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ABSTRACT

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We identify frictions in the market for liquidity as well as bank-specific and market-wide factors that affect the prices that banks pay for liquidity, captured here by borrowing rates in repos with the central bank and benchmarked by the overnight index swap. We have price data at the individual bank level and, unique to this paper, data on individual banks' reserve requirements and actual reserve holdings, thus allowing us to gauge the extent to which a bank is short or long liquidity. We find that the price a bank pays for liquidity depends on the liquidity positions of other banks, as well as its own. There is evidence that liquidity squeezes occasionally occur and short banks pay more the larger is the potential for a squeeze. The price paid for liquidity is decreasing in bank size and small banks are more adversely affected by an increased potential for a squeeze. Healthier banks pay less, but contrary to what one might expect, banks in formal liquidity networks do not.

JEL Classification: D44, E43, E58, G12 and G21
Keywords: banks, financial health, liquidity, money markets, repos and short squeezing

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Abstract

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Keywords: banks, liquidity, money markets, repos, short squeezing, financial health.
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1 Introduction

The recent financial crisis has brought to light the importance of the market for liquidity for the broader financial markets, as evidenced for example by the focus on the Libor - OIS spread as a gauge of the seriousness of the crisis.[1] The market for liquidity is used to meet short term funding needs and it underpins the business of banking. It is linked directly to securities markets through the role of securities as collateral in a variety of operations and transactions. As testified by the then Secretary of the Treasury, Henry M. Paulson Jr., and the Chairman of the Federal Reserve Board, Ben Bernanke, before the US House Financial Services Committee, September 23, 2008, during the crisis, the entire global banking and financial system were put at risk as liquidity was drying up.[2]

If turmoil in the market for liquidity can bring the global financial system to its knees, then it is important to enhance our understanding of this market. This is especially so because "...adverse financial conditions may prevent an economy from reaching its potential." (Bernanke, 2007). There is, for example, evidence that the recent turmoil led to reduced lending by banks to corporations (Ivashina and Scharfstein, 2008) and retail borrowers (Puri, Rocholl, and Steffen, 2009), which in the latter work is shown to be particularly due to a reduction in lending by liquidity-strapped banks. In this paper, we contribute by identifying frictions in the market for liquidity during pre-crisis times as well as other factors that affect the prices that banks pay for liquidity, captured here by borrowing rates in repos with the central bank and benchmarked by the overnight index swap. Our findings are potentially important for regulation and financial stability, since banks (with particular characteristics) that pay more for liquidity during times of normalcy may be more vulnerable during a liquidity crisis. Furthermore, insofar as conditions in the market for liquidity are transmitted to the broader financial markets, our findings may also have systemic risk and asset pricing relevance.

A large part of our efforts in this paper is directed towards examining the hypothesis

[1]Libor: London interbank offered rate. OIS: overnight index swap, a fixed-floating interest rate swap, where the floating leg is the overnight rate.

[2]See, e.g., http://blogs.wsj.com/economics/2008/09/23/bernanke-testimony-on-financial-markets-and-government-bailout/

that the distribution of liquidity across banks matters (Bindseil, Nyborg, and Strebulaev, 2009), and especially on the idea that more extreme liquidity positions leads to a tighter market where banks with liquidity shortfalls risk being squeezed or rationed by banks that are long (Nyborg and Strebulaev, 2004).[3] We find support for this. More generally, our findings show that the price a bank pays for liquidity is affected by the liquidity positions of other banks, as well as its own. This is especially significant since the sample period is taken from a time of relative normalcy, well before the onset of the current crisis. It also stands in contrast to a large swathe of asset pricing theory, where the distribution of an asset across agents is not a concern.

Liquidity can be obtained through numerous different types of contracts, varying in the degree and type of collateralization, tenor, and type of counterparty. Our data are from repos with the central bank. Specifically, we study the prices, or rates, German banks pay for liquidity in the European Central Bank's (ECB) main refinancing operation. These are the most significant sources of liquidity in the euro area.[4] During the sample period, June 2000 to December 2001, the average operation injected 84 billion euros of two-week money, against a broad set of collateral.[5] Over the crisis period, other central banks such as the Fed and the Bank of England have introduced similar operations to allow banks to obtain liquidity against an expanded set of collateral.

Unique to this paper, we have data on individual banks' reserve positions relative to what they are required to hold with the central bank. Thus we can measure the extent to which different banks are short or long liquidity. We are therefore in a unique position to address the fundamental questions as to whether the distribution of liquidity across banks matter and whether banks that are short liquidity fare worse in conditions when the theory says that the potential for the exercising of market power is larger.

[3]Related to this idea, Furfine (2000) finds evidence that there is a link between interbank payment flows and the federal funds rate.

[4]See, e.g., European Central Bank (2002a) or (2002b) for further information. See Hartmann and Valla (2008) for an overview of the euro money markets.

[5]Eligible collateral includes, but is not limited to, government bonds and covered bank bonds. See European Central Bank (2001) for detailed information regarding the various types of collateral that could be used in ECB main refinancing operations during the sample period.

Four other features of our data and the institutional setting make this ideal for studying differences across banks in the price paid for liquidity. First, during the sample period, the ECB's main refinancing operations are organized as discriminatory price auctions. Thus, different banks pay different prices, as a function of their bids. Second, these operations are open to all credit institutions in the euro area. Third, for each operation, we have all bids and allocations of all institutions from the largest euro area country (Germany). Fourth, all liquidity obtained in the operations have the same tenor (two weeks). Thus, since each operation provides us with a comprehensive set of bids and prices for collateralized loans of identical maturity at one point in time, they constitute a clean setting for studying the willingness to pay and the actual prices paid for liquidity by different banks.

Unique bank codes allow us to follow each bank over time and take account of bank specific characteristics such as size, type, and financial health. Size may matter because of economies of scale and scope. For example, diversification may make larger banks less exposed to liquidity shocks (Kashyap, Rajan, and Stein, 2002). Larger banks may also have better access to interbank markets, because they have larger networks of regular counterparties or because they possess a wider range of collateral. Larger banks may also put more resources into liquidity management, since they have more to gain from a reduction in the per unit cost of liquidity. Allen, Peristiani, and Saunders (1989) provide empirical evidence that there are differences in purchase behavior among differently sized banks in the federal funds market (see also Furfine 1999). With respect to the euro area, Nyborg, Bindseil, and Strebulaev (2002), Linzert, Nautz, and Bindseil (2007), and Craig and Fecht (2007) present evidence suggesting that large banks do better in ECB operations, but do not control for banks' liquidity positions.

Bank type may matter, for example because different types of financial institutions have different relationship networks to help them overcome frictions in the interbank market for liquidity (Freixas, Parigi, and Rochet, 2004). Empirical support for this idea is provided by Furfine (1999) and Cocco, Gomes, and Martins (2003). In Germany, every savings and cooperative bank belongs to formal networks of other savings and cooperative banks. Each network has its official and unique head institution through which liquidity is reallocated within the network. In contrast, private banks are left to their own devices. Ehrmann and Worms (2004) suggest that the formal liquidity networks of savings and cooperative banks can help them overcome disadvantages they may have due to being small. Thus, controlling for size and liquidity position, we might expect savings and cooperative banks to have an advantage over private banks and therefore pay less for liquidity. Savings banks (and their head institutions) have an additional advantage during the sample period in that regional governments guarantee the repayment of their borrowings.

