A Network View on Interbank Market Freezes

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Abstract

We study the liquidity allocation among European banks around the Lehman insolvency using a novel dataset of all interbank loans settled via the Eurosystem's payment system TARGET2. Following the Lehman insolvency, lenders in the overnight segment become sensitive to counterparty characteristics and banks start hoarding liquidity by shortening the maturity of their interbank lending. This aggregate change in liquidity reallocation is accompanied by a substantial structural change that can best be characterized as a shrinking of the interbank network. Such a change in the network structure is consequential: banks with higher centrality within the network have better access to liquidity and are able to charge larger intermediation spreads. Therefore, we show the existence of a sizeable *interbank lending channel*.

Keywords: Interbank loans, network topology, financial stability

JEL Classification: D85, E5, G1, G21

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1 Introduction

"Given heightened concerns about counterparty risk – which intensified dramatically after the failure of Lehman – cash-rich banks proved unwilling to lend to banks needing liquidity. As a result, the money market came close to a total freeze. [...] There was a clear and present danger that the resulting tightening of financial conditions would lead to augment the risk of a deflationary spiral, to trigger additional credit losses and a vicious downward cycle of financial and real distress." Trichet (2010)

The smooth and cost-efficient reallocation of liquidity in the interbank market is key for the resilience of the financial system and the implementation of the monetary policy stance, in particular so during periods of large adverse shocks. After the insolvency of the US investment bank Lehman Brothers on 15 September 2008, widespread fears mounted of an interbank market *freeze* in the euro area, i.e. a situation in which liquidity reallocation is severely impaired and even healthy banks are unable to obtain liquidity. To alleviate such fears, the European System of Central Banks (Eurosystem) decided to change the operational framework of monetary policy on 15 October 2008 from a variable-rate auction-based tender procedure to a fixed-rate full-allotment regime. Banks under this regime can obtain as much liquidity as they ask from the central bank, provided they can post sufficient collateral. The Eurosystem, as a result of this operational change, substituted a sizeable part of the interbank market with its own balance sheet. Doing so, Rochet and Tirole (1996) point out, reduces the extent of peer monitoring among banks which can have a lasting and severe impact on market discipline.

The European interbank market is an over-the-counter (OTC) market that can best be described as a network of lending relationships. Information about trading partners, volumes, and prices, however, is not typically available to the public.[1] Because data are elusive, many important questions about the effects of large adverse shocks on access to and price of liquidity are unanswered. Was there a near-total money market freeze in the wake of the Lehman insolvency, as ECB president Trichet asserts in the above quote? Were banks' decisions to provide liquidity sensitive to counterparty properties? And if so, did the fear of being rationed on the interbank market incentivize banks to start hoarding liquidity? There were clear signs of market turmoil, most notably in the LIBOR-OIS spread which reached unprecedented heights in the days following the Lehman insolvency. But how did this turmoil manifest on a disaggregated level? Did the structure of the interbank network change substantially as a result of the exogenous shock? Does this change matter for banks' access to liquidity and the efficiency of the interbank market? And what effect had the ECB's emergency measures on the market? We use a novel and unique dataset of all unsecured interbank loans settled between any two European banks between

[1] A notable exception is the Italian e-MID trading platform. Banks voluntarily choose whether or not to trade in a transparent way using e-MID. Since only the most viable banks will choose to trade transparently, e-MID likely suffers from a self-selection bias. In addition, e-MID only covered about 14% of the turnover in the euro area interbank market before the crisis, most of which involved Italian banks only.

July and December 2008 to answer these questions.[2]

We obtain data from TARGET2, the large value payment system of the euro area, which settles over 90% of all transactions between any European banks.[3] Interbank loans are identified using the algorithm originally developed by Furfine (1999) in the implementation of Arciero et al. (2013).[4] Our data contains unsecured interbank transactions with maturity of up to one year. We analyze not only the overnight segment of the interbank market, which accounts for most of the market turnover, but also the term segment, which accounts for most of the actual exposure between banks. In contrast to the existing literature, we not only have information about the banks involved in settlement, but also about the ultimate originator and beneficiary of a loan.[5] Since settlement banks do not carry counterparty risk, our data are ideally suited to study the role of counterparty risk in times of distress.[6]

To answer the question if and to what extent there was a market freeze in the euroarea interbank market, we first take an aggregate view at the market dynamics around the Lehman insolvency and study the extensive and intensive margin of liquidity provision. On the extensive margin in the overnight segment we find, relative to an initial reference period in early July 2008, a reduced probability that borrowers access the market even before the Lehman insolvency. This reduction is stronger, though following the Lehman event. For the amount borrowed we find no evidence for a significant reduction in interbank borrowing unless we introduce borrower fixed effects and even then only after the ECB conducted the special refinancing operation. In fact, for the period immediately after the Lehman insolvency, we find an *increase* in the amount banks borrow on the interbank market which confirms the results of Afonso et al. (2011) who show that the fed funds market in the United States was "stressed, but not frozen". We find that on Monday, 15 September banks pay on average 0.15 basis points more for liquidity than in the reference period. But already in the two weeks thereafter, and thus before the Eurosystem moved to the

[2]The settlement of secured interbank loans involves central counterparties which we drop from our data to ensure we only consider unsecured interbank loans. It is, however, a theoretical possibility that our data contain a small fraction of secured interbank loans.

[3]In 2012 TARGET2 settled 92% of the total large-value payment system traffic in euro. The remaining fraction of the total turnover is settled mostly via the EURO1 settlement system. See European Central Bank (2013).

[4]This implementation is extensively tested and verified using data on actual interbank transactions obtained from the e-MID trading platform in Italy and the Spanish MID trading platform. This verification reveals that the implementation of the Furfine algorithm used in this paper correctly identifies about 99% of all e-MID trades, and over 90% of all trades reported in MID. Concerns regarding the identification quality of the Furfine algorithm are voiced Armantier and Copeland (2012). However, Kovner and Skeie (2013) show that the identified interbank loans show a statistically significant correlation with interbank loans reported on the FRY-9C, which indicates that the Furfine algorithm can indeed be used to identify interbank loans.

[5]The only notable exception is the paper by Akram and Christophersen (2010) who, however, do not study the effects of large adverse shocks on liquidity reallocation in the interbank market.

[6]Furthermore, the additional information about ultimate originator and final beneficiary also makes the identification of interbank loans much less prone to type II errors, i.e. there are fewer false positives. This makes our analysis of the term segment of the interbank market much more reliable.

full-allotment regime of monetary policy, interest rates were reduced and banks paid less than in the reference period.

A significant reduction in the amount borrowed and the number of counterparties borrowed from can only be seen when we introduce borrower fixed effects. This indicates that lender were sensitive to borrower characteristics and that the market dynamics was driven by counterparty risk concerns. We do not find a similar effect when taking the lender perspective, i.e. there is no sensitivity of the intensive margin of liquidity provision to lender characteristics. We thus do not find direct evidence of liquidity hoarding in the overnight interbank segment. When looking at the term segment of the interbank market, however, we find a sizeable and lasting reduction in the amount borrowed, an increase in the price of liquidity, and a substantial reduction in the number of counterparties. We therefore provide evidence that banks increased the liquidity of their balance sheet by what can best be described as *maturity shortening* rather than a complete market freeze. This finding can be understood through various models of optimal maturity structure of financial institutions outlining mechanisms that can lead to a shortening of borrowing maturities. The most relevant of those is the paper by Farhi and Tirole (2012) who argue that the anticipation of non-targeted government policies (e.g. providing abundant central bank liquidity, or lowering the main refinancing rate) induces strategic complementarities in banks' liqudity choices which results in excessive maturity transformation. Creditors in He and Xiong (2012) are exposed to rollover risk which induces a coordination problem. Fundamental uncertainty increases the strategic uncertainty about other creditors' rollover decision and creditors use higher rollover thresholds, i.e. are less likely to roll over debt with a long maturity. Allen et al. (2012) show that short-term debt of banks can lead to excessive systemic risk if banks hold common assets. Finally, Brunnermeier and Oehmke (2013) show that banks' inefficient reliance on short-term funding can be the outcome of a maturity rat race caused by contractual externalities amongst creditors of the same borrower that provide funding with different maturity.

To complement the aggregate perspective, we take a highly disaggregated perspective and analyze the *network structure* of the interbank market. Empirical studies show that interbank networks tend to have a *core-periphery* structure, i.e. are comprised of a small group of highly connected banks (the core) and a large group of banks (the periphery) which is only connected through the core.[7] In the overnight interbank network, both the core and the periphery shrink after the Lehman insolvency, but the periphery shrinks more. In the term interbank network the core increases almost twofold, while the periphery shrinks substantially. It is noteworthy, however, that neither segment can really be characterized as a core-periphery network.[8]

[7]See, for example, Craig and von Peter (2014) for a study of the German interbank market. The notion of centrality in payment systems is more generally studied e.g. in Bech et al. (2010).

[8]Although de Andoain et al. (2014) document that the euro area interbank market is segmented along national borders, it remains a largely integrated network with a core of large European banks. The national interbank markets are more likely to be core-periphery, which implies that the joint European interbank network can best be characterized as a network of connected core-periphery

We find a substantial structural change in the interbank market due to the Lehman insolvency and the Eurosystem's emergency measures. It is a priori not clear whether this structural change is consequential for individual banks. We therefore quantify the effect that a bank's *position* within the interbank network has on access to, and price of liquidity. To this end, we study whether banks that borrow from more than one counterparty see a stronger reduction of interbank lending from lender-banks that are less central in the interbank network, i.e. lender-banks that might face a difficulty to raise liquidity themselves. We use the methodology of Khwaja and Mian (2008) and show the existence of a strong *interbank lending channel*: lender-banks that see a 1% reduction in interbank borrowing reduce their lending by 2%. A 1% reduction in the number of counterparties a lender-bank borrows from leads to a 0.2% reduction in the number of counterparties the bank lends to. A one-unit decrease in a lender-bank's betweenness centrality leads to a 0.61 unit decrease in the amount of liquidity provided. Similarly, a one-unit decrease in the eigenvector centrality implies a 0.85 unit decrease in the amount of liquidity provided.

We also study the extensive margin of liquidity, i.e. whether a bank has access to liquidity at all. A 1% decrease in borrowing of a lending-bank from the pre to the post period implies a 0.52% increase in the probability of loan non-renewal and 0.515% decrease in probability of new loan issuance in the post period. Finally, we study the effect of the interbank network structure on intermediation spreads. A one unit increase in betweenness centrality implies a 0.27 basis points higher intermediation spread and a one unit increase in eigenvector centrality implies a 1.66 basis points higher intermediation spread. These effects are sizeable and show that a lending-bank's position in the interbank market does not only imply a sizeable interbank lending channel on the intensive, but also on the extensive margin.

The paper closest to ours is Afonso et al. (2011) who empirically study the U.S. federal funds market around the Lehman failure to find a rather stressed (but not frozen) US overnight market. The stress is found to be characterized by a federal funds market that becomes highly sensitive to bank-specific information. Larger banks are found to have reduced borrowing activity both in terms of the volume and the number of distinct counterparties post-Lehman, while for smaller banks the authors observe the opposite. For the UK sterling market Acharya and Merrouche (2013) document that riskier UK settlement banks started hoarding liquidity by holding more reserves relative to expected payment value in the immediate aftermath of 9 August 2007, thus igniting the rise in interbank rates and the decline in traded volumes. Our analysis of the term segment of the interbank market complements both papers and we show that the market dynamics in the overnight segment cannot be seen independently of the term segments. Our findings are thus well in line with Ashcraft et al. (2011), who show that overnight money market lending in the fed funds and Eurodollar market increased during the early phase of the crisis and held up well, even after the failure of Lehman Brothers. Moreover, our observations for the longer-term euro area interbank market are consistent with the findings of Kuo

networks.

et al. (2013) for the US money market, who suggest that lending volumes generally fell, especially for maturities beyond the one-month bucket while term spreads increased. This supports our observation of a decline in the maturity-structure, where banks shifted their money market activity from longer-term segments to overnight as they faced rising costs of term borrowing.[9]

Our study is also closely linked to the literature that studies counterparty risk and liquidity hoarding as leading motives for aggregate liquidity shortages in money markets during periods of distress. Counterparty risk is studied, for example in Flannery (1996), Freixas and Jorge (2008), Bruche and Suarez (2010), and Philippon and Skreta (2012). In a model more directly applicable to our findings, Heider et al. (2010) show that during times of large asymmetric information banks anticipate a dry-up of interbank lending and start hoarding liquidity as a result. Acharya and Skeie (2011) and Acharya et al. (2011a) develop a model that predicts increasing term inter-bank lending rates and decreasing volumes at the same time, reflecting the precautionary demand for liquidity of lenders and an aversion of borrowers to trade at high rates of interest, both induced by their rollover risk. Acharya et al. (2011b) describe a more strategic motif that emphasizes a bank's preference for liquidity hoarding as a precautionary incentive because it expects troubled banks to fire sale their assets. Asset fire sales are also at the core of Diamond and Rajan (2011) who focus on the long-term credit contraction. They argue along the lines of the risk-shifting problem in Jensen and Meckling (1976) where during a period of adverse shocks banks might have an incentive to delay asset sales as part of their efforts to stay alive. Gale and Yorulmazer (2013) model both the precautionary and strategic motive for cash holdings and suggest that aggregate liquidity will fall as banks lend less than the maximum possible amount as in Acharya and Skeie (2011).

