Contagion Among Interbank Money Markets During the Subprime Crisis*

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Abstract

Starting in August 2007, the spreads between unsecured and secured money market rates (repo spreads) increased sharply and became highly correlated across regions. This paper investigates empirically whether this can be explained by contagious effects and to what extent central bank interventions were successful in easing the strains on the interbank market. Our results suggest that shocks to one market were transmitted to other money markets. Moreover, repo spreads decreased in reaction to the provision of liquidity by central banks in the same and in other regions. This suggests that liquidity problems lay at the core of the observed strains in interbank markets and of the transmission of shocks across regions.

Keywords: Contagion, subprime crisis, repo spreads, interbank money market.

JEL classification: E52, F33, G21.

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1 Introduction

The severity of the recent subprime crisis has taken many economists and financial market participants by surprise. One of the most remarkable symptoms of the crisis was the observed strain in interbank money markets, showing up in sharply increasing money market rates. The rates for unsecured and secured lending diverged tremendously. Interpreting the spread of these rates (*the repo spreads*) as risk premia for interbank lending, the crisis appears to have led to a massive decline in the banks' (perceived) creditworthiness.

Interestingly, repo spreads did not only increase, but they also became highly correlated across different regions (US, UK and euro area) during the turmoil. This paper investigates whether the observed rise in correlations is due to a contagion effect among interbank money markets. In fact, it is frequently argued that the problems underlying the recent financial turmoil originated in the United States and spilled over to other regions worldwide. The role of interbank money markets in this process will be discussed.

To shed light on these issues, we start by analyzing the dynamics of the repo spreads from the US, UK, and the euro area in a VAR framework. Our empirical results confirm the existence of contagion in interbank money markets during the crisis: a shock to the repo spread in one region is transmitted to the other regions; the same cannot be observed for the period prior to August 2007. Interestingly, shocks are not only transmitted from the US to the UK and the euro area, but - at least partly - also in the opposite direction.

We further analyze the effectiveness of central bank actions in easing the strains in interbank money markets. Central bank actions are found to have significantly decreased repo spreads in the respective money market during the crisis, indicating that central bank actions indeed contributed to a stabilization of interbank markets. Particularly large effects are found for central bank actions concerning the range of acceptable collateral and the introduction of new lending facilities. These results are remarkable because they imply that banks' risk premia (i.e., banks' *solvency*) are affected by the *liquidity* provision by central banks. They suggest that liquidity problems lay at the core of the turmoil in interbank money markets.

Another noteworthy finding concerns the transmission of liquidity-providing central bank actions across interbank money markets. We find that central bank operations in

one region also affected repo spreads in the other regions. Again this is especially true for transactions regarding collateral and new lending facilities. This suggests that liquidity also plays an important role in the transmission of shocks across interbank money markets.

Our paper is related to two strands in the literature. First, there are a number of empirical papers evaluating the effectiveness of the Term Auction Facility (TAF), introduced in December 2007, in cooling down the strains in the US money market (e.g. McAndrews, Sarkar, and Wang (2008), Sack and Meyer (2008), Taylor and Williams (2009) and Wu (2008)). The liquidity risk component in the expectations-adjusted interest rate spread (OIS spread) is at the center of these studies. These papers investigate neither the cross-country effects of these measures, nor the measures conducted by other central banks. The second group in the literature focuses on the risk decomposition in money market rates (e.g. Schwarz (2008) and Brunnermeier (2008)). They try to disentangle credit default risk from liquidity risk, but do not measure the effect of central bank interventions. The contribution our this study will be to analyzes all major central bank interventions for the euro area, UK and US on a national and cross-country basis. In addition, we will focus on the credit risk component of money market rates.

The remainder of this paper is structured as follows. In Section 2, we present the major stylized facts to be explained, in particular the rise in repo spreads and in the correlations of repo spreads across regions. Section 3 analyzes the transmission of shocks from one interbank market to another in a VAR model. In Section 4, we consider the effects of liquidity-providing central bank actions on the repo spreads of different regions. Section 5 concludes.

2 A Look at the Data

We will first motivate the use of repo spreads as measures of risk premia in interbank money markets. Then, the major stylized facts of repo spreads in the US, UK and the euro area are presented and explained.

2.1 Data description

For our empirical analysis, we use daily interbank money market rates from three markets: the United States (*US*), the United Kingdom (*UK*) and the euro area (*Euro*). For each market, we collected the (best available) proxy for the rates at which interbank term deposits with a maturity of three months are offered by one prime bank to another prime bank, namely the Euro interbank offered rate (Euribor)[1], and the London interbank offered rate (Libor) denominated in UK sterling and US dollars, respectively.[2] The three rates are published almost at the same time. The Euribor is published by the European Banking Federation (EBF) at 11.00 a. m. CET, while Libor rates are fixed and announced by the British Banker's Association (BBA) at 11.00 a. m. GMT. These interest rates play an important in the benchmarking of short-term rates. As the basis for the settlement of interest rate contracts they are used on many of the world's major futures and options exchanges. They reflect both current and expected overnight rates, expectations of future changes in central bank's key policy rates, and risk premia associated with credit risk and liquidity risk over the corresponding maturity. Since lending on these markets is *unsecured*, the lenders require a risk premium to be compensated for the possibility of a borrower's default. In normal times, such risk premium would be negligible for prime banks. The liquidity premium reflects banks' desire to protect their liquidity positions, especially in times of high uncertainty. It is affected by a bank's perception of its ability to borrow in the future, either from other banks or from the central bank.

For the purpose of our paper, we need to extract the credit risk premia in interbank lending. Taylor and Williams (2009) propose two different measures: (i) the *OIS spread*, i. e. the spread between unsecured money market rates and overnight index swap (*OIS*)

[1] Alternatively, we could use the Libor in euro instead of the Euribor for the Euro area. Despite technical differences, both fixing arrangements aim at reflecting true interbank money market rates, which are determined on a bilateral basis and are therefore notoriously hard to obtain. We reran all of our regressions using the Libor in euro. The results remain virtually unchanged.