Finally, as a bank's financial health decreases, it may face tighter conditions in the interbank market. This may result in a higher willingness to pay in repos with the central bank. We measure financial health by writeoffs and provisions, return on assets, and the equity ratio; with jumps in provisions and drops in return on assets and the equity ratio signifying poorer health.

Our analysis has three key elements. First, for each bidder in each operation in the sample, we calculate the *discount* and *underpricing* by subtracting the bidder's quantity weighted average rate bid and paid, respectively, from the contemporaneous two-week Eonia swap (the euro overnight index swap). This controls for time varying levels in interbank rates. Second, for each bank, whether bidding or not, we also calculate its size normalized liquidity position at the time of each operation, *the normalized net excess reserves*, based on the bank's reserve requirements, reserve fulfillment, and maturing repo from the operation two weeks back. Motivated by the theoretical results of Nyborg and Strebulaev (2004), we then calculate the liquidity *imbalance* as the standard deviation of the net normalized excess reserves across all German banks. Third, we run panel regressions, with and without a Heckman sample selection correction, of the discount and underpricing on various bank specific and market wide variables including, size, type, liquidity positions, financial health, and imbalance.

Our findings can be summarized as follows: i. Consistent with the view that market power/short squeezing is a feature of the market for liquidity, an increase in imbalance leads to smaller discounts and underpricing. Furthermore, the premium paid per unit that a bank is short is larger when the imbalance is larger. ii. Larger banks pay less. Furthermore, as imbalance increases, so does the extra cost of liquidity to smaller banks. Thus, smaller banks seem to be more vulnerable to liquidity squeezes. iii. Bank type matters, but perhaps not in the way we would expect; cooperatives have smaller discounts and underpricing than other banks and savings banks pay the same as private banks. This suggests that the liquidity networks of savings and cooperatives do not work well for all member institutions. iv. Banks pay more for liquidity as their financial health deteriorates.

To get an idea of the magnitudes in this market, the average auction has a price differential between the highest and lowest paying banks of 11.5 basis points (bp). On average, the 5% smallest banks pay in excess of 2 basis points more than the 1% largest banks. The average underpricing is 1.2 bp. By way of comparison, the average conditional volatility of the two-week interbank rate on main refinancing operation days is 5.3 bp.

Our results potentially have wide implications. The finding that banks suffer a higher price for liquidity as their financial health worsens suggests that banks are disciplined in the interbank market and that system wide tightness in the interbank market could result from a general deterioration in banks' financial health. In line with this reasoning, Acharya and Merrouche (2009) find evidence of precautionary liquidity hoarding by large settlement banks in the U.K. and that such hoarding contributed to increased interbank rates (relative to the policy rate) during the crisis. Furthermore, banks that hoarded more also had larger losses during the crisis. Tightening in the interbank market arising from squeezes, interbank credit rationing, or worsening financial health may, in turn, impact on asset prices, perhaps along the lines modelled by Allen and Gale (1994 and 2004) or Brunnermeier and Pedersen (2007 and 2009), and contribute towards commonality in liquidity across different securities and asset classes (Chordia, Subrahmanyam, and Roll 2000, Hasbrouck and Seppi 2001, Huberman and Halka 2001, Chordia, Sarkar, and Subrahmanyam 2005). Related to this, Nyborg and Östberg (2009) find that the Libor-OIS and TED spreads are associated with systematic stock market volume and price effects. Finally, the finding that large banks pay less for liquidity points to a source of competitive advantage to size in banking.[6]

This paper also relates to the literature on banking and liquidity spawned by Bryant

[6] Thus our findings may be relevant for the literature on the advantages and disadvantages to size in banking, see e.g., Peek and Rosengren (1998), Berger and Udell (2002), Sapienza (2002), and Berger, Miller, Petersen, Rajan, and Stein (2005).

(1980) and Diamond and Dybvig (1983), especially papers studying the functioning of the interbank market, among others Bhattacharya and Gale (1987), Donaldson (1992), Bhattacharya and Fulghieri (1994), and Allen and Gale (2000). Bhattacharya and Gale argue that aggregate liquidity shortfalls can occur as a result of banks free-riding on each other in providing liquidity. In the euro zone, the ECB's policy of adjusting the size of its operations to match the aggregate liquidity need of the entire banking system (ECB, 2002) should, in theory, solve this problem. But this also means that liquidity in the euro zone is tight. If one bank has more than it needs, another must have less, thus giving rise to the possibility of banks being able to exercise market power over marginal units, which our evidence suggests that they do from time to time.

The rest of this paper is organized as follows. Section 2 provides institutional background on the German banking sector, reserve requirements, and the role of the main refinancing operations. Section 2 also describes the datasets used in this paper. Section 3 defines liquidity status variables and provides descriptive statistics on these as well on discounts, underpricing, and other bidding measures. Section 4 studies the data cross-sectionally. Section 5 presents the panel analysis and provides the main results of the paper. Section 6 concludes.

2 Institutional Background and Data

2.1 The Structure of the German Banking Sector

The German banking system is traditionally a system of universal banking and has a three-pillar structure. The first pillar, the private domestic commercial banks, made up around 40% of the entire banking sector in terms of balance sheet total by the end of 2000. The second pillar are the public banks. This group comprises the savings banks and the savings banks' regional head institutions, the Landesbanks, which are jointly owned by the respective state and the regional association of savings banks. While the Landesbanks account for 20% of the German banking sector in terms of balance sheet total, the savings banks had around 16% of the German banking sector's asset under management by the end of 2000. The cooperative banking sector with the credit cooperatives and the cooperative central banks, which are primarily owned by the regional credit cooperatives, constitute the third pillar. They comprised 12% of the German banking sector of which the credit cooperatives accounted for 9 percentage points. Besides those major banking groups special purpose banks (like the Kreditanstalt für Wiederaufbau) and buildings societies (Bausparkassen) account for 7% and 2% of the banking sector, respectively. Branches of foreign banks operating in Germany made up 2% of the German banking sector by the end of 2000.[7]

This three pillar structure affects the way in which liquidity is reallocated in the banking sector. The public banks as well as the cooperative banking sector form a relatively closed giro system. On balance, the second-tier institutions – the savings banks and the credit cooperatives – typically achieve a significant liquidity surplus due to their retail business structure. Within the giro-systems, they pass this excess liquidity on to the respective (regional) head institution. Consequently, on average in the years 2000 and 2001 savings banks held almost 75% of their interbank overnight deposits with their respective Landesbank. At the same time only slightly more than 50% of savings banks' overnight borrowing was obtained from the regional Landesbank. Similarly, credit cooperatives granted more than 90% of their overnight interbank loans to one of the cooperative central banks, while they only received around 30% of their overnight interbank borrowing from the cooperative central banks. Conversely, the cooperative central banks obtained around 60% of the daily interbank liabilities from credit cooperatives, while Landesbanks, however, received less than 30% of their overnight interbank loans from the regional savings banks. Instead they obtained the majority of their short-term interbank funds from foreign banks.[8] Thus savings (i.e. public) and cooperative banks may have less of a need to participate directly in the market for reserves than private banks.

[7] For a more detailed description of the German banking sector see, for example, Hackethal (2004).

[8] For a broader discussion of the interbank linkages in the German banking sector in general and within the three pillars in particular see Deutsche Bundesbank (2000) and Upper and Worms (2004).