The network view on the interbank market we take in this paper provides empirical guidance for the literature that studies the formation and efficiency of interbank networks (see, for example Gofman (2011) and Farboodi (2014)). The endogenous network formation models of Leitner (2005) and Brusco and Castiglionesi (2007) study the trade-off between the completeness of the network, hence the degree of mutual insurance against uncertain liquidity needs due to having a large number of trading counterparties, and the risk of contagion. Differently from the seminal work by Allen and Gale (2000) both papers show that, under certain conditions, complete claims structures may be less robust than incomplete ones. In Leitner (2005) the whole network may collapse if liquidity is concentrated in a too small group of banks (see also Babus (2014), in't Veld et al. (2014), and Blasques et al. (2014)). More recently, Glode and Opp (2014) study intermediation chains as a means to overcome large asymmetric information. Their model predicts that, as asymmetric information gets larger it leads to an increase in trading activity before it ultimately becomes too large and the market breaks down, which is well in line with our results. Finally, our structural analysis of the interbank network structure contributes to the literature that studies structural changes in financial markets and their implications

[9]For an analysis of the interbank market based on trades settled via the e-MID platform, see for example Gabrieli (2009) and Angelini et al. (2011).

for financial stability (see, for example, Elliott et al. (2014), Acemoglu et al. (2014)).

The remainder of the paper is organized as follows. The institutional framework in the euro area and our data are discussed in Section 2. We take an aggregate view on the interbank market around the Lehman insolvency in Section 3 and study the role of counterparty risk and liquidity hoarding. The network view enters in Section 4 where we first study the change in the interbank network structure before we show that a bank's position in the interbank network has a significant impact on this bank's access to liquidity. Section 5 concludes.

2 The Institutional Framework

Turmoil in international financial markets reached a new high when the US investment bank Lehman Brothers filed for bankruptcy on 15 September 2008. Interbank markets in the euro area experienced an unprecedented surge of risk premia, measured as the spread between the London Interbank Offered Rate (LIBOR), and the most common proxy of a risk-free rate, the interest rate on a maturity matched index rate (OIS).[10] In response to this exacerbated financial turmoil, the Eurosystem took various exceptional measures to ensure the liquidity provision for European banks. On 30 September, the Eurosystem conducted a Special Refinancing Operation (SRO) to ease banks' mounting liquidity needs. Starting from October 15, 2008 the operational framework of monetary policy implementation was switched from the regular variable-rate tender procedure to a fixed-rate full allotment policy which would guarantee banks the allocation of the full amount of liquidity that they demand, provided they can provide sufficient collateral.

To understand the implications of the increased risk premia for the reallocation of liquidity within the euro interbank money market, an in-depth analysis of actual individual banks' transactions is required. The interbank money market, however, is mostly an over-the-counter (OTC) market where trade details are only known to the involved parties. Transaction level information is thus notoriously hard to obtain. One alternative to track interbank money market flows is through the way trades are actually settled. Interbank money market payments (denominated in euros) are mainly settled via TARGET2, the real-time gross settlement (RTGS) system owned and managed by the Eurosystem.[11] With a daily average of $354,185$ payments and EUR $2,477$ billion settled in 2012, TARGET2 is one of the largest payment systems in the world, alongside Fedwire in the United States and the CLS multi-currency cash settlement system.

[10] The LIBOR panel is updated periodically to only include the most trustworthy banks. This implies that there is a risk that the current LIBOR panel contains a bank which could experience distress in the future. This risk is priced and, thus, the LIBOR-OIS spread is positive.

[11] In 2012 TARGET2 settled 92% of the total large-value payment system traffic in euro. The remaining fraction of the total turnover is settled mostly via the EURO1 settlement system. However, it should be noted that as far as non-commercial payments are concerned, banks can also use other settlement channels, such as automated clearing houses and correspondent banking. See European Central Bank (2013).

The database we use in this paper relies on a methodology recently developed by the Eurosystem allowing to identify unsecured money market transactions (i.e. interbank loans) from interbank payments settled through TARGET2 for maturities ranging from one day (overnight) up to one year (see Arciero et al. (2013)). This methodology relies on a refined version of the algorithm originally developed by Furfine (1999) to find loan-refund combinations from payment data. In its simplest form the algorithm assumes a round value transferred from bank A to bank B at time *t* and the same value plus a plausible interest rate amount from bank B to bank A at time *t+1*. Among other enhancements, the refined version developed for the Eurosystem investigates several areas of plausibility for implied interest rates (i.e. several interest rate corridors) and develops a method to choose the most plausible duration in case of multiple loan-refund matches. Moreover, the implementation has been comprehensively validated against actual interbank money market transactions. In contrast with the validation exercise recently carried out by Armantier and Copeland (2012) on a "plain-vanilla" implementation of the Furfine algorithm done at the Federal Reserve Bank of New York, the performance of the Eurosystem's algorithm that we use has been found to be very encouraging. More specifically, Arciero et al. (2013) report a very low Type 2 error of 0.92% for the best algorithm setup, of which only 0.26% represent wrong matches (see Arciero et al. (2013) for more details on the sources used for and the results of the validation). In contrast to the Furfine implementation used for the Fedwire analyses, our data contains not only the settlement banks involved, but also the initial originator and final beneficiary of the transactions. In this paper we undertake a detailed analysis of the dynamics of the euroarea interbank market around the Lehman insolvency. We are, amongst other things, interested in the possible effect of counterparty risk. Settlment banks do not ultimately bear counterparty risk, and our question is thus more naturally answered using originator and beneficiary information. A more practical advantage is that the set of lender and borrower increases substantially. For the pre-Lehman period, for example, the number of originator increased from a mean of about 135 settlement banks per day to over 227 lender per day, while the number of recipients increased from about 106 settlement banks per day to over 147 daily borrower. As a consequence, the possibility that the Furfine algorithm identifies a false re-match is drastically reduced, which increases the reliability of our analysis in the term segments (See the Supplementary Information for more details).

We study the period between 28 August 2008 and 30 October 2008 and split our sample into five different periods: The period from 28 August to 12 September is denoted the *pre-Lehman* period. *Monday* 15 September and *Tuesday* 16 September are considered individually to focus on the insolvency of Lehman brothers rather than other market developments around the same time. The period from 15 September to 29 September is denoted the *post-Lehman period*. On 29 September the ECB announced a *Special Refinancing Operation (SRO)* which is conducted on 30 September 2008 and lasts until 14 October 2008.[12] On 15 October 2008, the ECB adopted a

[12]Technically, the SRO was conducted as a variable rate tender with no pre-set amount and the ECB alloted a total of EUR120 billion out of EUR141 billion total bids.

full-allotment regime which was announced on 8 October 2008. We include dates from 15 October until 30 October 2008 to have the same number of days in the pre-Lehman and the full-allotment period. In addition, we use the period from 04 July to 21 July as an *initial* reference period, and the *post-SRO* period from 10 November to 21 November to study the market in the full-allotment regime after the SRO has expired on 8 November. In Section 3 we consider 15 September and 16 September separately to focus on the direct impact of the Lehman insolvency and thus shorten the *post-Lehman* sample by two days.[13]

Figure 1 shows the normalized euro money market turnover, as implied by TARGET2 transactions, in the overnight and term segments from July 2008 and during the five different subperiods of our analysis. While a slow decline is evident in both segments in July-August 2008, we can observe a rebound in the overnight money market from the start of the sample period of our analysis on 29 August and until 29 September. This is in sharp contrast with the substantial decline observed for the term turnover in the same period. Table 1 provides further details about the aggregate dynamics of the interbank market in the different sample periods. Borrower in the term segment experienced a substantial decline in turnover, in particular after the Lehman insolvency, with the mean of daily borrowing dropping from 132.7 million borrowed from 2.4 counterparties to 85.39 million borrowed from 2.1 counterparties. This drop was more than compensated, however, by the *increased* activity in the overnight segment. In the pre-Lehman period, banks borrowed an average of 590.1 million Euro from 6.3 counterparties, while this number increased to 671.3 million Euro borrowed from 7.1 counterparties in the post-Lehman period. This is the first evidence of the different dynamics in the term and overnight segment of the euro area interbank market and highlights the importance of taking the term segment into account to understand the dynamics of the overnight interbank market.

3 Not Frozen, But Chilling Cold

We first provide an aggregate view on the euro area interbank market following the Lehman insolvency by looking at four dimensions of aggregate market activity: market access, amount borrowed, interbank loan spreads, and the number of counterparties per borrower. We directly compare the developments in Europe with those in the US. Afonso et al. (2011) show that while the overnight fed funds market did not freeze following the insolvency of Lehman brothers, it experienced considerable stress. The only evidence of an actual market freeze in the fed funds market is that on Monday 15 September banks borrowed significantly less from significantly fewer counterparties when borrower fixed effects are included. This finding is consistent with a market that is characterized by counterparty risk, i.e. lenders are sensitive to counterparty properties. However, the overall picture for the fed funds market does not suggest a massive market freeze in the overnight segment, at least from an

[13] Our sample choice makes a direct comparison of our results with Afonso et al. (2011) easier, who also split their sample by considering 15 September and 16 September separately.

aggregate perspective.

Our data, consisting of transactions with maturities from overnight to 12 months, allows a more nuanced view at the developments in the euro area interbank market. We first look at the effect of the Lehman insolvency on borrowers in the overnight segment, shown in Table 3. The sample period runs from 04 July to 30 October 2008. Model (1) is a simple probit with the dependent variable being equal to one if a bank accessed the interbank market on a given day and zero otherwise. For every period we introduce a dummy variable that is 1 during this period and zero otherwise. The overnight segment shows a decrease in the probability of access relative to the initial reference period (i.e. relative to the period from 04 to 21 July) already in the pre-Lehman period. The reduction is stronger, though, in the two days following the Lehman insolvency. In the post-Lehman period, access is reduced, but not as strongly. Access is further reduced in the full-allotment period. The second (2) and third (3) model we estimate consider the amount a bank borrows on the interbank market in the various periods with and without borrower fixed effects. Without controlling for fixed borrower characteristics, and similar to the US, we do not see any significant reduction in trading in the overnight segment. However, when borrower fixed effects are included, we see a significant reduction in the amount borrowed once the ECB conducted the special refinancing operation and, more importantly, once the full-allotment is implemented: in the latter case, the large point estimate (-270) suggests that certain banks reduced by more than 90% their recourse to interbank funding after mid-October 2008. Spreads are analyzed in models (4) and (5). They are computed as the difference between the weighted average interest rate paid by a given borrower and the minimum bid rate of the Eurosystem's Main Refinancing Operations (MRO). Spreads were higher already in the pre-Lehman period, but substantially more so on 15 September, when banks paid on average 0.15 basis points more than in the initial reference period to obtain liquidity. Borrowing spreads increased by additional 0.05 basis points on 16 September; controlling for borrower characteristics the increase is slightly higher. Then, starting in the post-Lehman period, spreads reduced and significantly so during the full-allotment period. The number of counterparties a bank borrows from is shown in models (6) and (7). It significantly reduced in the pre-Lehman period and on Tuesday 16 September, when a bank could borrow from about one counterparty less than in the reference period, and then even more following the special refinancing operation, but only if borrower fixed effects are considered. This shows that immediately after the Lehman insolvency lenders in the overnight interbank market become highly sensitive to counterparty properties. The effect is stronger with the onset of the ECB emergency measures. Then, especially after full-allotment, bank characteristics are important for the amount a bank could borrow and the number of counterparties it could borrow from. The overall picture for the overnight segment is thus very similar to the US, with the interbank market being stressed, but not frozen.