[2] In the recent financial turmoil some observers expressed their concerns about possible strategic misrepresentations by the contributing Libor panel banks (see e. g. Mollenkamp (2008)). Since these banks are asked to provide the rates at which *they* could borrow, they might prefer not to admit how large the credit premium is that they must pay in the unsecured funding market. However, Gyntelberg and Wooldridge (2008) and Schwarz (2008) discuss this issue in more detail and show that these deviations of Libor rates from their true values are negligible. The BBA also conducted a survey of the quality of the Libor on June 13, 2008, and concluded that BBA Libor is a fundamentally robust and accurate benchmark.

rates, and (ii) the *repo spread*, i. e. the spread between unsecured money market rates and general collateral repurchase agreement (*GC Repo*) rates between prime banks.

The *swap market* mirrors the expectations of future policy rates since swap contracts are used as a tool to speculate on and hedge against future interest rate movements. In a swap contract, two parties agree to exchange a fixed rate (the swap rate) against a floating rate (average overnight rate) for a pre-agreed period of time. While cash flows accrue on a daily basis, money does not physically change hands until the maturity date. At maturity, only interest rate differences are exchanged. Thus, the swap rate contains relatively low liquidity and counterparty credit risk. *The GC repo* is a collateralized lending transaction where one party agrees to sell securities to another and receives a transfer of funds in return. Simultaneously, the involved parties agree to repurchase the same or equivalent securities at a specific price in the future. Since this is a secured money market transaction, credit risk should be negligible whereas liquidity risk is still contained. However, swap rates and repo rates are subject to interest rate risk reflecting markets' uncertainty about the future path of central banks' interest rates. Both the OIS rates and the GC repo rates are fixed almost at the same time of day in the three markets, i.e. 11.00 a. m. CET for the euro area and 11.00 a. m. GMT for the US and the UK.[3]

Some recent papers argue for the use of the OIS spread to measure the risk premia in interbank transactions (see inter alia McAndrews, Sarkar, and Wang (2008), Sack and Meyer (2008), Taylor and Williams (2009) and Wu (2008)). These studies focus on the liquidity component in money market rates when evaluating the effectiveness of central bank measures. By using credit default swaps, the risk in the OIS spread associated with counterparty credit risk is - at least partly - distracted from the liquidity risk.[4] Our work concentrates on the credit default component. Therefore, repo spreads are more suitable for our purpose. Repo spreads are likely to contain less liquidity risk by construction because this risk is contained in both the unsecured and secured transactions and is eliminated through the differencing procedure.[5]

[3]See also www.bba.org.uk, www.eurepo.org and Reuters, respectively.

[4]See Michaud and Upper (2008) for an evaluation of this approach.

[5]There may still be a liquidity component even in the repo spread if the liquidity in secured and unsecured markets are affected differently by market developments. For example, there may be a shift from unsecured to secured transactions in times of high uncertainty, see e.g. Bank of England (2008).

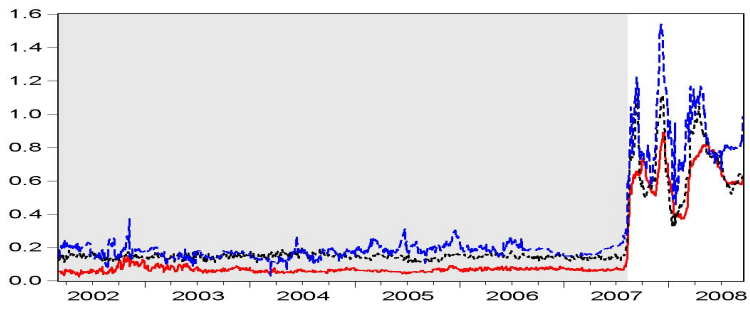
We use three-month repo rates from Reuters and the EBF. Our sample starts on March 4, 2002, when the European secured money market rate (Eurepo) was first launched, and it ends on September 14, 2008, just before the collapse of Lehman Brothers. In the aftermath of the Lehman default, the interbank money market, in particular the repo market, was severely impaired; it basically ceased to exist. Hence, the interest rates reported after the Lehman collapse are highly unreliable. Moreover, the post-Lehman period would dominate the interest rate movements in the pre-Lehman period. Therefore, we decided to focus on the pre-Lehman period. This leaves us with 1705 observations for each market.

In order to distinguish the crisis and the non-crisis period, we ran structural breakpoint tests (see Appendix). The Quandt-Andrews unknown breakpoint test suggests a structural break in the beginning of August 2007 (between August 3 and August 9 in the three regions, see Table B.2). In line with Goodhart (2008), we define August 9, 2007 as the beginning of the crisis. Following Table B.1, a simple Chow test confirms a structural break between the crisis period (August 9, 2007 - September 14, 2008) and the non-crisis period (March 4, 2002 - August 8, 2007).

2.2 Evolution of repo spreads

Figure 1 shows the 3-month repo spreads for the US, UK, and the euro area. We see that the spread was slightly positive before the crisis. However, as of August 9, the spreads widened rapidly and became highly volatile. Moreover, they have not stabilized since then. Hence, credit risk perceptions in interbank markets seem to have risen sharply in the crisis.

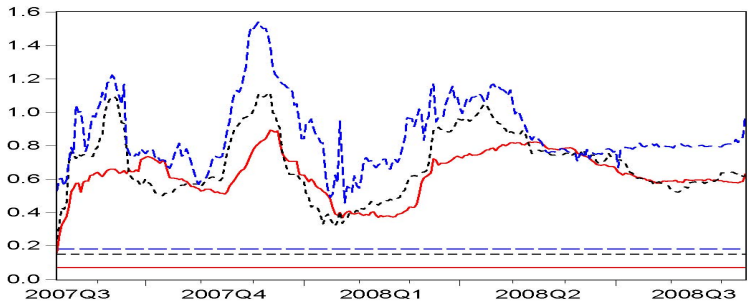
Figure 1: Evolution of the US, UK and Euro repo spreads for the full sample



Notes: The solid red, dotted black and dashed blue lines refer to the Euro, UK and US repo spreads for the full sample. The shaded area denotes the period prior to August 9, 2007. The unit of measurement of the y-axis is presented in % p. a. .