2.2 Minimum Reserve Requirements

According to ESCB (European System of Central Banks) regulation all German credit institution, including subsidiaries and branches of foreign banks in Germany, are subject to a minimum reserve requirement. The required reserves have to be held as average end-of-business-day balances over the maintenance period on account with the national central bank. During the sample period of this paper, reserve maintenance periods had a length of one month, starting on the 24th of each month and ending on the following 23rd, and German banks accounted for around 30% of total reserve requirements in the euro zone.

The basis for the calculation of a bank's reserve requirement is its end-of-calendar-month short-term liabilities held by non-banks or banks outside the euro area *two months before the beginning of the relevant maintenance period*.[9] For example, a bank's reserve requirements for the maintenance period starting May 24th are determined by its short term liabilities on March 31. The minimum reserve requirement is 2% of these liabilities. Thus banks that are financed primarily with short-term liabilities are required to hold relatively more reserves. Compliance with reserve requirements is a hard constraint; unlike the US, these cannot be rolled over into the next maintenance period.[10] Thus, banks cannot alter their reserve requirements within a maintenance period.

The required reserve holdings are remunerated at the average stop-out rate of the ECB main refinancing operations, during the respective maintenance period. Reserve holdings

[9] More precisely, these are the overnight deposits, deposits with an agreed maturity up to two years, deposits redeemable at notice up to two years, and issued debt securities with agreed maturity up to two years.

[10] If a bank fails to hold sufficient reserves, for example because it fails to make up a reserve shortfall at the marginal lending facility, the ECB can impose any of the following sanctions: It can require payment of 1) up to 5 percentage points above the marginal lending rate or 2) up to two times the marginal lending rate on the difference between the required and the actually held reserves. Furthermore, the ECB can call for the provision of non-interest bearing deposits up to three times the amount the respective bank failed to provide for. The maturity of those deposits must not exceed the period during which the institution failed to meet the reserve requirement. The ECB can impose additional sanctions if an institution repeatedly fails to comply with the reserve requirement. For a more detailed description of the Eurosystem's minimum reserve system see European Central Bank (2005).

that exceed the minimum requirement are not remunerated, but can be transferred to the standing deposit facility which is always 100 basis points below the minimum bid rate in the auctions during the sample period. The ECB also operates with a marginal lending facility, where banks can borrow against collateral at a rate which is 100 basis points above the minimum bid rate in the auction during the sample period.

2.3 Main Refinancing Operations

There is a main refinancing operation (or repo auction) every week, each with a tenor of two weeks during the sample period.[11] Thus there are up to five operations within each reserve maintenance period. Each operation is timed to coincide with the maturity of funds obtained in the second-to-previous operation. The operations are scheduled well in advance; the intended timing of all regular operations in a year are announced three months before the start of the year. Typically, the operations are scheduled for Tuesdays, 9:30 am, with terms being announced on Mondays, 3:30 pm. Results are announced on the auction day at 11:20 am. Winning bids are settled the following business day. The operations are open to all banks in the European Monetary Union that are subject to reserve requirements.

In each operation, or auction, each bidder can submit up to 10 bids which are rate-quantity pairs for two week money. The tick size is 1 basis point and the quantity multiple is 100,000 euros. There are no non-competitive bids. There is a pre-announced minimum bid rate. This rate is determined at the meetings of the ECB's Governing Council, normally held on the first and third Thursday of each month during the sample period. The minimum bid rate was changed six times during the sample period. It started out at 4.25%, changed to 4.5% in time for the 5 September 2000 auction, then increased to 4.75% in time for the 11 October 2000 auction, fell back to 4.50% for the auctions held on and after 14 May 2001, fell further to 4.25% for the auction on and after 4 September

[11] Once a month, the ECB also holds *longer-term refinancing operations* with a maturity of three months. We do not study these operations. See Linzert et al (2007). The ECB may also hold non-regular, fine-tuning operations with non-standard maturities, for example overnight, but none occurred during the sample period.

2001, to 3.75% on 18 September 2001 and to 3.25% on 13 November 2001, at which level it remained until the end of the sample period.

At the time of the auction announcement, the ECB publishes an estimate of liquidity needs for the entire euro area banking sector for the following week. Given the ECB's neutral allotment policy, this provides bidders with an unbiased estimate of the auction size. We refer to this liquidity neutral amount as the expected auction size. Deviations may occur because of the lag between the auction announcements (Mondays, 3.30pm) and the allotment decision (Tuesdays, 11.20am). During this period, the ECB may have updated its forecast of the banking sector's liquidity needs. Deviations from the expected auction size also occur in a few instances where banks in aggregate demanded less than the liquidity neutral amount, speculating on decreases in the minimum bid rate in time for the next auction in the maintenance period. However, deviations tend to be very small, averaging to less than 1% of the pre-announced liquidity neutral amount. Thus, bidders face little supply uncertainty in these auctions.

2.4 Data

Our analysis makes use of four data sources supplied by the Bundesbank. First, we have the complete set of bids made by German registered financial institutions, broken down by bidder, in all 78 ECB repo auctions (main refinancing operations) in the period 27 June 2000 to 18 December 2001. This covers 18 reserve maintenance periods. The number of German bidders in an auction varies from 122 to 546.

Second, we have reserve data from *all* 2,520 German registered financial institutions in the period May 2000 to December 2001 that were required to hold reserves with the central bank as of December 2001. The reserve data covers 842 bidders in the main refinancing operations and 1,678 non-bidders. A bidder is defined as a bank that bids at least once and therefore appears in the auction dataset. The reserve data consists of each institution's cumulative reserve holdings within the maintenance period, as well as its marginal reserve holding, at the end of each business day preceding an auction. In addition, we have each institution's reserve requirement for each maintenance period over the sample period. The reserve data are not available for 518 institutions that ceased operating as stand-alone entities during the sample period. 17 of these submitted bids in the auctions.

Third, we have end-of-month balance sheet data for each bank. German banks are required to report balance sheet statistics to the Bundesbank on a monthly basis. As a measure of size, we thus use the book value of a bank's total assets at the end of each calendar month.

Fourth, we have yearly income statements, from which we obtain writeoffs and provisions and return on assets for each bank. The third financial health variable, the equity ratio, is calculated from the balance sheet data on a monthly basis.

Unique bank codes allow us to track banks over time and correlate bidding decisions with characteristics such as size, financial health, and fulfillment of reserves. The complete bidding data consists of 59,644 individual bids and 25,345 individual demand schedules from 859 bidders. Deleting the bids from the 17 bidding banks for which we do not have reserve data reduces this to 59,156 individual bids and 25,120 individual demand schedules from 842 different bidders. We lack balance sheet data on 7 bidders, taking the number of bidders for which we have complete data down to 835.

The dataset is pruned further as follows: First, we exclude 45 banks that are registered with zero reserve requirement in every maintenance period during the sample period. Second, we throw out two extreme outliers; the first is a non-bidder that has an average reserve fulfillment (relative to required reserves) of 190,926%. The second is a bidder with an average reserve fulfillment of 3,011%. Without this bank, the average fulfillment of private domestic bidding banks is 100.1%; with this bank, the average is 131.8%. The next highest average reserve fulfillment among private banks is 146.8%. This takes the dataset down to 834 bidders and 1,632 non-bidders. Third, we exclude Bausparkassen and special purpose banks (14 institutions)[12]. The analysis below is thus carried out on a final set of 820 bidders (and 23,673 individual demand schedules) and 1,632 non-bidders.