So was there no market freeze in Europe at all? Not quite. A closer look at the term segment in Table 3 reveals a significant and sizeable impact of the Lehman insolvency.[14] From Monday 15 September onwards, access is significantly reduced and neither the SRO nor the full-allotment regime can restore market activity to pre-Lehman levels. A similar picture emerges for the amount borrowed (models (2) and (3)), which is substantially reduced starting from Monday 15 September and in all periods. Spreads increased both on Monday 15 and Tuesday 16 September (models (4) and (5)), but on Monday 15 September the economic magnitude of such effect is about one fifth compared to the increase observed in the overnight spread.[15] However, differently from the overnight segment, spreads continued to increase even after the ECB measures. Finally, the number of counterparties is significantly reduced on 15 and 16 September, and continues to decrease post-Lehman, with the implementation of the SRO and under the full allotment regime. In general, the effects are not sizably different once we introduce borrower fixed effects and are not as large as in the overnight segment. Compared to what we observe for the overnight segment, this provides milder evidence of lenders' sensitiveness to borrower characteristics in the term market: the drop in turnover volume was so large that all borrowers saw a substantial decrease in their interbank funding. Another indication that borrower characteristics were more relevant in the overnight segment is that the explanatory power of our regressions when borrower fixed effects are introduced increases much more in the overnight than in the term regressions. All in all, the picture for the term segment points more clearly to a market freeze.

On the lending side, Table 4 shows that on Monday 15 and Tuesday 16 lenders participated less in the overnight segment and charged higher interest rates on borrowers, while we do not observe a significant reduction in amounts lent nor in the number of counterparties. A significant drop occurs only on Tuesday 09/16 in the term segment. Moreover, adding fixed effects for lenders does not change the point estimates remarkably, thus suggesting that the higher spreads where indeed driven by borrower rather than lender characteristics. Note, however, that this does not imply that banks were not trying to increase the liquidity of their balance sheet, it just implies that lender characteristics were not the driving force behind the increased liquidity preference.

As a second step of the analysis, we take a more disaggregate view on the interbank market by introducing in the former regressions a set of bank-specific, *local* measures and splitting the sample according to the size of the banks. We denote as local all measures that are specific for an individual bank i and independent of the rest of the system. Since we are interested in bank's access to liquidity via the interbank market during times of distress, we focus on those local measures that possibly affect how much liquidity a bank is able to obtain. The most straightforward such measures are a bank's balance sheet characteristics. We focus on a bank i's balance sheet size (total asset size) $\text{assets}_{i,2007}$ and the amount of loan loss reserves $\text{llr}_{i,2007}$, both

[14] As a robustness check, we have conducted the analysis in this section for maturities up to three months only. All our results hold qualitatively.

[15] For each term maturity the term spread is computed as the difference between the weighted average interest paid by a borrower at that maturity and the average market rate for the same maturity. A unique spread is thereafter obtained by weigthing the various spreads with the turnover traded at the respective maturity.

measured at the end of 2007 and obtained from Bankscope.[16] While we include only traditional bank-specific balance sheet variables in this section, the network view taken in the next section will allow us to also consider measures that we will define as *almost-local*, i.e. measures involving a bank i and its direct counterparties in the interbank network, or *global*, i.e. variables involving a bank i and both its direct and indirect counterparties.

In Figure 2 we begin to disentangle the impact of the Lehman's bankruptcy on banks of different size by graphical inspection. Large banks are in the upper tercile while small banks are in the lower tercile of bank asset size at the end of 2007. Figure 2 shows borrowing (bottom) and lending (top) for large and small banks in the overnight and term segment. In the overnight segment lending from large banks fluctuated slightly until ECB's announcement of the full-allotment regime on 8 October, then increased shortly, and decreased again. In contrast, lending from small banks increased until early September, then decreased until the Lehman insolvency and increased to a peak of 50 percentage points above the 04 July reference date on the day that ECB conducted the special refinancing operation (30 September). Lending then decreased to the 4 July level by the time of the full-allotment regime. Borrowing by large banks was fairly constant around the time of the Lehman insolvency, increased shortly before the SRO was announced on 29 September and then picked up upon announcement of the full-allotment regime, which indicates that large banks were increasingly acting as intermediaries. Borrowing by small banks continuously declined to around 60% of the 4 July level during the sample period and picked up again only in late November.

The picture in the term segments is a bit more nuanced. Lending from large banks decreased continuously between 4 July and the Lehman insolvency. Between then and the special refinancing operation lending decreased even further until the troph of around 50% of the 4 July level. Lending by small banks, in contrast, increased continuously until it reached a peak of about twice the reference level on 15 October, i.e. upon adoption of the full-allotment regime. Lending then plummeted within days even below the original 4 July level. Borrowing for large banks fluctuated around the reference level until the Lehman insolvency but decreased sharply thereafter. This decrease was stopped when the special refinancing operation was conducted and reached pre-Lehman levels when the full-allotment regime was put in place. Borrowing then decreased again to about 60% of the reference level before picking up shortly before the first special refinancing operation matured on 8 November.

Before describing in detail the models that we estimate, it is useful to link the exercise that we do in this section with the network view taken in the next section by introducing some general notation. A network $\mathfrak{g}$ is a set of nodes together with a set of links between the nodes. We are interested in interbank networks, each node

[16] We used the percentage of non-performing loans instead of loan loss reserves as robustness check and our results were qualitatively unaffected. Loan loss reserves are more widely available for euro area banks, which is why we chose to use them instead of non-performing loans.

is thus a bank and each link a loan between two banks. The network is represented by an adjacency matrix g with $g_{ij} = 1$ whenever two banks have a loan with each other and $g_{ij} = 0$ otherwise.[17] A loan from bank i to bank j at time t in a maturity segment $m \in \{\text{on}, \text{term}\}$ is denoted as $\text{loan}^m_{ij,t}$ and money market turnover is thus given as:

$$\text{loan}^m_t = \sum_i \sum_{j:i} \text{loan}^m_{ij,t} \tag{1}$$

in each maturity segment for the sample period.

To further explore the dependency on borrower characteristics, we explicitly take bank i's size, $\text{assets}_{i,2007}$, and loan loss reserves $\text{llr}_{i,2007}$ as measure for borrower quality into account. Following Afonso et al. (2011) we estimate the following specifications:

$$\text{access}_{i,t} = \beta(\text{date}) + \delta(\text{date} \times \text{llr}_{i,2007}) + \gamma(\text{date} \times \text{assets}_{i,2007}) + \epsilon_{i,t} \tag{2}$$

where $\text{access}_{i,t}$ equals one if bank i borrowed on the interbank market in period t, i.e.:

$$\text{access}_{i,t} = \max_j \{g_{ij,t}\}. \tag{3}$$

$\text{assets}_{i,2007}$ are the assets of bank i at the end of 2007, and $\text{llr}_{i,2007}$ is the amount of loan loss reserves at the end of 2007.[18]

We also estimate an OLS regression for both maturity segments m with dependent variable $F^m_{i,t}$ = {amount borrowed, spread to the mean interbank interest rate, number of counterparties}. The amount borrowed by bank i in maturity segment m at time t is defined as:

$$\text{amount}^{\text{m}}_{i,t} = \sum_{j:i} \text{loan}^{\text{m}}_{ji,t}. \tag{4}$$

The amount of interbank liquidity is only one aspect of the intensive margin of obtaining interbank liquidity. The other aspect is the price a bank pays for liquidity, measured as the spread to the main refinancing rate (in the overnight segment) or the average interbank interest rate (for the maturity segments). For each point in time t and each maturity segment we have a network $\mathfrak{g}^{\text{m}}_t$.[19] Denote the price of a loan from i to j at time t with maturity m as $p^m_{ij,t}$ and the volume-weighted price in maturity segment m as $\widehat{\text{p}}^m_{ij,t}$. Then:

$$\widehat{\text{p}}^m_{ij,t} = p^m_{ij,t} \times \frac{\text{loan}^m_{ij,t}}{\sum_{j:i} \text{loan}^m_{ij,t}}. \tag{5}$$

[17] Technically, the adjacency matrix can contain the value of the loan from i to j as weight. We use the unweighted network, unless noted otherwise.

[18] Loan loss reserves provide information on the perceived riskiness by banks of their loan portfolio: banks anticipating higher losses should hold higher liquidity buffers. We also used the ratio of non-performing to total loans and our results were qualitatively unchanged. The coverage of loan loss reserves is slightly better, though, so we use it in our main regressions.

[19] Whenever a superscript is omitted, it is understood that we sum over all possible values the superscript can take.

The spread to the mean interbank interest rate that borrower i pays on the interbank market at time t in maturity m is defined as:

$$\mathrm{spread}_{i,t}^{m,l} = \sum_{j:i} \widehat{\mathrm{p}}_{ij,t}^{m} - \widehat{\mathrm{p}}_{t}^{m}. \tag{6}$$

where $\widehat{\mathrm{p}}_t^m$ is the average interbank interest rate in maturity segment m at time t, $\widehat{\mathrm{p}}_t^{\mathrm{m}} = \sum_i \sum_{j:i} \widehat{\mathrm{p}}_{ij,t}^m$.[20] To define the number of counterparties of bank i it is useful to draw on the networks literature. The set of nodes j to which node i has a loan at time t in maturity segment m is denoted as the asset-side neighborhood of i, defined as:

$$N_i^{m;a} = \left\{ j | \mathrm{loan}_{ij,t}^m > 0 \right\} \tag{7}$$

while the set of nodes j that have a loan to node i is denoted as the liability-side neighborhood of i: $N_i^{m;l} = \left\{ j | \mathrm{loan}_{ji,t}^m > 0 \right\}$. Bank i's asset-side diversification $\mathrm{div}_{i,t}^a$ is therefore defined as the size of the asset-side neighborhood, i.e. as the number of counterparties j to which i has a loan at time t in maturity segment m:

$$\mathrm{div}_{i,t}^{m;a} = |N_i^{m;a}| \tag{8}$$

Equivalently, a bank's liability side diversification $\mathrm{div}_{i,t}^{m;l}$ is the size of the liability-side neighborhood, i.e. the number of counterparties j that have a positive-value interbank loan to i at time t in maturity segment m.[21]

Using these definitions, we can specify OLS estimations that take borrower properties into account as:

$$\begin{aligned} F_{i,t} \quad = \quad & \beta(\mathrm{date}) + \delta(\mathrm{date} \times \mathrm{llr}_{i,2007}) + \gamma(\mathrm{date} \times \mathrm{assets}_{i,2007}) \\ & + \Theta \left(\frac{\mathrm{amount}_{i,t}}{\mathrm{assets}_{i,2007}} \right) + \alpha_i + \epsilon_{i,t} \end{aligned} \tag{9}$$

where $\mathrm{amount}_{i,t}$ is the amount borrowed by bank i in all maturity segments and α_i are bank fixed effects. As before, the sample period runs from 04 July 2008 to 30 October 2008. In Tables (5) to (8) we split our sample in two subsamples based on banks' asset size. Large banks are in the upper tercile of the asset size distribution, while small banks are in the lower tercile. Furthermore, interacting the period dummies with borrower quality, measured by a bank i's loan loss reserves, $\mathrm{llr}_{b,2007}$ tests whether the interbank market has become sensitive to bank characteristics post-crisis and whether the sensitivity is greater for large or small banks.

As pointed out by Afonso et al. (2011), if lenders respond to the crisis by hoarding liquidity, we would expect to find an aggregate decrease in amounts lent and worse

[20] While we denote all term segments for simplicity simply as m, the computation for the average interest rate was done for each maturity, measured in days, separately to ensure comparable results across maturities. Differently from the term maturities, the spread for the overnight maturity is defined relative to the MRO rate.