Figure 2 plots the evolution of the repo spreads for the crisis period in more detail. We see that the spreads fluctuated widely, but never returned to their pre-crisis levels. Table 1 summarizes these developments. In all three regions, the repo spreads of the crisis period were on average more than 50 basis points above those in tranquil times. It is remarkable that during the turmoil, the spreads reached maximum values of 89, 112 and 154 basis points, respectively. In other words, market participants at times were only able to borrow funds on the unsecured money market at a price that exceeded secured money market rates by more than 100 basis points. This dramatic divergence between unsecured and secured money market rates reflects the banks' reluctance to lend to each other. Furthermore, the spreads' standard deviations are more than five times larger during the crisis than during the tranquil period implying the uncertainty of market participants in the crisis.

Figure 2: Evolution of the US, UK and Euro repo spreads during the crisis



Notes: The repo spreads since August 9, 2007. The horizontal solid red, dotted black and dashed blue lines refer to the mean values of the Euro, UK and US repo spreads during the tranquil period.

Table 1: Descriptive statistics of repo spreads

	Pre-crisis			Crisis		
	Euro	UK	US	Euro	UK	US
Mean	0.07	0.15	0.18	0.63	0.69	0.88
Std.	0.02	0.01	0.04	0.13	0.19	0.21
Min	0.02	0.10	0.03	0.16	0.24	0.46
Max	0.15	0.23	0.37	0.89	1.12	1.54
Obs.		1418			287	

Notes: The pre-crisis period refers to the subsample March 4, 2002 - August 8, 2007 and the crisis period to August 9, 2007 - September 14, 2008. Euro, UK and US represent the corresponding repo spreads. Std. denotes the standard deviation and Obs. the number of observation. The unit of measurement is % p. a. .

2.3 Correlation coefficients

At the same time, Figure 2 shows strong co-movements across markets during the crisis which are not present in the pre-crisis period. This finding from the graphical analysis can be confirmed by looking at the correlation coefficients of the three repo spreads, distinguishing between the crisis and the pre-crisis period. The pre-crisis period is characterized by a low degree of correlation between any two markets. However, we observe high correlation coefficients among all three markets during the crisis.

Table 2: Correlation of repo spreads

	pre-crisis period			crisis period		
	Euro	UK	US	Euro	UK	US
Euro	-			-		
UK	0.12***	-		0.75***	-	
US	0.14***	0.02	-	0.58***	0.82***	-

Notes: *** indicates significance at the 1% level. See Table 1 for more details.

In the early literature on (stock market) contagion (such as King and Wadhwani (1990), Lee and Kim (1993), Calvo and Reinhart (1996) and Baig and Goldfajn (1999)) significant increases in cross-market correlations have been used to identify contagion effects.

However, Forbes and Rigobon (2002) argue that correlation coefficients are conditional on market volatility and thus biased in times of crises. They motivate an adjustment process that leads in several empirical applications to the conclusion that there is *no contagion, but only interdependence*. However, Corsetti, Pericoli, and Sbracia (2005) argue that these results are only achieved when imposing arbitrary and unrealistic restrictions on the variance of country specific shocks. Given these different views, correlation coefficients may not be sufficient to derive a causal relationship between different interbank markets. Therefore, we will now examine the relationship between the repo spreads in more detail.

3 Transmission of shocks

After checking the stationarity of the repo spreads, we will investigate whether shocks in one interbank money market spill over to the other regions. To this end, we estimate a vector autoregressive (VAR) model, as proposed by Sims (1980), and calculate the corresponding impulse response functions. In particular, we will compare the relationships between the three markets in the pre-crisis and in the crisis period.

3.1 Stationarity of repo spreads

Before applying a VAR methodology, we need to analyze the time series properties of the data in order to avoid spurious outcomes. The nature of integer roots in a given time series is usually examined by means of standard unit root tests, such as the Augmented Dickey Fuller (ADF) or the Phillips-Perron (PP) test. Both procedures test the null hypothesis that a unit root exists in the autoregressive representation of the time series, i.e. that it is I(1), against the alternative hypothesis that it is I(0). We applied both tests to our repo spread series. All tests confirmed that the spreads are I(0) and thereby justify a VAR model in levels.

3.2 VAR analysis

As a next step, we estimate a vector autoregressive (VAR) model, using the three repo spreads as endogenous variables. This allows us to describe the dynamic behavior of the repo spreads. Given the structural break in the data, we will run separate regressions

Table 3: Unit root tests

	Pre-crisis		Crisis	
	ADF	PP	ADF	PP
	$H_0 = I(1)$		$H_0 = I(1)$	
Euro	-5.06***	-8.66***	-3.61***	-3.70***
US	-8.04***	-14.20***	-2.95**	-2.95**
UK	-5.46***	-8.03***	-3.92***	-3.13**