[12]These institutions have very low reserve requirements, averaging to around 0.1% of total assets. This is substantially lower than for other banking sectors, reflecting that they have different functions than typical banks. The Bausparkassen sector also includes several extreme outliers with respect to reserve fulfillment.

3 Descriptive Statistics: Bank Characteristics, Pricing, and Bidding

The summary statistics we present in this section break our dataset out in two ways. First, we differentiate between bidders, i.e. those banks that submit bids in at least one auction, and non-bidders. Second, within these two categories, we differentiate between six different types of banks, as described above; private banks (domestic), savings banks, cooperatives, branches of foreign banks, Landesbanks, and cooperative central banks.

3.1 Bank Characteristics

3.1.1 Definitions of Liquidity Status Variables

To measure banks' liquidity status, we focus on the variables "fulfillment" and "normalized net excess reserves", described below. These are different ways of gauging the extent to which a bank is short or long reserves going into an auction.

Fulfillment is a bank's cumulative reserve holdings as a percentage of its cumulative required reserves, within a reserve maintenance period.

$$\text{fulfillment}_{ijp} = \frac{\text{cumulative holding}_{ijp}}{\text{cumulative required reserves}_{ijp}} \times 100, \tag{1}$$

where i refers to the bank, j to the auction, and p to the reserve maintenance period. Multiplying by 100 means that we express fulfillment as a percentage. The fulfillment is measured for each bank using reserve data at the close business the day before each auction. A fulfillment of 100% means that the bank has held reserves thus far in the maintenance period with a daily average exactly equal to the average daily requirement the bank faces this period. Thus, a fulfillment of less (more) than 100% indicates that the bank is short (long).

To define normalized net excess reserves, we start with the "gross excess reserves". This compares the reserves the bank has on deposit with the central bank the evening before the auction with what it needs to hold on a daily basis for the balance of the reserve maintenance period in order to exactly fulfill reserve requirements.

$$\text{gross excess reserves}_{ijp} = \text{holding}_{ijp} - \text{required remaining daily holding}_{ijp}, \tag{2}$$

where

$$\text{required remaining daily holding}_{ijp} = \frac{\text{required total monthly reserves}_{ip} - \text{cumulative holding}_{ijp}}{\text{days left of maintenance period}_{jp}}. \tag{3}$$

The "net excess reserves" nets out from a bank's holding the loan from two auctions ago that matures at the time of the current auction.

$$\text{net excess reserves}_{ijp} = \text{gross excess reserves}_{ijp} - \text{maturing repo}_{ijp} \tag{4}$$

where maturing repo_{ijp} is the amount the bidder won in auction $j-2$. Since this amount matures at the time of auction j, the net excess reserves is what the bank needs to borrow in the auction in order to be even with respect to its reserve requirements. A negative (positive) net excess reserves is indicative of the bank being short (long).

We normalize the net excess reserves for size by dividing it by the average daily required holding:

$$\text{normalized net excess reserves}_{ijp} = \frac{\text{net excess reserves}_{ijp}}{\text{average daily required reserves}_{ip}} \times 100. \tag{5}$$

In a similar way, we also define the "normalized gross excess reserves" by dividing the gross excess reserves by the average daily required reserves.

The normalized net excess reserves measure takes into account not only a bank's fulfillment thus far in the maintenance period, but also its liquidity need going forward, including the need to refinance maturing repos. For this reason, this measure is arguably a better indicator of liquidity need than fulfillment, and we therefore use it in the regression analysis. Normalization by required reserves means that the measure is independent of size, allowing us to distinguish between size and pure liquidity status effects. A bank that always has a fulfillment of 100% and borrows in every auction (borrows in no auction) will have negative (zero) normalized net excess reserves going into every auction.

3.1.2 Financial Health Variables

We capture a bank's financial health by three variables: (i) Writeoffs and provisions, measured annually as the writeoffs and provisions on loans and securities as a percent of total assets; (ii) Return on assets (ROA), measured annually as net income as a percent of total assets; (iii) Equity ratio, measured monthly as total book equity as a percent of total assets.

3.1.3 Summary Statistics

Table 1 provides summary statistics on the above bank characteristic variables as well as asset size and reserve requirements, broken down into the six bank categories. Table 2 does the same for non-bidding banks, but in this case there are only four bank categories since there are no Landesbanks or cooperative central banks that have not submitted bids in the auctions over the sample period. Comparing these two tables reveals that the average bidder differs substantially on two key dimensions from the average non-bidder.

First, category by category, bidders are larger than non-bidders by both asset size and reserve requirements. For example, for bidding private banks these measures average to (in euros): 22,794 mill (asset size) and 132.43 mill (average daily reserve requirement). The corresponding numbers for non-bidders are: 1,478 mill and 6.99 mill.

Second, bidders are shorter liquidity than non-bidders. For bidders, the average normalized net excess reserves is negative for all bank categories; whereas it is positive for non-bidders. So by this measure, bidders are short going into the auctions, while non-bidders are long. The average fulfillment is also smaller for bidders than it is for non-bidders. For example, for private banks: the average normalized net excess reserves is -243.82%, with a median of -83.39%; while for non-bidders the mean and median are 210.83% and 24.93%, respectively; and the mean and median fulfillment are 100.25% and 101.81% for bidders as compared with 169.61% and 108.13% for non-bidders. To summarize, non-bidders are comparatively small and long, while bidders are comparatively large and short.

With respect to the financial health variables, things are less clear cut. For all bank types, non-bidders have larger mean and media ROA's than bidders. So by this measure, non-bidders can be said to be financially more healthy. However, across the different bank types, we see both positive and negative differences between bidders and non-bidders with respect to mean and median writeoffs and provisions. The same holds true for the equity ratio. For private banks that bid in at least one auction, the mean (median) loan loss provision, ROA, and equity ratio are 0.35% (0.21%), 0.34% (0.21%), and 4.96% (4.06%), respectively. The corresponding numbers for non-bidders are 0.73% (0.31%), 0.89% (0.25%), and 13.8% (8.58%).

The tables also show significant differences across bank categories. Focusing on Table 1 (bidders), we see that Landesbanks and cooperative central banks are substantially larger than the other categories, including the private banks. Mean asset values are (in euros) 96,918 mill for Landesbanks, and 60,320 mill for cooperative central banks, as compared with 22,794 mill for private banks, 2,092 mill for savings banks, 678 mill for cooperatives, and 2,256 mill for branches of foreign banks. So, on average by asset value, Landesbanks and cooperative central banks are up to 4.5 times larger than private banks. At the same time, private banks are approximately 10 times larger than savings and foreign banks, which in turn are approximately 3 times as large as cooperatives. The smallest asset value in the sample is 25.96 million (a cooperative), and the largest value is 267,591 million (a domestic private bank).

Mean daily reserve requirements for bidders are: 132.4 million for private banks, 22.1 million for savings banks, 7.8 million for cooperatives, 17.1 million for foreign banks, 352.0 for Landesbanks, and 241.2 for cooperative central banks. By this measure, Landesbanks and cooperative central banks are on average about 2.5 times larger than private banks. Private banks are almost 6 times larger than savings banks, almost 8 times larger than foreign banks, and approximately 17 times larger than cooperatives. The largest average daily reserve requirement is 2,901.6 million (a domestic private bank). This is quite small in comparison to a typical auction size of around 90 billion.

