	[1.008]	[1.008]	[1.176]	[1.288]	[1.113]
ln(Payment volume)(t)*Break2		-1.705	-1.712	-1.604	-1.374	-1.754	-2.232*
		[1.189]	[1.186]	[1.183]	[1.433]	[1.532]	[1.318]
ln(Payment volume)(t)*Break3		-0.237	-0.224	-0.310	-0.893	0.330	-1.254
		[1.289]	[1.285]	[1.275]	[1.690]	[1.632]	[1.446]
Risk			0.003	0.399	-0.014***	0.005	-0.017*
			[0.080]	[0.506]	[0.002]	[0.007]	[0.010]
Risk*Break2			0.291***	1.320***	0.013***	-0.007	0.009
			[0.064]	[0.499]	[0.002]	[0.007]	[0.014]
Risk*Break3			0.074	1.351	0.001	0.003*	0.009
			[0.063]	[0.852]	[0.001]	[0.002]	[0.007]
Break1		0.079	0.079	0.077	0.182**	-0.055	0.152*
		[0.073]	[0.073]	[0.073]	[0.087]	[0.154]	[0.081]
Break2		-0.053	-0.171	-0.145	0.028	-0.446	0.102
		[0.283]	[0.284]	[0.284]	[0.341]	[0.411]	[0.314]
Break3		-0.465*	-0.494*	-0.486*	-0.513	-0.359	-0.455
		[0.262]	[0.262]	[0.261]	[0.346]	[0.420]	[0.293]
Uncovered OMO	-0.276	-0.207	-0.207	-0.210	-0.117	-0.268	-0.21
	[0.169]	[0.176]	[0.175]	[0.176]	[0.203]	[0.227]	[0.194]
Band-Widening	0.251***	0.126	0.127	0.157*	0.137	0.179	0.081
	[0.037]	[0.088]	[0.088]	[0.089]	[0.108]	[0.124]	[0.099]
Higher-Reserves-Target-Ceiling	0.505***	0.401***	0.403***	0.444***	0.379**	0.451***	0.352**
	[0.057]	[0.124]	[0.124]	[0.124]	[0.159]	[0.165]	[0.140]
Esupply	0.562***	0.488***	0.489***	0.475***	0.562***	0.457***	0.609***
	[0.066]	[0.083]	[0.083]	[0.083]	[0.100]	[0.114]	[0.093]
Constant	0.223	0.447	0.331	0.494**	0.108	0.913**	0.177
	[0.261]	[0.299]	[0.263]	[0.251]	[0.346]	[0.446]	[0.331]
Tests p-values X=ln(Payment value)							
X+X*Break2=0		0.112	0.110	0.136	0.718	0.113	0.129
X+X*Break2+X*Break3=0		**0.007**	**0.007**	**0.011**	**0.085**	0.195	**0.004**
Tests p-values X=ln(Payment volume)							
X+X*Break2=0		**0.000**	**0.000**	**0.001**	0.146	**0.052**	**0.001**
X+X*Break2+X*Break3=0		**0.001**	**0.001**	**0.001**	**0.093**	0.124	**0.000**
Risk+Risk*Break2=0			**0.000**	**0.005**	0.529	0.132	0.289
Risk+Risk*Break2+Risk*Break3=0			**0.000**	**0.002**	0.875	0.623	0.854
R-squared	0.09	0.09	0.09	0.09	0.11	0.08	0.14
Bank fixed effects	x	x	x	x	x	x	x
Maintenance days effects	x	x	x	x	x	x	x
OMO days fixed effects	x	x	x	x	x	x	x
Number Observ.	3780	3780	3780	3780	2582	2368	3016

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

Panel C. Overnight market rates

See Table 7 for details of the sample covered and definition of the variables used in the estimation.
3SLS estimates are reported. Robust standard errors are reported in brackets.

	Liquidity=ln(aggregate reserves balances)		Liquidity=aggregate reserves balances in % deviation from aggregate target		Liquidity=ln(aggregate reserves balances)		Liquidity=aggregate reserves balances in % deviation from aggregate target	
	(1)		(2)		(3)		(4)	
	secured spread	unsecured spread	secured spread	unsecured spread	secured spread	unsecured spread	secured spread	unsecured spread
Liquidity	-85.225*	-74.836	-0.643*	-0.571	-93.810*	-86.883	-0.695	-0.654
	[45.729]	[47.445]	[0.380]	[0.394]	[51.809]	[54.898]	[0.423]	[0.453]
Liquidity*Break2	79.919**	63.620*	0.631**	0.502	83.087**	68.852	0.640*	0.528
	[36.881]	[38.265]	[0.317]	[0.329]	[39.993]	[42.378]	[0.334]	[0.358]
Liquidity*Break3	2.752	6.828	0.067	0.105	-4.710	-0.670	-0.016	0.019
	[42.760]	[44.365]	[0.410]	[0.426]	[42.829]	[45.383]	[0.398]	[0.426]
Break2	-198.178**	-156.778*	-11.519	-7.656	-206.158**	-173.197	-10.523	-10.553
	[91.015]	[94.431]	[14.304]	[14.866]	[100.571]	[106.568]	[15.747]	[16.848]
Break3	-11.1	-13.084	-8.734	-0.906	10.022	4.908	-3.191	1.18
	[118.401]	[122.845]	[22.006]	[22.870]	[113.752]	[120.534]	[16.303]	[17.444]
Break1	22.546***	24.512***	22.742***	24.709***	22.723***	24.773***	22.842***	24.904***
	[6.483]	[6.726]	[6.821]	[7.089]	[6.881]	[7.291]	[7.141]	[7.641]
Uncovered OMO	39.405**	50.731***	41.791**	52.535***	36.473*	46.687**	39.527**	49.047**
	[17.574]	[18.234]	[17.951]	[18.655]	[19.553]	[20.719]	[19.678]	[21.054]
Band-Widening					-2.402	-1.56	-2.693	-1.795
					[6.072]	[6.434]	[6.264]	[6.702]
Higher-Reserves-Target-Ceiling					-0.206	2.006	-1.336	1.088
					[9.980]	[10.575]	[10.550]	[11.288]
Esupply					2.313	6.456	1.262	6.051
					[12.098]	[12.819]	[13.837]	[14.805]
Constant	244.976**	-	18.893	38.382**	247.319*	-	34.102*	42.085*
	[124.047]		[26.498]	[18.759]	[138.282]		[19.505]	[21.525]
Tests p-values X=Liquidity								
X+X*Break2=0	0.821	0.645	0.955	0.759	0.684	0.518	0.816	0.619
X+X*Break2+X*Break3=0	0.953	0.922	0.889	0.927	0.728	0.691	0.858	0.801
Maintenance days fixed effets	x	x	x	x	x	x	x	x
OMO days fixed effects	x	x	x	x	x	x	x	x
Maintenance period fixed effect	x	x	x	x	x	x	x	x
Hansen-Sargan Overidentification statistic=	11.601	11.601	12.223	12.223	9.237	9.237	10.383	10.383
P-value=	(0.478)	(0.478)	(0.428)	(0.428)	(10.683)	(10.683)	(0.582)	(0.582)
Number Observ.	295	296	295	296	296	296	295	295

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