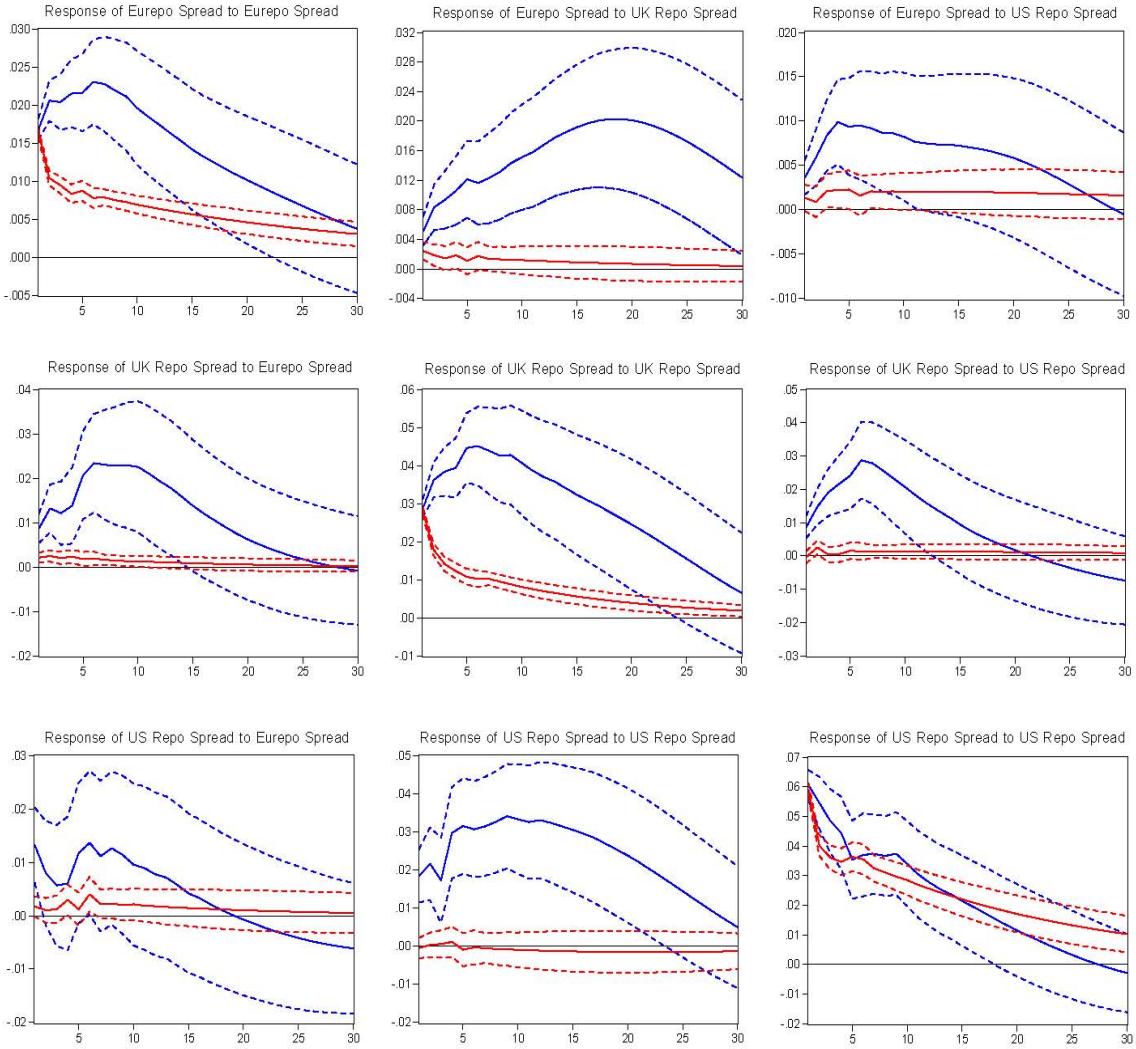
Notes: For the ADF-test t-statistics and for the PP-test *adjusted* t-statistics are given. ***,** ,* indicate significance at the 1%, 5%, 10% level. The lag length follows the Schwarz-information criterion and the bandwidth in the PP-test is chosen according to the Newey-West criterion using a Bartlett kernel.

for the pre-crisis and the crisis period. Causal effects can be derived from the resulting impulse response functions, which are calculated by applying a vector moving average (VMA) representation.

Typically, the lag order is selected arbitrarily allowing just enough lags to ensure the whiteness of the residuals. Alternatively, one may perform information criteria procedures such as the Akaike information criteria (AIC), the Schwarz information criteria (SIC), the final prediction error (FPE), or the likelihood ratio (LR) test. Since we use daily observations, a lag order of five days seems reasonable. This also happens to be the lag length suggested by AIC and FPE. The impulse response functions are estimated using the generalized impulse response (GIR) technique proposed by Pesaran and Shin (1998), which is invariant to the ordering of variables in the system. We consider the effects of a one-time shock of one standard deviation to the innovations on the current and future values of the repo spreads. Obviously, the standard deviation during the crisis will be much larger than that of the pre-crisis period. In order to compare the impulse responses, we will use the same shock for both periods, namely the standard deviation of the crisis period.

Figure 3 shows the resulting impulse response functions for the tranquil (red line) and the crisis (blue line) period. The figure shows a dramatic difference between crisis and non-

Figure 3: Generalized impulse responses to one s.d. innovations



Notes: The solid lines refer to the impulse responses to a one-time shock of one standard deviation to the innovations of the crisis period. The dashed lines show the confidence interval. The blue lines refer to the crisis period, while the red lines represent the tranquil period. The x-axis and the y-axis are measured in days and in % p. a. , respectively.

crisis periods. In particular, we find no indication for any linkage among interbank money markets before the crisis. In contrast, we observe strong and persistent effects during the crisis: a shock originating in one market appears to spread to all other markets. These effects are significant in all but one case (the US market is not significantly affected by the Euro market).

We interpret these findings to be consistent with contagion effects during the crisis. Before the crisis, the credit risk in interbank markets appears to be affected only by

national shocks. During the crisis, however, difficulties in one market spill over to other markets, causing a rise in the credit default risk in the other markets as well.

4 Liquidity provision by central banks

The reactions of repo spreads to liquidity-providing central bank actions will be at the center of the following analysis. We consider not only the reactions in the money market where the central bank is located, but also the transmission of central bank actions across different regions. First, the type of central bank actions that are considered in the empirical analysis need to be introduced. Then, we will describe the estimation procedure and present the regression results. Finally, some interpretations of our empirical findings are being provided.