There are also differences in liquidity status among bidding banks. As noted above, private domestic banks have a mean fulfillment of 100.25% . Savings banks and cooperatives have similar mean fulfillments, 102.65% and 102.94%, respectively. The mean fulfillment across foreign institutions is 142.30%. Landesbanks have the lowest fulfillment, 82.44%, while cooperative central banks have a fulfillment of 99.00%. So, on average, as measured by fulfillment, German private domestic banks, savings banks, and cooperatives are slightly long, while cooperative central banks and in particular Landesbanks are short going into the auctions. However, taking into account maturing repos, all categories of banks are on average short going into the auctions, as seen by the negative mean and median normalized net excess reserves. Again, Landesbanks and cooperative central bank appear to be shorter on average than the other bank categories. There is also substantial variation across individual banks. The smallest average fulfillment among bidders is 50.85% (a private bank) and the largest is 685.95% (a foreign bank). The normalized net excess reserves varies from $-3,739.82\%$ (a private bank) to 968.01% (a foreign bank).

3.2 Pricing and Bidding Measures and Statistics

Table 3 reports on various pricing and bidding variables, by bank type. It focuses on different bank categories' willingness to pay for liquidity and how much they actually pay. This table draws on all banks that bid at least once. For each bank, we measure the relevant variables first for each individual demand schedule (i.e. across the bidders' set of bids in a given auction). Then we average across demand schedules for each bank to obtain a population of bank level observations, whose summary statistics are reported in the table.

To benchmark bids and rates paid in the main refinancing operations, we use the two week Eonia swap rate taken as the midpoint of the bid and ask from Reuters quotations at 9:15 a.m. on the auction day. Our pricing variables are:

- Underpricing: This is a measure of the price paid by bidders relative to the contemporaneous swap rate. It equals the swap rate less the bidder's quantity weighted average winning bids. We borrow from the IPO (initial public offerings) and auction literatures and call this spread underpricing because the rate paid is typically below the contemporaneous swap rate (midpoint of the bid and ask).

- Relative underpricing: a bidder's underpricing in a given auction less the average underpricing in that auction across bidders (in the sample).

- Discount: This is a measure of the willingness to pay. It equals the swap rate less the bidder's quantity weighted average bid rate.[13]

- Relative discount: a bidder's discount in a given auction less the average discount in that auction across bidders.

The price of liquidity can be said to be higher the lower is the underpricing or the relative underpricing.

In addition to the pricing variables, we also report on a number of bidding variables, which help provide a more comprehensive picture of banks' bidding decisions.

- Stopout deviation: the quantity-weighted standard deviation of bids around the stopout rate.[14] This is a measure of how well a bank predicts the stop-out rate and therefore affects what it pays for liquidity. A small stop-out spread will tend to result in a relatively large underpricing.

- Award ratio: a bidder's award in an auction as a percentage of his demand.

- Demand to reserve requirement: demand (summed across individual bids) divided by the bank's reserve requirement (in the maintenance period where the auction occurs).

- Award to total award: a bidder's award in an auction as a percentage of aggregate award in that auction to financial institutions registered in Germany.

- Bidding frequency: percentage of auctions a bank participates in.[15]

- Number of bids: the number of interest rate-quantity pairs.

There are substantial differences across bank categories in the prices paid for liquidity, as captured by underpricing and relative underpricing. Private banks have an average

[13]We call this quantity discount because the rate bid is typically below the contemporaneous swap rate (midpoint of the bid and ask).

[14]The stopout, or marginal, rate is the rate of the lowest winning bid.

[15]This means that, unlike the other variables in this list, bidding frequency is not an average across a bank's demand schedules in different auctions.

underpricing and relative underpricing of 1.24 bp and 0.07 bp, respectively. For savings banks, the corresponding numbers are 1.66 bp and −0.01 bp; for cooperatives they are 0.78 bp and −0.87 bp; for foreign banks they are 0.69 bp and −0.18 bp; for Landesbanks they are 1.48 bp and 0.53 bp, and for cooperative central banks they are 2.82 bp and 0.51 bp. Thus Landesbanks are the best performers, having a relative underpricing which is 1.40 bp higher than cooperatives, which are the worst performers. The Landesbanks are closely followed by the cooperative central banks.[16]

We see very similar results when we analyze the willingness to pay for liquidity across different bank categories, as captured by discount and relative discount. Private banks have an average discount and relative discount of 3.04 bp and 0.14 bp, respectively. For savings banks, the corresponding numbers are 3.32 bp and −0.09 bp; for cooperatives they are 3.47 bp and −0.18 bp; for foreign banks they are 2.84 bp and −0.15 bp; for Landesbanks they are 2.83 bp and 0.50 bp, and for cooperative central banks they are 4.27 bp and 0.45 bp. Thus Landesbanks and cooperative central banks, followed by the private banks, are willing to pay less for liquidity than the rest of the banks.

The stopout deviation captures the banks' ability to correctly predict the stopout rate in a given auction. It is lowest for the Landesbanks, 1.04 bp, and cooperative central banks, 1.17 bp, and highest for the cooperatives, 2.80 bp. These results are thus consistent again with the larger relative underpricing we observe for the Landesbanks and cooperative central banks.

The award ratio measures the relative aggressiveness of a bidder. An award ratio of 100% in a given auction means that all of a bidder's bids won, i.e. all his bids were above the stop-out rate. Thus the bidder can be said to have been highly aggressive relative to other bidders. An award ratio of 0 is indicative of very cautious bidding. Cooperative central banks have the lowest award ratio, 42.34%, followed by the Landesbanks with an

[16] A caveat with respect to using the raw underpricing number, instead of the relative underpricing, to gauge what banks pay relative to each other is that the raw underpricing measure gives more weight to the early auctions in the sample period, since these auctions had a higher participation rate (see Nyborg et al (2002) for a discussion of the decreasing time trend in the number of bidders). Since interbank rates were higher around these auctions, the underpricing in these auctions was higher than in later auctions.

award ratio of 48.54%. There are only relatively small differences in award ratios across the other bank categories. The range is from 54.90% for private banks to 58.97% for cooperatives.

The award to total award varies between 0.03% (cooperatives), 0.09% (savings), 0.17% (foreign), 0.63% (private), 1.45% (cooperative central banks), and 1.68% (Landesbanks). The maximum is 11.58% (a private domestic bank). These numbers illustrate how small any bank in this market is compared to the market size.

The average demand to reserve requirement ratio goes from 249.83% (cooperatives) to 1221.95% (cooperative central banks). These high averages are influenced by some extremely large observations. The largest single observation is 12,124.14% (a private bank).

Landesbanks participate more frequently than other banks, specifically they bid on average in 80.45% of the 78 auctions. Cooperative bidders participate in the fewest number of auctions, only 27.51%. As seen by comparing Tables 1 and 2 the cooperative sector also has the smallest participation rate, as measured by the percentage of banks in the sector that bid at least once. The average number of bids per demand schedule varies from 1.87 (foreign banks) to 3.51 (cooperative central banks).

The univariate statistics for the pricing and bidding variables in this section do not control for bank characteristics, except for type, or market conditions. This will be addressed in the subsequent regression analysis.

4 Cross-Sectional Regressions

In this section, we take a preliminary look at to what extent the bank characteristics discussed above affect the prices banks pay for liquidity by running cross-sectional regressions. This analysis is refined in the next section where we take advantage of the panel structure of the data, which allows us to incorporate market conditions and banks' liquidity status at the time of each operation into the analysis. The cross-sectional regressions in the current section are arguably most relevant for features that are permanent or relatively time invariant, such as bank type and size.