[21] The literature on financial networks denotes the asset side diversification of a bank i as out-degree and the liability side diversification as in-degree. We adopt a nomenclature that is easier to interpret in economic terms.

performing banks lending less. If instead uncertainty about counterparty risk increases after a shock but banks can still discriminate between risks, then we would expect to find a large shift in the distribution of funds and rates in the cross section of borrowers and worse performing banks borrowing less and/or paying higher rates. The aggregate view of market developments taken so far allows us to exclude an aggregate decrease in amounts lent after the bankruptcy of Lehman (with the only exception of the reduction on Tuesday 09/16 in the term segment). Moreover, in Table 3 we saw that bank-specific characteristics drove a relatively high increase in overnight borrowing rates and a reduction in the number of counterparties from which banks could obtain liquidity. Only in the term segment these developments are associated to a generalized decrease in borrowed amounts. This overall picture seems consistent with an increase in counterparty risk in the euro money market around the Lehman event, especially in the ovenight segment, and a more generalized freeze only in the term segment.

Tables (5) and (6) corroborate and shed further light on this picture. Access to the market is reduced on Monday 15 and Tuesday 16, and especially so for small borrowers and for the overnight segment (models (1) and (2)). In models (3) and (4) we add interactions of the period dummies with loan loss reserves as a proxy for borrower quality. The interaction terms reveal that large borrowers whose loan portfolio is riskier pre-crisis access the overnight market less, both around the Lehman event and afterwards. No such effect is visible for small borrowers. In contrast, in the term segment large, worse performing borrowers are found to actually increase their participation pre-Lehman and especially on Tuesday 16 September (model (7)). Evidence from Table (6) confirms that there was no decrease in amounts borrowed overnight around Lehman, not even for the worse performing banks. The significant and large coefficient on the large banks for the full-allotment period in model (3) tells us that it was large borrowers who strongly reduced their interbank funding after the Eurosystem switched to full-allotment operations in mid-October 2008. It were small banks that reduced their interbank funding in the term segment on Monday 15 September and in the full-allotment regime, instead.

Table (7) shows that both large and small banks see an increase in overnight spreads on Monday 15 September. However, the increase persists only for small banks on Tuesday 16 September, while large banks actually start borrowing at a discount, relative to the initial reference period, both in the post-Lehman period and especially after the ECB measures (SRO and full-allotment). When we add interactions of the period dummies with loan loss reserves, models (3) and (4), we still observe the increase in spreads on Monday 15 September (larger for small banks), but we do not see a significant deterioration of borrowing terms for small worse performing banks immediately after the Lehman's bankruptcy. The only significant and positive coefficient appears for the interaction between loan loss reserves and the SRO period dummy, which suggests that small banks with a riskier loan portfolio pre-crisis could not obtain all the liquidity they needed at the Eurosystem's special refinancing operation. For the term segment, models (7) and (8) show that immediately after the crisis the relationship between spreads and borrower quality was not significantly different from that for the initial reference period, i.e. interest rates in the term segment did not become increasingly sensitive to measures of borrower quality.

We find similar evidence in Table (8) for the number of counterparties a bank borrows from. The results do not provide strong evidence of a changed market sensitivity to borrower size, nor to borrower quality immediately after the Lehman insolvency. The only significant and economically sizeable effect can be observed after the adoption of the full-allotment regime on 15 October, when large banks experience a large reduction in the number of counterparties from which they borrow (-2.6 counterparties in model (1) and -3.4 in model (3)). A similar effect is found in the term segment, again for large banks, but this effect is not as large as in the overnight segment.

Overall, these tables do not show a drastic change in the distribution of loans and rates in the cross section of borrowers depending on borrower pre-crisis quality, at least not immediately after the Lehman insolvency. This does not mean, however, that the market was not sensitive to counterparty risks, as we have shown in the aggregate perspective in Table (3). In a situation of stress, lenders may rather start to manage their unsecured interbank exposures by the amount they lend to a particular bank or even whether they lend to a given bank at all. Bank-to-bank relationships may actually become more important for the lenders' decision because they convey *soft* information that cannot be otherwide obtained from pre-crisis balance sheets. But this means that a more granular analysis of bilateral links between banks is needed. This motivates our network view in the rest of the paper.

4 Location, Location, Location

Before we can address the question if a bank's position in the interbank network affects access to liquidity, we have to specify in more detail *which* network we are using. There are two ways to specify the interbank network. The first is to use the daily networks of newly established interbank loans $\mathfrak{g}_t^m$ directly (i.e. the daily turnover networks), compute the relevant network measures, and then average them over a sample period. The alternative is to compute the interbank network as an aggregate over a sample period and then compute the network measures.[22] In this paper, we follow the latter approach because banks, by their very nature, engage in maturity transformation. Their lending decision and subsequently the endogenously chosen network structure at date t depends not only on their borrowing at t, but also on the borrowing (network structure) in $t - \Delta t$. Aggregating over a sample period is also the more natural choice if one is interested in access to liquidity because an interbank link that exists at some point during the aggregation period indicates that the two banks in question are able to engage in interbank lending. A link in the sample period is therefore indicative of the potential to raise liquidity, i.e.

[22]Because network measures are not additive, e.g. the betweenness on a sum of networks is different from sum of the betweenness of the individual networks.

determines the access to liquidity. Thus, all network measures in this section are computed for a reference period:

$$\mathfrak{g}^m_{\text{ref}} = \bigcup_{t\in\text{ref}} \mathfrak{g}^m_t = \sum_{t\in\text{ref}} g^m_{ij,t} \quad \text{ref} \in \{\text{pre}, \text{post}\} \tag{10}$$

and we next study their dynamics in the various sub-periods.

4.1 Measures of a Bank's Position in the Interbank Network

The next level of disaggregation takes the network structure of the OTC interbank market explicitly into account. Network theory provides a wide variety of measures to quantify a bank's position in the interbank network and we will use those measures that have a natural economic interpretation to gain a deeper insight into the dynamics of the interbank market around the Lehman insolvency. *Global network measures* incorporate not just information about bank i's neighbors, but also about neighbors of neighbors and so on. We are interested in such global measures that proxy a bank's access to liquidity at a given time t. To this end, we first define a shortest path between two nodes i and j in network $\mathfrak{g}^m_{\text{ref}}$. A path from node i to node j in a network $\mathfrak{g}^m_{\text{ref}}$ is a sequence of nodes $i, \dots, j$ in which all nodes are distinct and each node has a link to its successor. The length of the path is the number of nodes it contains minus one. If more than one path exists from node i to node j, the shortest such paths is called geodesic and denoted $\sigma^m_{ij,\text{ref}}$. The distance $d^m_{ij,\text{ref}}$ from node i to node j in the network with maturity m is defined as the length of the shortest path between them, $d^m_{ij,\text{ref}} = |\sigma_{ij,\text{ref}}|$. The average shortest path for bank i is the mean geodesic distance separating the bank from all other banks in the network.

$$\overline{d^m_{i,\text{ref}}} = \frac{\sum_{j:i} d^m_{ji,\text{ref}}}{|N| - 1} \tag{11}$$

The average shortest path length of the network is the sum over all nodes' individual shortest path divided by the number of nodes and gives the average number of links that connect any two nodes in the network. Similarly, the diameter of the network is the length of the longest of shortest path between any two nodes in the network. We say that a network is connected if there exists a path between any two nodes in the network. The largest connected component is the largest connected set of nodes.

A most useful measure is the betweenness centrality of node i, defined as the fraction of all shortest paths between any two nodes j and k that pass through i:

$$\text{betweenness}^m_{i,\text{ref}} = \frac{\sum_{j:i} a^m_{jk,\text{ref}|i} / a^m_{jk,\text{ref}}}{(|N| - 1) \times (|N| - 2)} \tag{12}$$

where $a^m_{jk,\text{ref}|i}$ denotes the number of geodesics between j and k that contains i, $a^m_{jk,\text{ref}}$ is the total number of geodesics between j and k.[23] The betweenness of bank i is a

[23]Dividing by $(|N| - 1) \times (|N| - 2)$ allows to obtain a normalised version of betweenness because this factor represents the maximum number of pairs of players not including i, hence the maximum value that this indicator can take. Our measure for betweenness is thus normalized $\text{betweenness}^m_{i,\text{ref}} \in [0, 1]$.

proxy for how easy it is for this bank to access liquidity in the interbank market, i.e. flowing between any two banks in the market. It is also a direct measure for a bank i's intermediation function. Banks with a high betweenness are in a larger number of intermediation chains. Thus, they are more relevant for financial intermediation as a shock at such pivotal banks will affect the smooth flow of funds more strongly.

As a robustness check, we will also use the Katz centrality, which computes the relative influence of bank i within a network by measuring the number of its immediate neighbours (lenders) and also of all other banks in the network that lend to bank i through these immediate neighbours. The Katz centrality for bank i is defined as:

$$\mathrm{katz}^{m}_{i,\mathrm{ref}} = \alpha \sum_{j:i} g^{m}_{ji,\mathrm{ref}} + \beta \tag{13}$$

where $g^{m}_{ji,\mathrm{ref}}$ is the adjacency matrix representing the network with eigenvalues λ, and $\beta = 1$. The parameter $\alpha \leq 1/\lambda_{max}$ is an attenuation factor that allows to penalize loans made with distant neighbours, i.e. with lenders of lenders (of lenders of ...) of bank i. Moreover, extra weight can be provided to immediate neighbours (lenders) of bank i through the parameter β, which controls for the initial centrality.[24]

A very broad, but useful global measure is the network density, which is defined as the ratio of actual links in a reference period $\#\mathrm{loans}_{\mathrm{ref}}$ to possible links. For an undirected network, the density is defined as:

$$\rho^{\mathrm{m}}_{\mathrm{ref}} = \frac{\#\mathrm{loans}_{\mathrm{ref}}}{\mathrm{N}_{\mathrm{ref}} \times (\mathrm{N}_{\mathrm{ref}} - 1)}. \tag{14}$$

4.2 The Lehman Insolvency and the Changing Interbank Network Structure

The measures defined above can be used as a first step to quantify the change in the network structure of the interbank market. We focus on the change from the pre-Lehman to the post-Lehman period and in addition to the measures defined above, we also use the total volume of loans, the number of loans, and the number of borrower and lender in a given term segment (see also Section 3).

We turn to the overnight segment first. As can be seen in Table 9, the volume of loans increased from the Pre- to the Post-Lehman period by almost 10%, reaching the level of the Initial period. This increase is accompanied by a similar increase in the number of loans. Following the ECB's special refinancing operation and during the full-allotment period the volume of loans shrinks by over 35% while the number of loans is reduced by over 33%. From the Pre- to the Post-Lehman period, the number of borrowers decreased by about 7%, while the number of lenders remained roughly constant: fewer banks obtained more liquidity via more linkages from a roughly constant number of lenders. As a result of this process, the network density

[24] For $\alpha = 1/\lambda_{\max}$, and $\beta = 1$ katz centrality is the same as eigenvector centrality.

slightly increased, the average shortest path length slightly decreased, and the diameter decreased from 9 to 7. The size of the largest connected component increased slightly, while the share of nodes in the largest connected component remained very high with over 98% of nodes being part of the largest connected component. Betweenness and Katz centrality decreased slightly, although this global decrease does not yet reveal the heterogeneity across banks. The number of borrowers and lenders continuously decreased, from the pre-Lehman to the full-allotment period by around 13%. The density decreased by around 10%, while the shortest average path length increased by around 5% and the diameter remained constant at 7. The betweenness fluctuates by around 10% between periods, while the Katz centrality substantially declines by 37% from the Pre-Lehman to the full-allotment period.

In the term segment, the volume from the pre- to the post-Lehman period dropped substantially from 123.9 billion Euro to 78.5 billion Euro (a 37% reduction). The total number of loans also declined substantially, by 25% from 2122 to 1591. The number of borrowers decreased only slightly, but unlike in the overnight segment, the number of lenders also decreased substantially by over 10%. The change in the number of borrowers and lenders is consistent with a widespread shortening of maturities of interbank lending. Density decreased by more than 10% and the average shortest path-length increased. The diameter decreased slightly, and the size of the largest connected component decreased by roughly 10% from 692 to 636, although the fraction of nodes in the largest connected component remained with over 95% very high. While the Katz centrality did not change much, betweenness centrality increased by about 15%. During the SRO and full-allotment period the volume decreased further until it leveled at slightly over 50% of the Initial period level. The number of loans fluctuated by around 10% until the full-allotment period when 1506 loans were issued (a drop of almost 30% from the Initial period). The number of borrowers declined eventually by about 20% and the number of lenders dropped from the Post-Lehman to the SRO period before it stabilized. Density increased following the SRO period and reached Initial- and pre-Lehman period values. The average shortest path length increases by about 10% from the pre-Lehman to the SRO period before slightly decreasing in the Full-allotment period. The diameter decreased further until the full-allotment period and the size of the largest component continuously decreases. During the Full-allotment period the fraction of nodes in the largest component drops somewhat to 91%. The betweenness centrality continues to increase and the Katz centrality is very volatile, dropping by roughly 70% from the Post-Lehman to the SRO period before increasing by almost 250% in the Full-allotment period.