4.1 Central bank actions

During the past months, we have seen an unprecedented provision of liquidity by the central banks of all major economies. Given the huge dollar investments by financial institutions outside the US in recent years, a liquidity shortage developed not only in local currencies, but also in dollars (see McGuire and von Peter (2008) and European Central Bank (2008)). Hence, solely injecting euros or sterling in the corresponding interbank money market was not considered to be sufficient to restore the functioning of money markets. Therefore, various monetary policy authorities cooperated intimately. For instance, since December 2007, the Federal Reserve (Fed) and the European Central Bank (ECB) have been conducting term auction facilities (TAFs) in order to provide US dollar liquidity to US and euro area banks against eligible collateral. Beside the TAFs, we will investigate the impact of the policy measures taken by the ECB and the Bank of England (BoE). The ECB, for instance, decided on August 22, 2007, to conduct supplementary liquidity-providing longer-term refinancing operations (sLTRO) with a maturity of three months in addition to its regular refinancing operations. The goal of these measures was the normalization of the functioning of the euro money market. In a similar vein, the BoE announced a plan on September 19, 2007, to undertake a series of supplementary three-month open market operations (sOMO). Furthermore, we will take other central bank

responses into account, such as announcements related to the provision of new lending facilities, the acceptance of a wider range of collateral in liquidity providing auctions, as well as the supply of high-quality securities for use in repo markets and for other collateralized lending (see Table A.4).

It is crucial to distinguish between the announcement and the actual implementation of the operation. On the one hand, the announcement of a central bank operation may already have an effect if it restores confidence to the interbank market and increases the willingness of market participants to lend to each other. On the other hand, the actual operation may have an additional effect if the announcement alone is not sufficient to revive interbank lending. Therefore, it is important to consider the cumulative effect of the announcement and the actual operation. We will, therefore, introduce two dummies for each operation. One dummy will be equal to one on the announcement day and zero otherwise ($D^{AN}_{operation}$), and another dummy will be equal to one on the bid submission day and zero otherwise ($D_{Operation}$). On the bid submission day, any information related to the operation to be conducted has already been announced by the corresponding central bank in advance and should therefore be reflected in the Libor and Repo data set on the release day. The information related to a US announcement will not be reflected in the US Libor and US Repo rates on the same day. Let us recall that US Libor and US Repo rates are fixed around 11.00 a. m. GMT which is 6.00 a. m. ET. According to the monetary policy press release platform on the US Fed web-page, announcements referring to TAF auctions are on average released between 10.00 a. m. ET and 12.00 p. m. ET, which is clearly *after* the US Libor and US Repo fixing. Hence, this information should be reflected in the US Libor and US Repo rates of the subsequent day (see McAndrews, Sarkar, and Wang (2008) for a similar approach). In talks with central bankers, we have confirmed that announcements in the euro and sterling money market are usually published before Libor and Euribor fixing. Occasionally, there have been more than one announcement and operation in the same market on the same day. At these days, we cannot trace the reactions of repo spreads to a single central bank measure. Therefore, we have to treat them separately.

4.2 Estimation and results

The empirical model measures the reactions of repo spreads to central bank actions by a simple dummy-variable approach. Note that this procedure is not sufficient to identify the causal effects of central bank actions. Rather, the results should be seen as a description of repo spread movements after central bank actions or their announcements.

Our univariate estimation model for each market will be specified as follows:

$$\begin{aligned} y_t = c + \alpha_1 y_{t-1} + \alpha_2 y_{t-2} \quad &+ \quad \sum_{i=1}^{12} \beta_i D^{AN}_{TAF,i} + \sum_{j=1}^{18} \gamma_j D_{TAF,j} \\ &+ \quad \sum_{l=1}^{6} \delta_l D^{AN}_{sLTRO,l} + \sum_{m=1}^{8} \mu_m D_{sLTRO,m} + \\ &+ \quad \sum_{k=1}^{3} \nu_k D^{AN}_{sOMO,k} + \sum_{p=1}^{10} \omega_p D_{sOMO,p} + \\ &+ \quad \sum_{q=1}^{7} \lambda_q D_{CBN,q} \sum_{r=1}^{4} \phi_r D_{other,r} + \epsilon_t, \end{aligned} \tag{1}$$

where y_t is the repo spread of the respective money market. D^{AN}_{TAF}, D^{AN}_{sLTRO} and D^{AN}_{sOMO} capture the announcement day of each TAF, sLTRO, sOMO, repectively, and D_{TAF}, D_{sLTRO} and D_{sOMO} each bid submission day of the actual operation. Days at which different events took place are considered separately by D_{other}. D_{CBN} will represent central bank news concerning a wider range of collateral accepted and the introduction of new lending facilities (see Table A.4). y_{t-1} and y_{t-2} denote the first and second lag of the corresponding repo spread which are used in the model to correct for first and second order serial correlation and ϵ_t represents the error term. If central bank measures are effective in easing the strains in interbank money markets, the estimated coefficients in equation 1 should be negative, indicating a decline in repo spreads.

Table 4 summarizes our results obtained for the three different regions. Since we have no reason to believe that all interventions have an homogeneous effect, we treat every event separately and present the number of negative and positive coefficients, the coefficients' averages, and the number of significant coefficients.

Let us first consider the reactions of repo spreads to central bank actions in the same region. We find, similar to McAndrews, Sarkar, and Wang (2008), that both the announce-

ments and the actual operations have the expected effect in most cases. The average reaction is always negative, and there are very few individual coefficient signs that go in the opposite direction. This suggests that central bank actions were on average successful in easing the strains in interbank money markets.

Next, we consider the reactions of repo spreads to central bank actions in another region. Interestingly, we find significant effects on many occasions. The average coefficient of the different operations shows the expected (negative) sign in many cases. Moreover, the number of negative coefficients typically exceeds the number of positive coefficients. However, there are also some positive (and even significant) reactions of repo spreads to central bank operations in other regions.