For each bidding bank, we consider the following dependent variables, as averages across the auctions where the bank participated or won some units:[17] underpricing, relative underpricing, discount, relative discount, stopout deviation, award ratio, and demand to reserve requirements. As independent variables, we employ for each bank: the natural log of the bank's assets, the net normalized excess reserves, writeoffs and provisions, return on assets, and equity ratio, all as averages over the sample period. We also include bank sector dummy variables for savings, cooperatives, foreign banks, Landesbanks, and cooperative central banks, thus taking private domestic banks as the benchmark. Finally, to examine whether small banks are especially sensitive to being short, for example due to being more vulnerable to predation along the lines of Carlin, Lobo, and Viswanathan (2007), we include an interaction variable, small×nex, where small is a dummy variable that takes 1 if the bank has average assets of less than 100 million euros over the sample period and 0 otherwise. The expression *nex* is shorthand for the normalized net excess reserves. Standard errors are adjusted for heteroscedasticity by using the Huber/White estimate of variance.

Results are reported in Table 4. The price of liquidity decreases in bank size. The coefficient on ln(assets) in the relative underpricing regression is .186 and is statistically significant at the 1% level. In other words, an increase in size (in millions) by a factor of e leads to a .186 bp increase in relative underpricing. In the (plain) underpricing regression, the coefficient is .146. The smaller underpricing of larger banks can be explained by two factors: (i) They bid at lower rates; the regression coefficient on ln(assets) in the discount regression, for example, is -.201 (significant at the 10% level). (ii) Larger banks cluster their bids closer around the stop-out rate; the regression coefficient on ln(size) in the stopout deviation regression is -.320 (significant at the 1% level). Thus, larger banks tend to win with lower bids than smaller banks. These results can also be seen from simple sorts on size. For example, the 5% and 6-10% smallest banks have an average underpricing of -1.33 bp and -.39 bp; whereas banks in the 98th and 99th size percentiles have average underpricings of -.80 bp and .76bp.[18]

[17]Underpricing and relative underpricing can only be calculated conditional on winning. The other dependent variables are calculated conditional on bidding.

[18]The average size of banks in these groups are 71.22, 130.6, 23,995.47, 105,928.50 (all in millions of

With respect to bank type, the most notable result is that cooperative banks have a lower underpricing than other banks. They pay a significant .395 bp more for liquidity than private banks.

The regression coefficients on the normalized net excess reserves and the small×nex interaction variable suggests only a weak relation between a bank's typical liquidity position and the underpricing and discount variables. Moreover, for the normalized net excess reserves, the sign in one of the four pricing regressions is negative, rather than positive, as one would expect from a short squeezing line of argument. However, since a bank's liquidity position changes over time, cross-sectional regressions are not the appropriate way to examine the effect of liquidity positions.

With the exception of the equity ratio, the financial health variables are statistically insignificant in all regressions. Surprisingly, an increase in the equity ratio is associated with a significantly higher willingness to pay for liquidity, as seen from its coefficients of -.178 and -.114 in the discount and relative discount regressions, respectively. The coefficients in the two underpricing regressions are negative too, but only (marginally) significant in one of them. However, these regressions also ignore time variation in the equity ratio as well as operation specific market conditions.

5 Panel Regressions

This section contains the main analysis of the paper. We start by running plain panel regressions on the sample of bidding banks, examining the impact on the key pricing and bidding variables of a range of bank characteristics and market conditions. We then examine the robustness of these findings by running Heckman selection regressions to take into account a bank's decision to participate in a given auction, using bidding as well as non-bidding banks.

euros) for the 0-5th, 6-10th, 98th, and 99th percentiles, respectively. Details and further results on size sorted groups are available in an earlier version of this paper.

5.1 Explanatory Variables

The explanatory variables can be divided into five categories. First, we have the (more or less) permanent basic bank characteristics, ln(assets) and bank type. Second, we have liquidity condition variables, which include a temporary bank characteristic, normalized net excess reserves; a market condition, imbalance; and three interaction variables, small×nex, imbalance×nex, and imbalance×ln(assets).[19] Third, we have the bank characteristics that relate to financial health; writeoffs and provisions, return on assets, and equity ratio. Fourth, we have auction specific market conditions, expected auction size and the size ratio. Fifth, we have interbank rate variables, the swap spread, the negative swap spread, and volatility. These are described in more detail below (but not the bank characteristics, which are discussed in earlier sections).

Liquidity position variables: We use our reserve position data to calculate a measure of imbalance in the market. In particular, for each operation, we define *imbalance* to be the standard deviation of the normalized net excess reserves across all banks, bidders and non-bidders alike. The purpose of including this variable in our regressions is to examine the hypothesis that liquidity is more expensive when there is a greater imbalance in liquidity positions across banks. For each bank, we interact imbalance with the normalized net excess reserves (nex), in order to examine the extent to which more short banks may be more vulnerable to a greater imbalance in the market. Under the hypothesis that short squeezing is an issue, Nyborg and Strebulaev (2004) show that a more extreme dispersion of holdings across banks leads to more aggressive bidding by shorts that are subject to the possibility of being squeezed as well as by banks that have sufficient market power to implement a squeeze. Given the importance of bank size, documented in the previous section, we also interact imbalance with ln(assets) to examine the extent to which smaller banks may have a further disadvantage in more imbalanced markets.

Operation specific market conditions: Under the hypothesis that positions matter and that short squeezing may be a concern, we would expect that the price of liquidity is larger when the operation offers a poor opportunity for refinancing maturing loans from

[19] Recall that nex is the normalized net excess reserves.

the operations two weeks ago. To examine this, we define the *size ratio* to be the expected size of the current operation as a percentage of the size of the operation two weeks ago, and which now needs to be refinanced. To control for the absolute size of an auction, we include the *expected auction size*, defined as the liquidity neutral amount as announced by the ECB the afternoon before the operation.

Interbank rate variables: (i) *swap spread*. This is the two week Eonia swap rate at 9:15 on operation days (see above) less the minimum bid rate in the auction. Since bidders cannot submit bids below the minimum bid rate, the swap spread puts an upper bound on a bidder's underpricing and discount. (ii) The conditional *volatility* of the Eonia swap rate on operation days. This is calculated using a modified GARCH model, based on daily observations at 9:15 am (see Appendix 2) in the period 4 January 1999 to 20 December 2001. (iii) The *negative swap spread* is a dummy variable which is 1 if the swap rate is below the minimum bid rate and zero otherwise.[20]

Summary statistics for the market condition variables, including the two market condition interaction variables, are in Table 5. Imbalance has a mean of 1,144% and a standard deviation of 3,331%. It is highly skewed; the minimum is 86%, the median is 400%, and the maximum is 26,997%. Imbalance×nex has a mean of -208,065%^{2} and a standard deviation of approximately 10 times that. Imbalance×ln(assets) has a mean of 7,543 and a standard deviation of around three times that. The size ratio averages to 1.24 and has a standard deviation of 1.75. Its minimum is .2 and its maximum is 15.8, illustrating that there is a substantial range in this measure. There is substantially larger scope to refinance a repo when the current auction is 15.8 times larger than the previous one as compared with when the size ratio is merely .2. The expected auction size has an average of 84.256 billion euros, with a standard deviation of 28.829 billion. On auction days, the swap spread has an average of 5.91 bp, with a standard deviation of 8.66 bp. The volatility of the swap rate has an average of 5.32 bp on auction days, with a standard deviation of 1.33 bp.