In Section 3 we show that lenders are sensitive to borrower characteristics in the overnight segment of the interbank market around the Lehman insolvency which is an indication of heightened asymmetric information and counterparty risk concerns. Asymmetric information is a determinant of the interbank network structure in Glode and Opp (2014), who develop a model of financial intermediation in which intermediaries facilitate trade by reducing asymmetric information between an originator and a beneficiary. As long as asymmetric information is not too large, the model of Glode and Opp (2014) predicts that larger asymmetric information is associated with longer intermediation chains and thus more trade. The Lehman insolvency was clearly a pivotal event in the financial crisis and in Section 3 we argue that asymmetric information was so large that it caused a cessation of trading in the term segment and a substantially heightened sensitivity to counterparty risk even in the overnight segment of the interbank market (see the massive spreads in the overnight segment on Monday, 15, and Tuesday, 16 September in Table 3). This explains the decreased average shortest path length in the Post-Lehman period. Once the ECB provided large amounts of liquidity, particularly bad borrowers will resort to central bank liquidity and thus leave the market. The result is reduced market participation, lowered spreads, and longer intermediation chains. This is perfectly consistent with our findings.[25]

Characterizing the change in the interbank network structure around the Lehman insolvency and ECB intervention is also important to understand the welfare implications of different network structures. Gofman (2011) shows the existence of a bargaining friction in over-the-counter markets such as the interbank market we study. This bargaining friction implies that not all network structures are equally efficient. More specifically, Gofman (2011) shows that networks which are *under*-connected, i.e. which have a too low network density, are inefficient. From this perspective, the overnight segment is likely to become more efficient after the Lehman insolvency as the network density increases. At the same time, however, the term market is more likely to become less efficient. The situation is reversed once the ECB steps in: the density of the overnight segment increases, indicating a likely higher efficiency, while the density of the term segment is substantially reduced. Another consequence of the bargaining friction described in Gofman (2011) is that financial institutions with many counterparties can improve trading efficiency. Across all segments and events (Lehman + ECB intervention) we find a substantial reduction in the number of active trading partners which increases the inefficiency of the network. Overall, our results show that the interbank market did not just drop in volume, the change in the network structure left it less efficient, which is an aspect that can only be seen when the market freeze is studied through a network lense.

Using measures from network theory is only one possibility to quantify the change in the interbank network structure. Another possibility is to see to what extent the network structure is of core-periphery type. Empirical studies of interbank networks found that they tend to have a core-periphery stucture in which a subset of nodes (the core) is highly interconnected, and a distinct subset of nodes (the periphery) is connected only to the core. We identify core- and periphery nodes following the methodology of Craig and von Peter (2014). Yet another possibility is to define a measure of the structural persistence based on individual transactions. The structural persistence of a network can be quantified using the Jaccard index $\mathrm{J}(A, B)$. In it's most general form the Jaccard index measures how similar two sets

[25] We do not find sensitivity to counterparty properties in the term segment, where asymmetric information is still mounting, even after ECB intervention, as the substantial spreads in Table 3 show.

are and is defined as:

$$\mathrm{J}(A, B) = \left| \frac{A \cap B}{A \cup B} \right|. \tag{15}$$

We measure the Jaccard index on subsets of links in the pre and post period.

The overnight segment has 732 nodes with 3936 links. The size of the core in the pre period is 25 (and the size of the periphery thus 707) and 22 in the post period. In the pre period, there are 253 links within the core, 1650 links within the periphery, and 2033 links between the core and the periphery. The overnight interbank network in the pre period is thus not exactly following a core-periphery structure and the error score defined by Craig and von Peter (2014) is 0.507. In the post period there are only 617 of the banks in the periphery active and there are 232 links within the core, 2070s links between core and periphery, and 1755 links within the periphery. The error score slightly increases to 0.52 in the post period. Both, the core and the periphery shrink between the pre and the post period, but the periphery shrinks more. The Jaccard-Index is 0.4 for the comparison between all links, 0.54 for the comparison of links within the core, 0.38 for links within the periphery, and 0.43 for links between the core and the periphery. As expected, the core maintains the highest structural stability, while lending between banks in the periphery is the least structurally stable.

In the term interbank market there are 724 nodes and 2122 links in the pre period and 673 nodes and 1591 links in the post period. The core size is 9 and thus significantly smaller than in the overnight segment. There are only 25 links within the core in the pre period, and 1477 links within the periphery, as well as 620 links between the core and the periphery. The term segment is thus even less of a core-periphery type than the overnight segment and the error score is 0.72. 515 of the periphery nodes are still active in the post period and, interestingly, the core-size has almost doubled to 17 banks between which there are 65 links. There are 986 links within the periphery, and 398 links between the core and the periphery. The error score slightly decreases to 0.69, but the network does still not resemble a core-periphery network well. The Jaccard-Index of the comparison between all links in the pre and post period is 0.2 for all links, 0.32 for links within the core, 0.21 for links within the periphery, and 0.22 for links between the core and the periphery. Again, despite the substantial increase in size, the core exhibits the largest structural stability.

Our results unveil the different dynamics of the core- and periphery in the overnight and term segment. In the overnight interbank network, both the core and the periphery shrink, but the periphery shrinks more. In the term interbank network the core increases almost twicefold, while the periphery shrinks substantially, which is consistent with concerns about counterparty risk behaviour. It is noteworthy that neither segment can be characterized as a core-periphery network, as the error scores are extremely high with about 0.5 and 0.7 compared to the error score for the German interbank market of 0.12. There might be institutional reasons for this finding: the euro area interbank market is highly integrated and has a core of large European banks. The national interbank markets are more likely to be core-periphery, which implies that the joint European interbank network can best be characterized as a network of connected core-periphery networks. The structural persistence of the interbank network can be understood in the context of relationship lending (see, for example Braeuning and Fecht (2013), Abbassi et al. (2014), and Afonso et al. (2014)).

4.3 Liquidity Shocks and Network Position

The final step in our analysis is to look at the variation in impact that a bank's position in the interbank network, measured by the amount borrowed, the number of counterparties a bank borrows from, betweenness centrality, and eigenvector centrality, has on the extensive and intensive margin of access to liquidity following an unanticipated shock. The hypothesis is that banks that are more central have it easier to obtain liquidity because they are in a position within the network that makes it relatively easy to access larger amounts of liquidity. The result should be increased access to, and higher amounts of liquidity obtained. Strategically well positioned banks should also find it easier to extract higher intermediation spreads. We follow the methodology of Khwaja and Mian (2008) and construct a panel of interbank loans that exist before and after the Lehman insolvency and use borrowing-bank fixed effects after first-differencing the data to absorb all borrowing-bank specific demand shocks. Starting from an extremely simplified bank balance sheet:

$$D_{i;t} + B_{i;t} = L_{ij;t} \tag{16}$$

where $D_{i;t}$ is the sum of demand deposits (from households, non-financial firms, etc.) and interbank deposits (from other banks) and $B_{i;t}$ is the amount of alternative financing, e.g. from bonds and equity, bank i faces at time t. $L_{ij;t}$ is the amount of interbank lending from bank i to bank j in period t. We assume that the demand and supply of interbank deposits is linear in each period. Taking the first difference obtains the equilibrium values of L_{ij} and B_i because of the linear model setup. As Khwaja and Mian (2008) show, this model can be estimated without bias by introducing borrowing-bank fixed effects after first-differencing. This yields our baseline regression:

$$\Delta L_{ij} = \beta_j + \beta_1 \Delta D_i + \epsilon_{ij}. \tag{17}$$

The assumption we make is that a bank's access to interbank liquidity, D_i, depends linearly on it's position in the interbank network, while the access to demand deposits is independent of the position in the interbank network. Thus, $D_i \equiv \alpha \times \text{netpos}_i$, where $\text{netpos}_i \in \{\#\text{lender}_i, \text{betweenness}_i, \text{katz}_i\}$.

We focus on the overnight segment of the interbank market for two reasons. First, we focus on the time period around the Lehman insolvency, with our pre period ranging from 28 August to 12 September and our post period spanning from 15 September until 29 September. In such a period of time, there will be only few term interbank loans that mature and because interbank loans cannot be terminated prematurely, banks can only decide to cancel maturing loans. Since about 90% of the turnover in the interbank market is in the overnight segment, it is thus much more likely that an overnight interbank loan matures in our sample period. A similar argument holds for demand deposits held by households and firms. Second, while there is a non-trivial network structure in the term interbank market, a much smaller subset of banks borrows from two counterparties in the pre period, which significantly limits the scope of our analysis. Summary statistics for our sample can be found in Table 2

The coefficient of interest is β_1, which determines the strength of the interbank lending channel. Table 10 shows the results of regression (17). Standard errors are clustered at the lending-bank level. There are 3064 interbank loans to banks that borrow from two or more counterparties in the pre and post period in our sample. We use change in logged amount of interbank liquidity L_{ij} and log amount borrowed in Column 1 in Table 10. Our results indicate an extremely strong interbank lending channel, a 1% reduction in interbank liquidity for the lending-bank implies a 2% reduction in the amount lent. Column 2 in Table 10 shows that a 1% reduction in the number of counterparties a lending-bank borrows from implies a 0.2% reduction in the amount lent. The average betweenness centrality is of the order 0.006 (see Table 9) which implies that a meaningful order of magnitude for a change in betweenness is 0.001. Therefore, a one unit increase in betweenness implies an 0.61 unit increase in the amount of liquidity provided. The results are comparable in size for the eigenvector centrality. A meaningful order of magnitude for a change in eigenvector centrality is 0.01 and thus a one unit increase in eigenvector centrality implies a 0.85 unit increase in the amount of liquidity provided. Overall, our results show the significance of a lending-bank's network position on the amount of liquidity this bank provides.

In addition to the intensive margin of *how much* liquidity banks obtain, we can also look at the extensive margin *if* they obtain liquidity at all. The extensive margin can be measured by constructing a variable exit_{ij} for each loan in the pre period which is one if the loan is no longer present in the post period, and zero otherwise. Similarly, we construct a variable entry_{ij} for each loan in the post period, which is one if the loan was not present in the pre period and zero otherwise. Our borrower-bank fixed effect regression for the extensive margin is thus:

$$\text{exit}_{ij} = \beta_j + \beta_1 \Delta D_i + \epsilon_{ij}, \tag{18}$$

and similarly for entry_{ij}. Results for this regression are shown in Table 11. Column (1) shows that a 1% decrease in borrowing of a lending-bank from the pre to the post period implies a 0.52% increase in the probability of loan non-renewal and 0.515% decrease in probability of new loan issuance in the post period. The increase in the probability of non-renewal is 0.11% for a unit reduction in the number of counterparties that a bank could borrow from post- versus pre-Lehman. Similarly, the increase in the probability of new issuance for a one unit increase in the number of counterparties a lending-bank borrows from implies a 0.75% increase in the probability of providing liquidity in the post period. Column (3) in Panel A of Table 11 shows that a unit reduction in betweeness centrality post to pre-shock corresponds to an increase in the probability of non-renewal of a loan post-Lehman by 16.6 basis point. Column (4) shows that a unit reduction in eigenvector centrality post to pre-shock corresponds to an increase in the probability of non renewal by 17 basis points. Similarly, Column (3) in Panel B of Table 11 shows that a one unit increase in betweenness from the pre to the post period implies a 25 basis points increase in the probability that a loan is newly issued. A one unit increase in the eigenvector centrality implies a 19 basis points increase in the probability that a loan is newly issued in the post period.

Because of the sizeable interbank lending channel, one can assume that a lending-bank's interbank network position also affects the spread it makes from intermediating liquidity. The intermediation spread of a loan $\text{loan}_{ij,t}$ can be measured as:

$$\text{spread}_{ij,t} = \text{p}_{ij,t} \times \text{loan}_{ij,t} - \sum_{k:i} \widehat{\text{p}}_{ki,t} \tag{19}$$

i.e. as the difference between the price of the loan and the volume-weighted average refinancing cost of the lending-bank. We estimate the effect of the interbank network position on the intermediation spread analogously to the intensive margin, i.e the amount lent. Results are shown in Table 12. Column (1) shows that a 1% increase in the amount a lending-bank borrows translates into 1.2 basis points higher intermediation spread. Lending-banks that borrow from one more counterparty see an increase of their intermediation spread of 0.7 basis points. A one unit increase in betweenness centrality implies a 0.27 basis points higher intermediation spread and a one unit increase in eigenvector centrality implies a 1.66 basis points higher intermediation spread, as shown in Column (4).