It should be noted, however, that our results may be blurred by the fact that bad news from the financial sector or from the real economy may have been published on the day of a central bank operation. Such news might be expected to drive up repo spreads (because there were hardly any good news in the considered time period). Therefore, our results may even *understate* (in absolute terms) the actual reaction of spreads to central bank measures.[6]

4.3 Interpretation of results

The results from these regressions are intriguing. In fact, it is far from clear that the provision of liquidity by a central bank should affect repo spreads at all. In normal times, a bank's creditworthiness should not depend on market liquidity. In contrast, our findings suggest that, in times of crisis, the liquidity provision by central banks is an important determinant of repo spreads and hence of banks' (perceived) creditworthiness. This supports the view that the observed decline in banks' creditworthiness, as indicated by the increase in repo spreads, was at least partly due to a liquidity squeeze.

The transmission of liquidity-providing central bank actions across regions is the second noteworthy result. In fact, this result may help us to better understand the finding from the first part of the paper, namely the existence of contagion among interbank money

[6] To demonstrate this point, we present several cases of overlapping central bank measures and (bad) financial news in the appendix (see Table A.5).

Table 4: Effect of central bank actions on repo spreads

		Dependent Variable: $(i_{unsecured} - i_{secured})_t^{3month}$								
		US Repo Spread			EU Repo Spread			UK Repo Spread		
CB measures	#	∅-Coef.	(−)	(+)	∅-Coef.	(−)	(+)	∅-Coef.	(−)	(+)
Announcement:										
TAF	12	-0.031	12 [12]	0	-0.007	9 [7]	3 [1]	-0.013	7 [4]	5 [5]
sLTRO	6	-0.024	5 [5]	1 [1]	-0.005	4 [4]	1 [2]	0.023	4 [2]	2 [2]
sOMO	3	0.034	2 [2]	1 [1]	0.0139	1 [0]	2 [2]	-0.003	1 [1]	2 [1]
Actual Operation:										
TAF	18	-0.024	14 [12]	4 [0]	0.004	8 [5]	10 [6]	-0.001	8 [7]	10 [7]
sLTRO	8	-0.009	4 [3]	4 [2]	-0.005	5 [3]	3 [3]	-0.006	4 [4]	4 [2]
sOMO	10	-0.033	6 [5]	4 [2]	-0.012	6 [5]	2 [2]	-0.008	5 [5]	5 [3]
Others	4	-0.007	3 [2]	1 [1]	-0.006	4 [2]	0	-0.010	4 [3]	0
Central Bank News:										
λ_1	1	-0.056	1 [1]	0	-0.021	1 [1]	0	-0.044	1 [1]	0
λ_2	1	-0.061	1 [1]	0	-0.101	1 [1]	0	-0.013	1 [1]	0
λ_3	1	-0.371	1 [1]	0	-0.024	1 [1]	0	-0.150	1 [1]	0
λ_4	1	-0.171	1 [1]	0	-0.003	1 [0]	0	-0.006	1 [1]	0
λ_5	1	0.030	0	1 [0]	0.079	0	1 [1]	0.071	0	1 [1]
λ_6	1	-0.079	1 [1]	0	0.010	0	1 [1]	0.019	0	1 [1]
λ_7	1	-0.018	1 [1]	0	-0.013	1 [1]	0	0.005	0	1 [0]
AR(1)			1.032^{***} [0.125]			1.386^{***} [0.137]			1.419^{***} [0.078]	
AR(2)			-0.071 [0.117]			-0.414^{***} [0.139]			-0.439^{***} [0.078]	
Obs			287			287			287	
R^2, adj.			0.92			0.98			0.98	
DW			1.88			1.97			2.15	

Notes: Estimation results refer to equation 1. *** indicates significance at the 1% level. The number of significant estimated parameters are displayed in brackets. # denotes the number of central bank actions. DW is the Durbin-Watson statistic and AR the autoregressive term of the corresponding repo spread. See Table A.1 - A.5 for an overview of all central bank measures during the turmoil.

markets. Our results suggest that liquidity effects are felt well beyond the local market. This indicates that liquidity also plays an important role in the transmission of shocks across interbank money markets.

This finding could be explained by a contagion effect working through asset prices: If international banks are holding similar asset portfolios and the provision of liquidity in one

market prevents fire sales of assets, this also puts some relief on banks in other regions.[7] With mark-to-market accounting, such liquidity problems easily translate into solvency problems.[8] Our findings would also be consistent with a domino effect due to contractual relationships between international banks as in Allen and Gale (2000) and Freixas, Parigi, and Rochet (2000). If the provision of liquidity improves the banks' solvency in one region, the banks' counterparties in another region would also benefit. Note that the underlying cause would be a liquidity squeeze in the banking sector in both cases.

5 Conclusion

Since the second half of 2007, repo spreads of the US, UK and the euro area increased dramatically and became highly correlated. In a VAR analysis, we show that this increase in correlations can be explained by a contagion effect. During the crisis, shocks in one market transmitted into markets in other regions. Such spill-overs are not observed in the pre-crisis period. Moreover, the provision of liquidity by central banks produced sizeable decreases in the repo spreads of the same region and of other regions. Hence, central bank actions also seem to spill over to other regions.

Our results indicate that liquidity problems were at the core of the observed strains in interbank money markets. The observed decrease in repo spreads in reaction to liquidity injections suggests that banks' solvency and liquidity were closely connected during the crisis. One explanation is that the provision of liquidity prevented banks from fire sales of assets. This may also explain why interbank money markets responded to the liquidity provision in other regions: If fire sales could be avoided, this would also be beneficial for banks in other regions who were holding the same types of assets. In addition, counterparty risk would be reduced.

These findings stress the role of central banks in preventing banks' liquidity problems from translating into solvency problems. The loosening of the eligibility criteria of collateral appear to have been particularly important in this respect. The presence of

[7] See Allen and Gale (2004) for an early model of contagion effects through asset prices and Schnabel and Shin (2004) for evidence that this type of contagion is by no means a modern phenomenon.