[20]The expected size, the swap spread, volatility, and negative swap spread are included as control variables. Nyborg et al (2002), who first examined their impact, found they were significant and that the swap spread in particular contributes to a high R^2. Our findings with respect to these variables are similar.

5.2 Plain Panel Regressions

In this subsection, we run panel regressions of underpricing, relative underpricing, discount, relative discount, stopout deviation, award ratio, and demand to reserve requirement on the explanatory variables discussed above. The liquidity status, auction specific market conditions, and interbank rate variables are available for each individual operation. ln(assets) and the equity ratio are available monthly. In the regressions, for each operation we use the values of these two variables at the end of the month prior to the start of the maintenance period that the operation falls under. Writeoffs and provisions and return on assets are measured at the end of the year before the respective operation. To allow for variations in conditions in different maintenance periods, the regressions are run with maintenance period fixed effects. Standard errors are adjusted for heteroscedasticity by using the Huber/White estimate of variance and are clustered on the auctions.[21]

Table 6 reports the results. Each column represents a different regression, and we discuss each in turn. The underpricing regression confirms our earlier results that large banks pay less for liquidity; the coefficient on ln(size) in the underpricing regression is a statistically significant (at the 1% level) 0.174. Looking at the bank type dummies, we see that only the cooperatives have an underpricing that is statistically different from that of private banks. So the univariate results that Landesbanks and cooperative head institutions pay less do not survive the multivariate analysis. Controlling for all other factors, cooperatives pay .415 bp more for liquidity than private banks.

With respect to the liquidity status variables, note first that the coefficient on the normalized net excess reserves is statistically insignificant in both the underpricing and relative underpricing regressions. However, when we separate out small banks, we do get a significant effect. In both cases, the coefficient on small×nex is significantly positive, albeit small. Thus, for small banks, the shorter they are, the lower is their underpricing; i.e., the higher is the price they pay for liquidity. It appears that it is especially small banks that suffer from being short.

[21]We have also run the panel estimations with standard errors clustered on banks and obtain similar results.

The results relating to the distribution of liquidity positions across banks are stronger. The coefficients on imbalance in the underpricing regressions is negative and statistically significant, meaning that the price of liquidity in repos with the central bank relative to the contemporaneous swap rate increases when there is greater imbalance in liquidity positions across banks. The effect is small, but so are the magnitudes we are dealing with in this market. A one standard deviation increase in imbalance leads to a decrease in underpricing of approximately .033 bp. The coefficient on the interaction variable imbalance×nex is positive and statistically significant. A one standard deviation increase in this variable has a .002 bp effect on underpricing. Thus as imbalance increases, banks pay more for liquidity the shorter they are. The interaction variable imbalance×ln(assets) is also positive and statistically significant. In this case, a one standard deviation increase in the independent variable leads to an increase in underpricing of approximately .01 bp. In other words, as imbalance increases, large banks suffer less than small banks, in terms of the price they pay for liquidity. This is further support for the view that small banks are more vulnerable to tightness in the interbank market.

Turning now to the operation specific market condition variables, the coefficients on the size ratio and the expected size are .098 and .022, respectively, both significant at the 1% level. So as the auction size grows, the price paid for liquidity falls. The positive coefficient on expected size may reflect that increasingly expensive collateral has to be used as the auction size grows. The positive size ratio coefficient tells us that the price of liquidity gets relatively more expensive when the scope for refinancing falls. This illustrates that aggregate positions matter.

Worse financial health is associated with an increase in the price of liquidity. A 1 percentage point worsening writeoffs and provisions, the equity ratio, and the return on assets lead to a decrease in underpricing of 17.258 bp, .025 bp, and 6.228 bp, respectively. The coefficient on the loan loss provision is large, especially given an average underpricing of .74 to 1.94 and a standard deviation of writeoffs and provisions of .12 to .60 depending on bank type.

Finally, underpricing increases in the swap spread and decreases in volatility. The negative swap spread dummy variable has a negative coefficient, since bids below the minimum bid rate are not admissible.

The relative underpricing regression is similar, except that most of the market condition variables have lost or reduced statistical and economic significance, as one would expect. The coefficient on imbalance and the two interaction variables, are still statistically significant. The negative coefficient on imbalance is interesting. It means that the distribution of the price paid for liquidity across banks in an operation is skewed towards higher rates. This is consistent with the view that a larger imbalance leads to a larger chance of a liquidity squeeze.

The discount and relative discount regressions are also in line with the underpricing regression, but with some notable exceptions. First, paralleling the cross-sectional regressions, we see that ln(assets) is not significantly different from zero. Second, the normalized net excess reserves is now significant at the 1% level. Specifically, in the plain discount regression the coefficient is 2.3×10^{-4}, showing that the shorter a banks is the smaller is the discount. This is equivalent to saying that a one standard deviation (for private banks) decrease in the normalized net excess reserve, leads to increase in the relative willingness to pay by approximately .1 bp. Savings banks and branches of foreign banks have a lower discount, and thus a higher willingness to pay, than private banks, yet do not end up paying more. A part of the explanation for this, at least for savings banks, is that they have a significantly lower stopout deviation.

The stopout deviation measures how close to the stopout rate banks submit their bids. A low stopout deviation tends to reduce the price paid for liquidity. A consistently low stopout deviation could be the result of ability or an informational advantage with respect to "where the market is." It could also arise for banks that are not concerned with being squeezed or rationed in the interbank market, since such banks need not be so aggressive in the auctions as banks that are concerned with these issues. Large banks may have a lower stopout deviation for both of these reasons. Our results also show that banks with large writeoffs and provisions or small equity ratios have larger stopout deviations. Coupled with the fact that writeoffs and provisions do not affect discounts, this suggests that less financially healthy banks use a strategy where they try to counteract high bids, placed to ensure success in the auction, with low bids, to try to reduce the overall price paid. As discussed above, the end result is that they end up paying more. We also see that small short banks have larger stopout deviations – but these banks also have smaller discounts.

The award ratio regression shows that this variable tends to increase in writeoffs and provisions, which is in line with the results above that financially unhealthy banks are more desperate to obtain funds from the central bank. An alternative and not wholly unrelated interpretation is that bid more aggressively because they are in possession of collateral of specially low quality. Shorter banks also bid more aggressively, as measured by the award ratio. Again, this is in line with our other findings. The demand to reserves requirements regression shows that a bank's total demand relative to its reserves is decreasing in the normalized net excess reserves, i.e., banks demand relatively more the shorter they are.

To summarize, the panel regressions confirm the finding from our cross-sectional analysis that banks pay more for liquidity the smaller they are. In addition, the panel regressions show that liquidity positions affect the price paid for liquidity and the willingness to pay. But it is not just a bank's own position that matters; it is especially how liquidity is distributed across banks. The more imbalance there is, the more are banks willing to pay and the more do they end up paying, especially the shorter and smaller they are.[22] Our results also show that financial health is important; less healthy banks bid more aggressively and pay more for liquidity than more healthy banks.

5.3 Panel Regressions with Heckman Correction

The estimation methodology in the previous section does not consider a bank's decision to participate in an auction or not. If this decision is non-random, the estimated coefficients

[22]While the evidence is thus consistent with short squeezing being a concern, from a theoretical perspective one could also contemplate the possibility that banks with excess liquidity could be "squeezed", since their alternative to trading in the market would be to use the deposit facility, which is 100 bp below the minimum bid rate in the auctions. Reasons for why it may be worse being short than long include, i. a short bank needs eligible collateral to access the marginal lending facility, ii. given the ECB's liquidity neutral policy, if some liquidity is taken out of the interbank market through inefficient liquidity management at the individual bank level (e.g., due to a bank with a small amount of excess liquidity not participating in the interbank market) the ECB's liquidity neutral policy will give rise to a shortage of liquidity in the interbank market.

would be inconsistent. In this section, we correct for the possibility of a selection bias by using a Heckman selection model. This model combines a selection mechanism for participating in the main refinancing operation with a regression model.