These effects are sizeable and show that a lending-bank's position in the interbank market does not only imply a sizeable interbank lending channel on the intensive margin, but also on the extensive margin.

5 Conclusion

Banking theory suggests that a financial crisis is characterized by reduced volumes and extreme levels of rates for term money market loans. At the extreme one might observe a complete dry-up of money markets that endangers the proper functioning of the financial system as a whole. During the recent financial crisis we have seen periods of unprecedented high term risk premia, especially so after the failure of Lehman Brothers. Our understanding of the dynamics of the overnight interbank market, however, is hampered by a lack of data about the term segment of the interbank market since banks take a joint decision of their asset and liability side for *all* maturities. The first contribution of this paper is therefore to use term money market transactions that we have obtained from the Eurosystem's payment system TARGET2 and study the changes in aggregate volumes around the bankruptcy of Lehman. Our second contribution is to use these data and employ techniques from network theory to understand potential changes in the structure of the overnight and of the term segments of the euro money market, and hence to study the reallocation of liquidity among banks at various maturities. We thus characterize the dynamics of the interbank network structure which can guide theoretical models of network formation. This *network view* allows us to also address issues of efficiency of the interbank network–a perspective not yet studied empirically. The third contribution of our paper is to investigate if bank-specific (local) network measures carry explanatory power for a bank's access to liquidity.

Our findings show that, while overnight money market volumes increased and held up even after the Lehman event, there was a substantial decrease in term interbank lending and that banks were effectively shortening the maturity of their interbank lending. Our global network measures reveal that during the pre-Lehman period the overnight segment is characterized by a closely connected (European) core and less closely connected peripheral banks, although the euro area interbank market does not follow a strict core-periphery structure. In the aftermath of the Lehman insolvency, network measures highlight the robustness of the overnight market whereas the term show a higher density and become much more focussed on 'market makers' at the core of the system. Our exercise on the basis of local network measures leads to the conclusion that in the overnight segment those banks with the best access to liquidity suffered the least. We interpret these findings as a network shrinking process with reduced interbank activity in the periphery of the system in the longer-term segments, in line with empirical findings of segmentation of the euro area interbank market. Finally, we show that a bank's position in the interbank market is a significant variable for the extensive and intensive margin of liquidity. Our network view on interbank market freezes thus shows that a bank's position does indeed matter for access to liquidity.

Our analysis provides cautionary evidence for central bank intervention. Following the switch from the variable-rate auction-based tender system to a full-allotment regime of monetary policy, the structure of the interbank network has changed such that the recently studied models of efficiency in networks indicate a lower efficiency. While substituting a large part of the interbank market, as the Eurosystem did as a reaction to the Lehman insolvency, has alleviated immediate liquidity shortages, the impact on market discipline and efficiency is unclear, but likely to be negative. This aspect of the Eurosystem's crisis measures has not been studied before but warrants attention, as the shift to a full-allotment regime of monetary policy is still in place and discussions about a "graceful exit" are ongoing.

Appendix

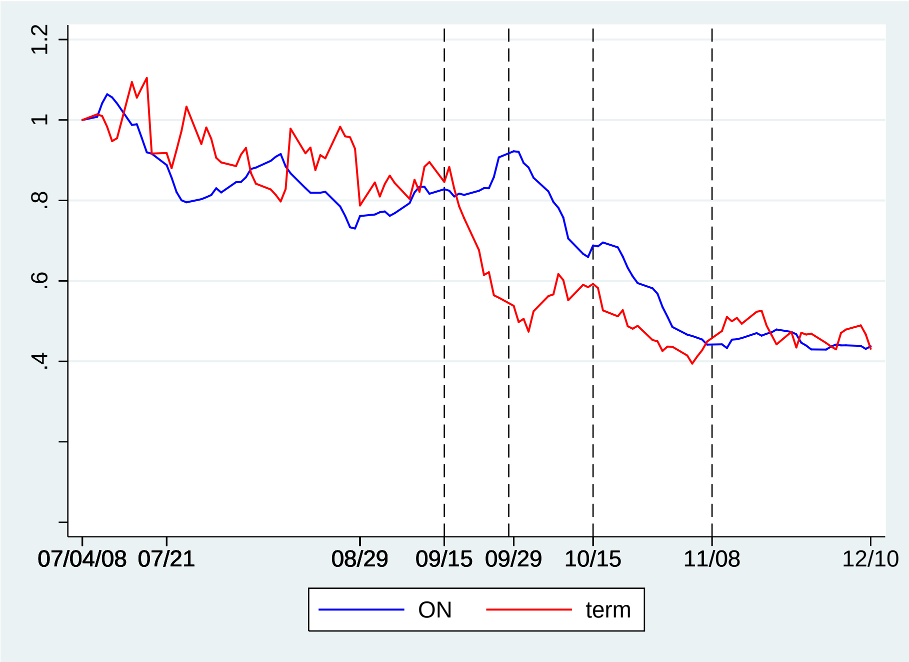

Figure 1: Normalized volume of the Euroarea overnight (blue) and term (red) interbank market between 04 July 2008 and 10 December 2008. Volumes in the overnight and term segment are normalized to the respective volume on 04 July 2008. Dates indicate our five sample periods: (i) initial reference period (04 July - 21 July), (ii) pre-Lehman period (28 August - 12 September), (iii) post-Lehman period (15 September - 29 September), (iv) SRO period (30 September - 14 October), and full-allotment period (15 October - 30 October).

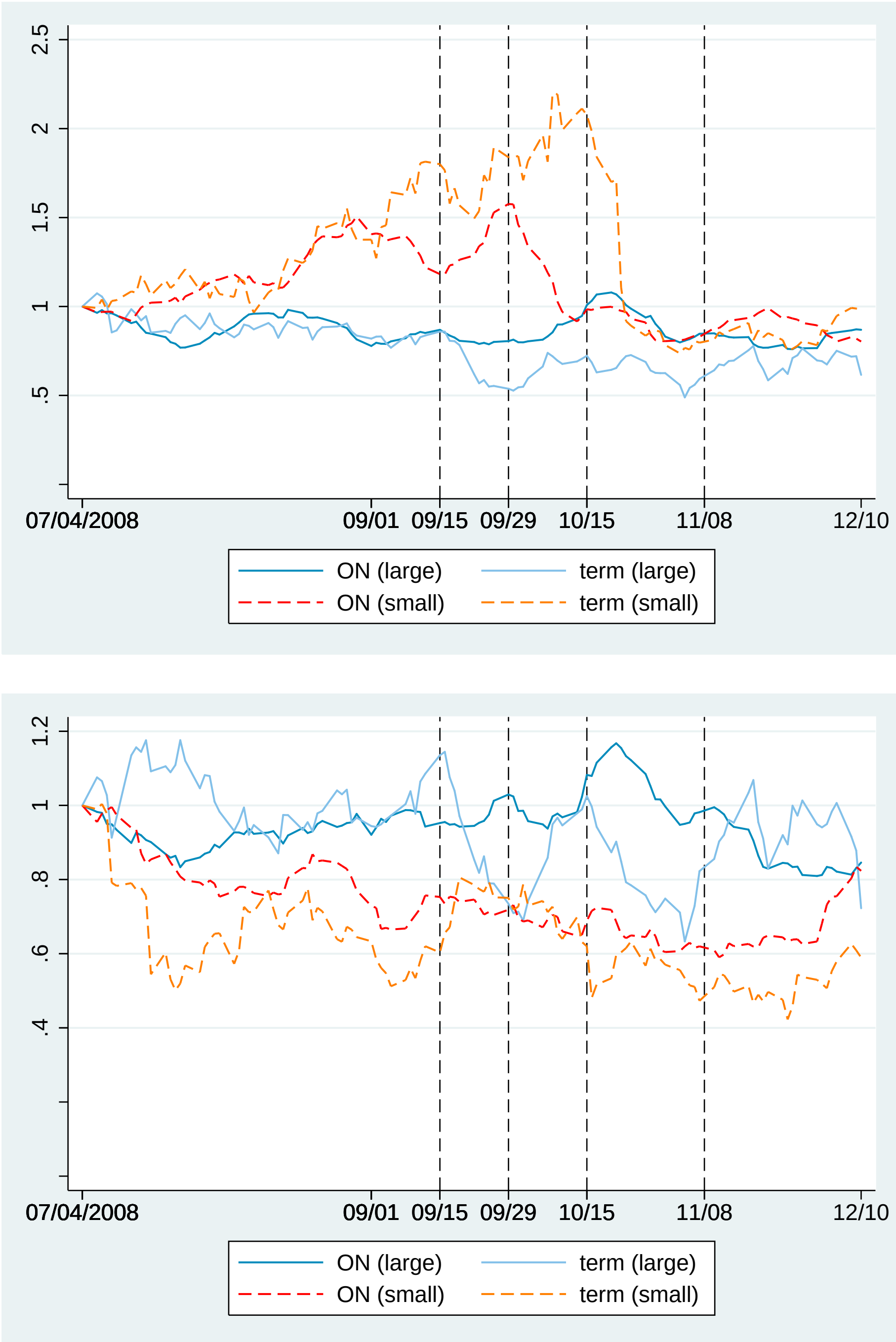

Figure 2: Normalized volume of lending (top) and borrowing (bottom) in the Euroarea interbank market by lender (top) and borrower (bottom) size between 04 July 2008 and 10 December 2008. Large (small) banks are in the upper (lower) tercile in terms of asset size as of end-2007. Dates indicate our five sample periods: (i) initial reference period (04 July - 21 July), (ii) pre-Lehman period (28 August - 12 September), (iii) post-Lehman period (15 September - 29 September), (iv) SRO period (30 September - 14 October), and full-allotment period (15 October - 30 October).

Table 1: Summary Statistics for Section 3

Panel A – ON Segment

	Amount			#Lender			Spread		
	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD
Init	648.343	160.0	1143.485	6.806	3.0	8.376	-0.032	-0.014	0.155
Pre	590.146	130.0	1104.222	6.335	3.0	7.589	-0.015	0.02	0.184
Monday 09/15	659.092	158.5	1243.87	7.018	4.0	8.209	0.123	0.102	0.11
Tuesday 09/16	642.428	173.9	1044.085	6.804	3.0	7.678	0.016	0.02	0.199
Post	671.273	150.0	1178.385	7.113	3.0	8.781	-0.064	0.0	0.267
SRO	570.355	165.0	1092.479	6.174	3.0	7.615	-0.076	-0.109	0.404
Full	505.625	150.0	944.405	5.087	3.0	5.767	-0.246	-0.309	0.247

Panel B – Term Segment

	Amount			#Lender			Spread			Maturity		
	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD
Init	150.04	33.2	341.768	2.547	2.0	2.797	0.04	0.007	0.093	36.488	19.0	50.758
Pre	132.666	30.74	271.567	2.366	1.0	2.813	0.047	0.008	0.11	38.802	17.568	56.591
Monday 09/15	93.262	22.0	201.497	1.941	1.0	1.741	0.06	0.019	0.119	69.769	30.0	90.054
Tuesday 09/16	60.979	30.0	85.024	2.0	1.0	1.675	0.071	0.014	0.143	39.994	24.25	51.728
Post	85.39	25.0	166.505	2.106	1.0	2.554	0.057	0.01	0.114	30.342	9.0	52.711
SRO	104.312	25.0	394.382	2.016	1.0	1.844	0.105	0.034	0.166	27.901	7.0	48.752
Full	88.516	28.5	169.046	2.005	1.0	1.824	0.068	0.006	0.139	35.797	8.333	61.607

Note: The dates for the periods are as follows. Init: 04 July - 21 July; Pre: 28 August - 12 September; Monday: 15 September; Tuesday: 16 September; Post: 17 September - 29 September; SRO: 30 September - 14 October; Full: 15 October - 30 October. We take a borrower perspective, so that #Lender is the number of lender a bank borrows from. Spread is measured as the difference of average interest rate to the main refinancing rate.