[8] See Allen and Carletti (2008). According to Hellwig (2008), this mechanism played an important role in the current crisis.

externalities of money market shocks and also of liquidity-providing central bank actions across regions implies that there may be insufficient incentives for a regional central bank to deal with problems in the interbank market if the crisis has a global dimension. Therefore, the observed interdependence among interbank money markets requires a globally coordinated response of central banks to resolve liquidity crunches.

However, this study also points to the limitations of central bank policy in easing the strains in interbank money markets. Even though liquidity injections seem to have slowed down the vicious circle of banks' liquidity and solvency problems, they were unable to bring back repo spreads to their pre-crisis levels. While the lack of liquidity can impair banks' solvency, the provision of liquidity cannot restore banks' solvency, but only mitigate the accelerating effects of liquidity squeezes.

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A Tables and Figures

A.1 Dates of TAF announcements and operations

Date	Action
12.12.2007	Fed and ECB announce the first two TAF operations to be conducted on December 17 and 20, 2007.
17.12.2007	1st TAF operation
20.12.2007	2nd TAF operation
04.01.2008	Fed announces its January TAF operations to be conducted on January 14, 2008 and 28, 2008.
10.01.2008	ECB announces its participation in the January TAF operations to be conducted on January 14 and 28, 2008.
14.01.2008	3rd TAF operation.
28.01.2008	4th TAF operation.
01.02.2008	Fed announces its February TAF operations to be conducted on February 11, 2008 and 25, 2008. ECB announces that it will not participate in Fed's February TAF operations.
11.02.2008	5th TAF operation.
25.02.2008	6th TAF operation.
29.02.2008	Fed announces its March TAF operations to be conducted on March 10, 2008 and 24, 2008.
07.03.2008	Fed announces that it will expand the amount of allotment in its March TAF operations.
10.03.2008	7th TAF operation.
11.03.2008	ECB announces that it will resume TAF operations and its participation on March 24, 2008.
24.03.2008	8th TAF operation.
28.03.2008	Fed announces its April TAF operations to be conducted on April 7 and 21, 2008.
07.04.2008	9th TAF operation.
21.04.2008	10th TAF operation.
02.05.2008	Fed and ECB announce an expansion of liquidity measures.
05.05.2008	11th TAF operation.
19.05.2008	12th TAF operation.
29.05.2008	Fed announces its June TAF operations to be conducted on June 2, 16 and 30, 2008.
02.06.2008	13th TAF operation.
16.06.2008	14th TAF operation.
30.06.2008	15th TAF operation.
01.07.2007	Fed announces its July TAF operations to be conducted on June 14 and 28, 2008.
14.07.2008	16th TAF operation.
28.07.2008	17th TAF operation.
30.07.2008	Fed and ECB announce a cycle of 84-day TAF operation beginning on August 11, 2008. Specifically, TAF auctions will be conducted bi-weekly, alternating between auctions of $ 75 billion of 28-day credit and auctions of $ 25 billion of 84-day credit.
11.08.2008	18th TAF operation. ECB announces its TAF operation to be conducted on August 12, 2008.
12.08.2008	Fed announced its TAF operation to be conducted today. 19th TAF operation.
22.08.2008	ECB announces its TAF operation to be conducted on August 25, 2008.
25.08.2008	Fed announced its TAF operation to be conducted today. 20th TAF operation.
05.09.2008	ECB announces its TAF operation to be conducted on September 8, 2008.
08.09.2008	Fed announced its TAF operation to be conducted today. 21st TAF operation. ECB annnounces its TAF operation to be conducted on September 9, 2008.
09.09.2008	Fed announced its TAF operation to be conducted today. 22nd TAF operation.

Source: The Federal Reserve System monetary policy press releases (`www.federalreserve.gov/newsevents/press/monetary/2008monetary.htm`), the Eurosystem's indicative list of USD operations (`www.ecb.int/mopo/implement/omo/pdf/cal_sup_ops.pdf`) and its summary of ad hoc communication (`www.ecb.eu/mopo/implement/omo/html/communication.en.html`).

A.2 Dates of sLTRO announcements and operations

Date	Actions
22.08.2007	ECB announces a supplementary LTRO with a maturity of three months to be conducted on August 23, 2007.
23.08.2007	1st sLTRO.
06.09.2007	ECB announces a supplementary LTRO with a maturity of three months to be conducted on September 11, 2007.
11.09.2007	2nd sLTRO.
08.11.2007	Renewal of the supplementary sLTROs allotted on 23 August 2007 and on 12 September, 2007. ECB announces two supplementary LTROs with a maturity of three months to be conducted on November 22, 2007, and December 11, 2007.
22.11.2007	3rd sLTRO.
11.12.2007	4th sLTRO.
07.02.2008	ECB announces two supplementary LTROs with a maturity of three months to be conducted on January 19, 2008, and March 11, 2008 .
19.02.2008	5th sLTRO.
11.03.2008	6th sLTRO.
28.03.2008	ECB announces two supplementary LTROs with a maturity of six months to be conducted on April 1, 2008, and July 8, 2008. and two supplementary LTROs with a maturity of three months to be conducted on May 19, 2008, and June 10, 2008.
01.04.2008	7th sLTRO.
19.05.2008	8th sLTRO.
10.06.2008	9th sLTRO.
08.07.2008	10th sLTRO.
31.07.2008	ECB announces two supplementary LTROs with a maturity of three months to be conducted on August 12, 2008, and September 9, 2008 .
12.08.2008	11th sLTRO.
04.09.2008	ECB announces a supplementary LTROs with a maturity of six months to be conducted on October 7, 2008 and two supplementary LTROs with a maturity of three months to be conducted on November 11, 2008, and December 9, 2008.
09.09.2008	12th sLTRO.

Source: The Eurosystem's indicative list of longer-term and supplementary EUR-refinancing operations (`www.ecb.eu/mopo/implement/omo/pdf/cal_sup_eur_ops.pdf?b20cdbbe041b4e62e8cb69bd479020e6`) and ECB's press releases (`www.ecb.eu/press/pr/date/2008/html/index.en.html`).

A.3 Dates of sOMO announcements and operations

Date	Actions
21.09.2007	BoE announces its sOMO to be conducted on September 26, 2007 and October 2, 10 and 17, 2007.
26.09.2007	1st sOMO.
02.10.2007	2nd sOMO.
10.10.2007	3rd sOMO.
17.10.2007	4th sOMO.
12.12.2007	BoE announces an expansion of the total amount of reserves offered at the three-month maturity and a wider range of collateral accepted in the sOMOs to be conducted on December 18, 2007, and January 15, 2008.
18.12.2007	5th sOMO.
15.01.2008	6th sOMO.
11.03.2008	BoE announces its maintenance of expanded three-month sOMOs against a wider range of high-quality collateral. It applies to schedule operations on March 18, 2008, and April 15, 2008.
18.03.2008	7th sOMO.
15.04.2008	8th sOMO.
13.05.2008	BoE announces its maintenance of expanded three-month sOMOs against a wider range of high-quality collateral. It applies to schedule operations on June 17, 2008, and July 15, 2008.
17.06.2008	9th sOMO.
15.07.2008	10th sOMO.

Source: BoE's Open market operations news releases and notices (`www.bankofengland.co.uk/markets/news/money/index.htm`), its list of term auctions (`www.bankofengland.co.uk/markets/termauctions/index.htm`) and the BoE's timetable of crisis events (`www.bankofengland.co.uk/publications/fsr/2008/fsrannex0810.pdf`).

A.4 Other operations and other central bank news

Date	Actions
Other Operations:	
19.05.2008	12th TAF and 8th sLTRO.
12.08.2008	Announcement and conduct of 19th TAF and 11th sLTRO.
08.09.2008	Announcement and conduct of 21st TAF and ECB's announcement of 22nd TAF.
09.09.2008	Announcement and conduct of 22nd TAF and 12th sLTRO.
Central Bank News:	
17.08.2007	Fed approves temporary 50 basis points reduction in the discount window borrowing rate, extends term financing and notes that it will accept a broad range of collateral. (λ_1)
13.09.2007	BoE announces that it will widen the range of banks' reserve targets within which they are remunerated at Bank Rate. (λ_2)
19.09.2008	BoE announces plan to undertake a series of three-month auctions against a broader range of collateral including mortgage collateral. (λ_3)
11.03.2008	Fed announces the introduction of a 28-day Term Securities Lending Facility. (λ_4)
16.03.2008	Fed announces establishment of Primary Dealer Credit Facility. (λ_5)
21.04.2008	BoE launches its Special Liquidity Scheme to allow banks to swap temporarily their high-liquidity mortgage-backed and other securities for UK Treasury bills. (λ_6)
30.07.2008	Fed and ECB announce the introduction of a 84-day Term Securities Lending Facility. (λ_7)

Source: The BoE's timetable of crisis events (`www.bankofengland.co.uk/publications/fsr/2008/fsrannex0810.pdf`) , the Federal Reserve System (`www.federalreserve.gov`) and the ECB (`www.ecb.int`).

A.5 Examples for overlapping CB measures and (bad) financial news

Date	Event
10.2007	2nd, 3rd and 4th sOMO; Citigroup, Merrill Lynch and UBS report significant write-downs.
08.11.2007	Announcement of 3rd and 4th sLTRO; Moody's announces its re-estimation of capital adequacy ratios of US financial guarantors.
10.12.2007 – 11.12.2007	UBS announces measures to address capital concerns following further write-downs; 4th sLTRO.
20.12.2007	2nd TAF; Bear Stearns announces expected 2007 quarter four write-downs.
15.01.2008	6th sOMO; Citi announces its rise in new capital by US$14.5 billion.
01.02.2008	The Fed announces its 5th and 6th TAF operation; the ECB announces that it will not participate in Fed's February TAF plans.
11.02.2008	5th TAF; American International Group (AIG) announces its auditors have found a 'material weakness' in its internal controls over the valuation of the AIGFP super senior credit default swap portfolio.
19.02.2008	5th sLTRO; Credit Suisse announces mismarkings and pricing errors by a small number of traders.
05.05.2008	11th TAF; increasing insolvencies in UK; Fannie Mae reveals huge losses; UBS and Morgan Stanley start downsizing.
02.06.2008	13th TAF; Bradford & Bingley discloses that private equity firm TPG Capital is to obtain a 23% stake.
16.06.2008 – 18.06.2008	14th TAF and 9th sOMO; Lehman Brothers confirms a net loss of US$ 2.8 billion in the second quarter; Morgan Stanley reports losses from mortgage proprietary trading and bad loans.
15.07.2008	10th sOMO; US Securities and Exchange Commission (SEC) issues an emergency order to enhance investor protection against 'naked short-selling'.

Source: The BoE's timetable of crisis events (`www.bankofengland.co.uk/publications/fsr/2008/fsrannex0810.pdf`) the Financial Times, the FAZ and the New York Times.

B Structural breakpoint test

B.1 Chow's breakpoint test

H_0 : No (structural) breaks at specified breakpoints			
	Test Date	F-statistic	Log likelihood ratio
Euro	8/09/2007	48.59***	269.71***
US	8/09/2007	25.71***	148.50***
UK	8/09/2007	46.90***	261.62***

Notes: ***,**,* indicates significance at the 1%, 5%, 10% level. The F-statistic is based on the comparison of the restricted and unrestricted sum of squared residuals. The log likelihood ratio statistic compares the restricted and unrestricted maximum of the (Gaussian) log likelihood function.

B.2 Quandt-Andrews unknown breakpoint test

	Date	Maximum LR F-Statistic	p-value
Euro	8/06/2007	50.85	0.0000
US	8/09/2007	25.71	0.0094
UK	8/03/2007	67.61	0.0000

Notes: The distribution of the maximum F-statistic is non-standard and follows Andrews (1993), and (approximate asymptotic) probabilities were calculated using Hansens's (1997) method. For this matter we allowed a symmetric "trimming" of 5%.