Table 2: Summary Statistics for Balanced Panel in Section 4.3

	Pre				Post			
	Total	Mean	Median	SD	Total	Mean	Median	SD
Volume [bn]	66.167				72.665			
#Loans	3064				3064			
#Lender	368				368			
Loan volume [mio]		21.595	73.838	2.5		23.716	79.379	3.636
Loan spread		0.759	1.731	0.142		0.571	1.142	0.136
#Borrower		19.939	13.201	20.0		19.939	13.201	20.0

Note: The pre sample starts on 28 August and goes until 12 September. The post sample starts on 15 September and goes until 29 September. Volume and Loan Volume are in Euros. Because the panel is balanced, the number of loans, the number of lender, and the mean, median and standard deviation of the number of borrowers per lender is the same in the pre- and post-sample. All values are end-of-year 2007 and obtained from Bankscope.

Table 3: The Impact of the Lehman Event on Borrowers.

Panel A: Overnight Segment

	Access	Amount		Spread		Counterparties	
	Probit	OLS	OLS	OLS	OLS	OLS	OLS
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Pre-Lehman	-0.063*	-58.197	-90.941*	0.017**	0.023***	-0.471	-0.749**
	(0.033)	(50.054)	(48.808)	(0.007)	(0.005)	(0.328)	(0.320)
Monday 09/15	-1.546***	10.749	-56.962	0.155***	0.161***	0.212	-0.213
	(0.048)	(82.476)	(79.808)	(0.009)	(0.008)	(0.479)	(0.435)
Tuesday 09/16	-1.606***	-5.915	-99.624	0.047***	0.053***	-0.002	-0.774*
	(0.050)	(86.159)	(86.777)	(0.017)	(0.016)	(0.469)	(0.410)
Post-Lehman	-0.156***	22.931	18.294	-0.032***	-0.028***	0.307	0.334
	(0.033)	(63.386)	(63.810)	(0.010)	(0.010)	(0.387)	(0.387)
SRO	-0.142***	-77.988	-149.345*	-0.044**	-0.059***	-0.632	-1.071*
	(0.043)	(75.493)	(83.554)	(0.021)	(0.021)	(0.584)	(0.627)
Full-allotment	-0.230***	-142.718	-270.051***	-0.215***	-0.223***	-1.719***	-2.624***
	(0.048)	(88.907)	(101.591)	(0.022)	(0.021)	(0.557)	(0.635)
Fixed Effects	No	No	Yes	No	Yes	No	Yes
N	7,834	6,385	6,385	6,385	6,385	6,385	6,385
Adjusted R^2		0.002	0.533	0.096	0.384	0.006	0.628

Panel B: Term Segment

	Access	Amount		Spread		Counterparties	
	Probit	OLS	OLS	OLS	OLS	OLS	OLS
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Pre-Lehman	0.042	-17.520	-17.849	0.009*	0.006	-0.183	-0.120
	(0.035)	(16.341)	(16.479)	(0.005)	(0.004)	(0.119)	(0.129)
Monday 09/15	-1.326***	-56.778**	-49.000**	0.031**	0.027*	-0.606***	-0.347**
	(0.062)	(23.959)	(24.324)	(0.015)	(0.016)	(0.181)	(0.148)
Tuesday 09/16	-1.610***	-89.061***	-92.879***	0.043**	0.043**	-0.547**	-0.533**
	(0.072)	(24.368)	(28.155)	(0.020)	(0.021)	(0.224)	(0.239)
Post-Lehman	-0.209***	-64.792***	-69.635***	0.019***	0.018***	-0.443**	-0.418*
	(0.036)	(21.292)	(23.635)	(0.006)	(0.006)	(0.187)	(0.225)
SRO	-0.174***	-45.204**	-55.014**	0.060***	0.056***	-0.530***	-0.554**
	(0.041)	(21.424)	(25.030)	(0.006)	(0.006)	(0.195)	(0.232)
Full-allotment	-0.116***	-60.446**	-75.820***	0.029***	0.028***	-0.506**	-0.619***
	(0.040)	(23.570)	(26.890)	(0.008)	(0.008)	(0.200)	(0.225)
Fixed Effects	No	No	Yes	No	Yes	No	Yes
N	5,450	3,646	3,646	3,646	3,646	3,646	3,646
Adjusted R^2		0.007	0.162	0.030	0.236	0.006	0.331

Note: Panel A (top) shows the reaction of the overnight segment of the interbank market to the Lehmen insolvency, Panel B (bottom) the reaction of the term ($1d \leq$ maturity $\leq 1yr$) segment.

Table 4: The Impact of the Lehman Event on Lenders.

Panel A: Overnight Segment

	Access	Amount		Spread		Counterparties	
	Probit	OLS	OLS	OLS	OLS	OLS	OLS
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Pre-Lehman	-0.065**	-4.796	-1.885	0.084***	0.078***	-0.147	-0.148
	(0.032)	(22.871)	(24.657)	(0.004)	(0.005)	(0.131)	(0.129)
Monday 09/15	-1.563***	-8.827	-24.880	0.223***	0.222***	-0.102	-0.206
	(0.050)	(48.948)	(52.237)	(0.007)	(0.009)	(0.191)	(0.202)
Tuesday 09/16	-1.660***	-12.281	-2.338	0.049***	0.056***	-0.014	-0.200
	(0.050)	(55.425)	(51.206)	(0.015)	(0.016)	(0.187)	(0.191)
Post-Lehman	-0.144***	22.140	38.514	0.035***	0.040***	0.204	0.252
	(0.035)	(41.777)	(42.720)	(0.008)	(0.009)	(0.171)	(0.170)
SRO	-0.189***	11.673	-9.023	-0.227***	-0.233***	0.035	-0.109
	(0.038)	(37.332)	(36.659)	(0.016)	(0.016)	(0.157)	(0.159)
Full-allotment	-0.179***	-15.658	-42.869	-0.703***	-0.707***	-0.066	-0.219
	(0.040)	(31.809)	(37.056)	(0.017)	(0.017)	(0.188)	(0.196)
Fixed Effects	No	No	Yes	No	Yes	No	Yes
N	$13,295$	$11,172$	$11,172$	$11,172$	$11,172$	$11,172$	$11,172$
Adjusted R^2		-0.000	0.541	0.502	0.597	0.001	0.604

Panel B: Term Segment

	Access	Amount		Spread		Counterparties	
	Probit	OLS	OLS	OLS	OLS	OLS	OLS
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Pre-Lehman	-0.041	3.949	2.339	0.026	0.038	-0.014	-0.018
	(0.042)	(14.294)	(12.705)	(0.038)	(0.042)	(0.081)	(0.086)
Monday 09/15	-1.485***	3.339	18.707	0.039	0.075	-0.055	-0.012
	(0.072)	(30.052)	(30.551)	(0.067)	(0.073)	(0.184)	(0.187)
Tuesday 09/16	-1.598***	-62.604***	-57.046*	-0.110	-0.080	-0.284**	-0.233*
	(0.077)	(17.507)	(29.449)	(0.071)	(0.075)	(0.144)	(0.140)
Post-Lehman	-0.377***	-11.797	-1.563	-0.011	0.029	-0.144	-0.149
	(0.051)	(19.898)	(14.231)	(0.040)	(0.049)	(0.099)	(0.104)
SRO	-0.289***	10.632	18.704	0.051	0.065	-0.182*	-0.106
	(0.050)	(22.536)	(21.499)	(0.043)	(0.047)	(0.104)	(0.079)
Full-allotment	-0.179***	-31.793*	0.189	-0.405***	-0.364***	-0.167**	-0.131*
	(0.053)	(16.683)	(12.205)	(0.041)	(0.045)	(0.076)	(0.078)
Fixed Effects	No	No	Yes	No	Yes	No	Yes
N	$5,773$	$3,279$	$3,279$	$3,279$	$3,279$	$3,279$	$3,279$
Adjusted R^2		0.002	0.344	0.069	0.188	0.002	0.183

Note: Panel A (top) shows the reaction of the overnight segment of the interbank market to the Lehmen insolvency, Panel B (bottom) the reaction of the term ($1d \leq$ maturity $\leq 1yr$) segment.

Table 5: Impact of Lehman Event on Borrower Access

	Overnight				Term			
	Large	Small	Large	Small	Large	Small	Large	Small
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-Lehman	-0.107	-0.125*	-0.193**	-0.141	0.041	0.090	0.131	0.062
	(0.066)	(0.073)	(0.084)	(0.134)	(0.071)	(0.074)	(0.082)	(0.105)
Monday 09/15	-1.332***	-1.678***	-1.393***	-1.569***	-1.226***	-1.401***	-1.078***	-1.342***
	(0.112)	(0.098)	(0.131)	(0.154)	(0.129)	(0.121)	(0.174)	(0.173)
Tuesday 09/16	-1.409***	-1.760***	-1.484***	-1.784***	-1.669***	-1.639***	-1.437***	-1.462***
	(0.120)	(0.088)	(0.139)	(0.144)	(0.117)	(0.154)	(0.149)	(0.211)
Post-Lehman	-0.145*	-0.171**	-0.283***	-0.127	-0.182***	-0.156**	-0.251***	-0.089
	(0.080)	(0.071)	(0.094)	(0.126)	(0.065)	(0.075)	(0.072)	(0.102)
SRO	-0.055	-0.176**	-0.141	-0.108	-0.174**	-0.106	-0.181	0.002
	(0.097)	(0.088)	(0.115)	(0.139)	(0.080)	(0.081)	(0.114)	(0.117)
Full-allotment	-0.239**	-0.275***	-0.336***	-0.237	-0.060	-0.166*	-0.073	-0.188
	(0.106)	(0.096)	(0.128)	(0.162)	(0.083)	(0.093)	(0.114)	(0.134)
Pre-Lehman×llr			-0.00001**	-0.001			0.00002***	0.001
			(0.000)	(0.001)			(0.000)	(0.001)
Monday 09/15×llr			-0.00004*	-0.003			0.000	0.003
			(0.000)	(0.002)			(0.000)	(0.002)
Tuesday 09/16×llr			-0.00004**	-0.002			0.00005***	-0.001
			(0.000)	(0.002)			(0.000)	(0.002)
Post-Lehman×llr			-0.00001***	-0.001			0.000	-0.001
			(0.000)	(0.001)			(0.000)	(0.001)
SRO×llr			-0.00001**	-0.001			-0.000	0.001
			(0.000)	(0.001)			(0.000)	(0.001)
Full-allotment×llr			-0.00001***	-0.001			0.000	-0.000
			(0.000)	(0.002)			(0.000)	(0.001)
Fixed Effects	No	No	No	No	No	No	No	No
N	2,617	2,618	2,617	2,618	1,828	1,838	1,828	1,838

Table 6: Impact of Lehman Event on Amount Borrowed

	Overnight				Term			
	Large	Small	Large	Small	Large	Small	Large	Small
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-Lehman	-15.897	-31.272	-121.607	-19.971	-11.781	0.013	0.597	-1.826
	(83.580)	(27.379)	(122.829)	(44.188)	(20.781)	(3.789)	(24.867)	(4.006)
Monday 09/15	50.663	-44.416	162.055	4.311	-28.681	-7.505*	22.506	-11.111*
	(146.412)	(31.025)	(146.990)	(36.883)	(29.299)	(4.345)	(29.048)	(6.472)
Tuesday 09/16	-118.438	-62.499	270.409	-49.364	-25.449	-5.061	-26.910	-6.057
	(138.670)	(46.566)	(188.503)	(70.471)	(24.296)	(6.718)	(24.563)	(8.063)
Post-Lehman	99.841	-19.466	115.431	-19.180	-28.564	-3.491	-27.411	-5.027
	(101.786)	(27.104)	(107.064)	(37.730)	(23.021)	(3.947)	(23.565)	(3.719)
SRO	102.118	-41.257	-57.506	-13.249	-11.825	-5.289	-3.275	-6.106
	(108.614)	(32.738)	(105.887)	(42.819)	(24.458)	(3.808)	(28.265)	(4.552)
Full-allotment	-75.521	-46.039	-331.0**	-36.074	-30.793	-2.969	-6.050	-14.609***
	(125.772)	(27.985)	(134.859)	(40.637)	(31.499)	(3.707)	(28.912)	(5.524)
Pre-Lehman×llr			-0.004	0.008			0.001	0.014
			(0.021)	(0.205)			(0.005)	(0.051)
Monday 09/15×llr			-0.033	-0.272			-0.005	0.009
			(0.026)	(0.240)			(0.004)	(0.046)
Tuesday 09/16×llr			-0.056	0.139			-0.004	-0.008
			(0.042)	(0.316)			(0.006)	(0.157)
Post-Lehman×llr			-0.005	0.200			0.000	0.009
			(0.021)	(0.186)			(0.005)	(0.060)
SRO×llr			-0.004	0.044			-0.003	0.030
			(0.022)	(0.191)			(0.006)	(0.065)
Full-allotment×llr			-0.005	0.062			0.001	0.140*
			(0.022)	(0.199)			(0.006)	(0.081)
Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	2,409	1,810	2,409	1,810	1,560	874	1,560	874
Adjusted R^2	0.770	0.595	0.776	0.645	0.757	0.545	0.761	0.545

Table 7: Impact of Lehman Event on Spreads

	Overnight				Term			
	Large	Small	Large	Small	Large	Small	Large	Small
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-Lehman	0.024***	0.020*	-0.000	0.049**	0.006	0.006	0.011	0.006
	(0.008)	(0.012)	(0.020)	(0.021)	(0.008)	(0.007)	(0.011)	(0.013)
Monday 09/15	0.157***	0.158***	0.142***	0.165***	0.005	0.064	0.008	0.092
	(0.011)	(0.021)	(0.026)	(0.037)	(0.011)	(0.056)	(0.015)	(0.095)
Tuesday 09/16	-0.021	0.133***	-0.007	0.125***	0.041	0.026	0.083	0.035
	(0.026)	(0.026)	(0.035)	(0.045)	(0.031)	(0.017)	(0.062)	(0.028)
Post-Lehman	-0.076***	0.025	-0.123***	0.018	0.017**	0.030**	0.030*	0.009
	(0.017)	(0.017)	(0.027)	(0.029)	(0.008)	(0.013)	(0.011)	(0.014)
SRO	-0.132***	0.061	-0.224***	-0.006	0.052***	0.061***	0.056***	0.070***
	(0.031)	(0.039)	(0.035)	(0.062)	(0.009)	(0.012)	(0.012)	(0.019)
Full-allotment	-0.296***	-0.126***	-0.358***	-0.119	0.031**	0.011	0.042**	-0.000
	(0.020)	(0.043)	(0.026)	(0.083)	(0.013)	(0.010)	(0.016)	(0.013)
Pre-Lehman×llr			0.000	-0.0003**			-0.000	-0.000
			(0.000)	(0.000)			(0.000)	(0.000)
Monday 09/15×llr			0.000	0.000			-0.000	-0.000
			(0.000)	(0.000)			(0.000)	(0.000)
Tuesday 09/16×llr			-0.000	0.000			-0.000005*	-0.000
			(0.000)	(0.000)			(0.000)	(0.000)
Post-Lehman×llr			0.000	0.000			-0.000001*	0.000
			(0.000)	(0.000)			(0.000)	(0.000)
SRO×llr			0.000	0.001**			-0.000	-0.000
			(0.000)	(0.000)			(0.000)	(0.000)
Full-allotment×llr			0.000	-0.000			-0.00002***	0.000
			(0.000)	(0.001)			(0.000)	(0.000)
Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	2,409	1,810	2,409	1,810	1,560	874	1,560	874
Adjusted R^2	0.333	0.480	0.346	0.488	0.207	0.410	0.206	0.418

Table 8: Impact of Lehman Event on Number of Counterparties

	Overnight				Term			
	Large	Small	Large	Small	Large	Small	Large	Small
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-Lehman	-0.615	0.117	-1.206	0.550	-0.262	0.183	-0.056	0.408
	(0.468)	(0.576)	(1.053)	(1.163)	(0.185)	(0.304)	(0.261)	(0.591)
Monday 09/15	0.201	0.034	1.242	0.606	-0.566**	-0.143	-0.155	-0.026
	(0.780)	(0.621)	(0.895)	(1.153)	(0.219)	(0.303)	(0.260)	(0.489)
Tuesday 09/16	-1.316*	-0.283	0.430	0.128	-0.420	-0.032	-0.402	0.317
	(0.715)	(0.515)	(1.015)	(0.778)	(0.423)	(0.386)	(0.550)	(0.741)
Post-Lehman	0.628	0.450	-0.582	0.962	-0.585*	0.190	-0.298	0.580
	(0.457)	(0.363)	(0.983)	(0.687)	(0.298)	(0.467)	(0.277)	(0.838)
SRO	-0.551	0.415	-1.564	1.074	-0.858**	-0.098	-0.230	0.112
	(1.063)	(0.467)	(0.824)	(0.847)	(0.352)	(0.167)	(0.337)	(0.339)
Full-allotment	-2.615***	-0.081	-3.393***	0.450	-0.748**	-0.329	-0.453	-0.543
	(0.849)	(0.536)	(1.261)	(1.099)	(0.334)	(0.265)	(0.322)	(0.446)
Pre-Lehman×llr			0.000	-0.004			0.000	-0.002
			(0.000)	(0.006)			(0.000)	(0.003)
Monday 09/15×llr			-0.000	-0.006			-0.000	-0.001
			(0.000)	(0.007)			(0.000)	(0.003)
Tuesday 09/16×llr			-0.000	-0.004			-0.000	-0.005
			(0.000)	(0.004)			(0.000)	(0.005)
Post-Lehman×llr			0.000	-0.005			0.000	-0.005
			(0.000)	(0.004)			(0.000)	(0.005)
SRO×llr			0.000	-0.005			0.000	-0.002
			(0.000)	(0.004)			(0.000)	(0.002)
Full-allotment×llr			0.000	-0.005			0.00005**	0.002
			(0.000)	(0.006)			(0.000)	(0.003)
Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	2,409	1,810	2,409	1,810	1,560	874	1,560	874
Adjusted R^2	0.735	0.722	0.738	0.724	0.453	0.275	0.494	0.267

Table 9: Global Network Measures

Panel A – ON Segment

	Volume	# Loans	# Borrower	# Lender	Density	Avg. Shortest Path Length	Diameter	Size of Largest Component	Fraction of Nodes in Largest Comp.	Betweenness	Katz Centrality
Initial	408.204	4185.0	331.0	670.0	0.0078	2.9	8.0	734.0	1.0	0.0062	0.0113
Pre-Lehman	371.208	3936.0	318.0	667.0	0.0074	2.97	9.0	716.0	0.98	0.0064	0.0116
Post-Lehman	402.657	4221.0	302.0	670.0	0.0077	2.91	7.0	730.0	0.99	0.0059	0.0115
SRO	329.777	3562.0	298.0	635.0	0.0073	3.0	7.0	689.0	0.99	0.0062	0.0092
Full-Allotment	260.312	2798.0	278.0	578.0	0.0066	3.11	7.0	638.0	0.98	0.0069	0.0073

Panel B – Term Segment

	Volume	# Loans	# Borrower	# Lender	Density	Avg. Shortest Path Length	Diameter	Size of Largest Component	Fraction of Nodes in Largest Comp.	Betweenness	Katz Centrality
Initial	125.974	2101.0	318.0	539.0	0.0044	3.33	7.0	664.0	0.96	0.006	0.0106
Pre-Lehman	123.916	2122.0	324.0	592.0	0.0041	3.43	11.0	692.0	0.96	0.0067	0.0106
Post-Lehman	78.537	1591.0	312.0	531.0	0.0035	3.75	10.0	636.0	0.95	0.0075	0.0105
SRO	99.41	1438.0	278.0	497.0	0.0036	3.79	10.0	602.0	0.96	0.0076	0.0032
Full-Allotment	68.804	1506.0	259.0	493.0	0.0042	3.54	8.0	548.0	0.91	0.0083	0.0112

Note: The dates for the periods are as follows. Init: 04 July - 21 July; Pre: 28 August - 12 September; Monday: 15 September; Tuesday: 16 September; Post: 17 September - 29 September; SRO: 30 September - 14 October; Full: 15 October - 30 October. We take a borrower perspective, so that #Lender is the number of lender a bank borrows from. Spread is measured as the difference of average interest rate to the main refinancing rate.

Table 10: The Interbank Lending Channel – Intensive Margin, Amount

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Borrowing	2.072***				2.068***			
	(0.053)				(0.052)			
#Lenders		0.198***				0.198***		
		(0.019)				(0.019)		
Betweenness			619.261***				618.901***	
			(95.809)				(93.018)	
Eigenvector				85.904***				86.041***
				(14.630)				(14.197)
Borrower fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3064	3064	3064	3064	3064	3064	3064	3064
R^2	0.675	0.419	0.374	0.430	0.676	0.422	0.378	0.430
Adjusted R^2	0.641	0.358	0.308	0.370	0.642	0.361	0.312	0.369

*p $<$ 0.1, **p $<$ 0.05, ***p $<$ 0.01. Standard errors in parentheses.

Note: Dependent variable is the change in log amount borrowed from bank i by bank j. *Borrowing* is the change in log amount borrowed by bank i, *# Lenders* is the change in the number of lender a bank i borrows from, *Betweenness* is bank i's change in betweenness centrality, and *Eigenvector* is bank i's change in eigenvector centrality. Changes are always computed as post-Lehman value minus pre-Lehman value. Controls include the total asset size, ratio of short-term to long-term funding, and loan loss reserves of lender i.

Table 11: The Interbank Lending Channel – Extensive Margin

Panel A – Exit

	(1) exit	(2) exit	(3) exit	(4) exit
Borrowing	-0.520^{***}			
	(0.078)			
#Lenders		-0.111^{***}		
		(0.030)		
Betweenness			-165.668^{***}	
			(32.463)	
Eigenvector				-16.763^{***}
				(4.625)
Borrower fixed effects	Yes	Yes	Yes	Yes
Observations	2691	2691	2691	2691

Panel B – Entry

	(1) entry	(2) entry	(3) entry	(4) entry
Borrowing	0.515^{***}			
	(0.049)			
#Lenders		0.075^{***}		
		(0.011)		
Betweenness			250.333^{***}	
			(86.773)	
Eigenvector				19.099^{***}
				(3.527)
Borrower fixed effects	Yes	Yes	Yes	Yes
Observations	2768	2768	2768	2768

*p < 0.1, **p < 0.05, ***p < 0.01. Standard errors in parentheses.

Note: The dependent variable is Panel A is $Exit_{ij}$, which equals one if a loan existed in the pre-Lehman sample, but is not renewed in the post-Lehman sample. The dependent variable in Panel B is $Entry_{ij}$, which equals one if a loan that exists in the post-Lehman sample did not exist in the pre-Lehman sample. *Borrowing* is the change in log amount borrowed by bank i, *# Lenders* is the change in the number of lender a bank i borrows from, *Betweenness* is bank i's change in betweenness centrality, and *Eigenvector* is bank i's change in eigenvector centrality. Changes are always computed as post-Lehman value minus pre-Lehman value. Controls include the total asset size, ratio of short-term to long-term funding, and loan loss reserves of lender i. All regressions have borrower fixed-effects and the sample is restricted to loans where the borrower bank borrows from at least two lender banks.

Table 12: The Interbank Lending Channel – Intensive Margin, Intermediation Spread

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Borrowing	0.121***				0.120***			
	(0.040)				(0.039)			
#Lenders		0.007**				0.007**		
		(0.003)				(0.003)		
Betweenness			27.518***				27.610***	
			(9.631)				(9.742)	
Eigenvector				16.548***				16.382***
				(3.715)				(3.545)
Borrower fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3064	3064	3064	3064	3064	3064	3064	3064
R^2	0.183	0.121	0.124	0.511	0.197	0.137	0.140	0.515
Adjusted R^2	0.097	0.028	0.032	0.460	0.112	0.045	0.049	0.463

$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. Standard errors in parentheses.

Note: Dependent variable is the intermediation spread bank i makes when lending to bank j, i.e. the difference between the interest rate of the loan from i to j minus the average refinancing cost of i. *Borrowing* is the change in log amount borrowed by bank i, *# Lenders* is the change in the number of lender a bank i borrows from, *Betweenness* is bank i's change in betweenness centrality, and *Eigenvector* is bank i's change in eigenvector centrality. Changes are always computed as post-Lehman value minus pre-Lehman value. Controls include the total asset size, ratio of short-term to long-term funding, and loan loss reserves of lender i.

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