Indexing banks by i and operations by j, the selection equation is

$$z_{ij}^{*} = \gamma' w_{ij} + \mu_{ij}. \tag{6}$$

The regression model is

$$y_{ij} = \beta' x_{ij} + \epsilon_{ij}, \tag{7}$$

where $(\mu_{ij}, \epsilon_{ij})$ are assumed to be bivariate normal $[0, 0, 1, \sigma_\epsilon, \rho]$.

z_{ij}^{*} is not observed; the variable is observed as $z_{ij} = 1$ if $z_{ij}^{*} > 0$ and 0 otherwise with probabilities $\text{Prob}(z_{ij} = 1) = \Phi(\gamma' w_{ij})$ and $\text{Prob}(z_{ij} = 0) = 1\text{-}\Phi(\gamma' w_{ij})$. $z_i = 1$ indicates that the bank participates and Φ is the standardized normal cumulative distribution function.

In the selected sample,

$$E[y_{ij}|z_{ij} = 1] = \beta' x_{ij} + \rho\sigma_\epsilon\lambda(\gamma' w_{ij}), \tag{8}$$

where λ is the inverse Mills ratio.

The model is estimated by maximum likelihood, see Greene (2000), which provides consistent, asymptotically efficient parameter estimates. Standard errors are adjusted for heteroscedasticity by using the Huber/White estimate of variance and are clustered at the auction level.

The set of explanatory variables, x, in the regression model are the same as in the panel regressions in the previous subsection.[23] In the selection equation, we use two additional variables, namely *maturing repo* and *last auction*. Maturing repo is 1 if the bank won some units two operations ago, and last auction is the aggregate underpricing in the previous main refinancing operation. We expect that a bank is more likely to participate if it has to refinance (maturing repo is 1). The results are virtually the same with or without the variable last auction.

[23]Except that we now do not include maintenance period fixed effects.

The Heckman model is run on the full dataset, including bidding banks and non-bidding banks. Results are in Table 7. Panel (a) presents the regression model, panel (b) the selection model, and panel (c) provides statistics on the parameters.

Comparing panel (a) to the plain panel regression in Table 6, we see few notable differences. For the most part, the variables that were significant remain so, though sometimes with altered p-levels, and the coefficients are very close to what they were before. Few variables go from being insignificant to significant. The most notable exceptions are as follows: First, ln(assets)goes from being insignificant in the plain panel relative underpricing and award ratios regressions to being significantly positive and negative, respectively. So larger banks bid at lower rates than smaller banks are less aggressive overall. This supports our other findings. Second, larger writeoffs and provisions do not lead to significantly larger award ratios after all. Third, imbalance×nex is not significant after all in the relative discount regression, however its coefficient is still significantly positive in the two underpricing regressions. Fourth, the coefficient on imbalance×ln(assets) reverses sign in the discount regression. With the Heckman correction, it is positive – just as in the relative underpricing regression. In other words, as imbalance increases, larger banks pay relatively less than smaller banks. In sum, overall, these changes serve to strengthen our results.[24] The conclusions from the previous subsection remain intact.

In panel (b), we see that the selection equation is very similar for the different independent variables. This illustrates its robustness. We note that increased bank size is associated with a larger likelihood to participate, as is being a savings bank. Cooperatives and foreign banks are less likely to participate. With respect to liquidity status, we see that a larger imbalance is associated with a larger participation rate, consistent with the interpretation that this variable is associated with squeezes; the more likely a squeeze is, the more important it is to participate in order to cover one's short position, or possibly being able to squeeze. An increase in return on assets is associated with a decrease the likelihood of bidding, perhaps because banks that are generating larger earnings have less need to obtain liquidity from others. Loss of financial health as measured by an increase

[24]The size ratio also behaves slightly differently with the Heckman correction and the demand to reserve requirements regression appears to be the least stable.

in writeoffs and provisions is surprisingly associated with a fall in the probability of participating. This may reflect a lack of collateral. A bank is more likely to participate when the size ratio is large. This is not surprising, since a larger relative auction size is indicative of an increased need for liquidity in the banking system. Banks are also more likely to participate when the swap spread is large, perhaps because this is associated with larger underpricing. A negative swap spread is, not surprisingly, associated with less participation. An increase in volatility and expected auction size are both associated with an increased likelihood of bidding. The positive coefficients on maturing repo and last auction confirm that banks are more likely to participate if they have a refinancing need and also when the previous auction was highly underpriced.

Panel c reports the different parameters for the Heckman estimation, i.e. ρ, σ, and λ. The results suggest that these parameters are significant for each of the estimations, except for the underpricing estimation. In particular, the correlation of the residuals in the bidding and performance model and the selection model, which is captured by ρ, is significant at the 5% level. This suggests that it is important to use the Heckman approach to take into account the decision whether to submit a bid for the analysis of how bidders submit their bids. Nevertheless, as we have seen, the results from the Heckman panel regression are very similar as in the plain panel regression.

6 Conclusion

This paper documents that the price of liquidity systematically depends on bank characteristics and market conditions. We specifically test four hypotheses, which are derived from economic theory, and find the following results. First, our findings are consistent with the existence of periodically occurring liquidity squeezes. A greater imbalance in liquidity positions across banks is associated with a rise in the price of liquidity, relative to the benchmark, as predicted by the theoretical work by Nyborg and Strebulaev (2004). Furthermore, the shorter a bank is the more adversely it is affected by an increase in imbalance, *ceteris paribus*. Since the sample period of this paper is a time of relative normalcy in the interbank markets, this shows that liquidity squeezes are not just a crisis phenomenon.

Second, we document a systematic relation between bank size and the price of liquidity. Controlling for a variety of factors, we find that larger banks pay less than do smaller banks. This effect is even more pronounced when there is an increase in the imbalance of the liquidity positions. Smaller banks thus appear to be more vulnerable to a liquidity squeeze, *ceteris paribus*. This may also help explain why smaller banks tend to be relatively less short than larger banks prior to refinancing operations.

Third, we find that financial health affects the price banks pay for liquidity. Less healthy banks pay more. The results on health are especially significant, statistically and economically, for the writeoffs and provisions variable.

Fourth, we find that membership in a formal relationship lending network does not reduce the price a bank pays for liquidity. German savings and cooperative banks, which formally belong to these networks, do not pay less than other banks, which are not part of these networks. Cooperative banks even bid and pay more than other banks. This gives rise to the notion that these formal networks may induce banks to free-ride on the efforts of other banks in the network, along the lines of Bhattacharya and Gale (1987). An alternative view is that cooperatives and savings banks that participate in the main refinancing operations do so because they experience rationing by their respective networks. This may carry stigma in the interbank market, giving them an increased willingness to pay in open market operations.

There are several ways this line of research can be broadened. An important question is whether banks with poor collateral are more exposed to adverse liquidity conditions and therefore bid and pay more in the primary market. That underpricing in the main refinancing operations is increasing in the size of the operation is consistent with the view that different collateral have different opportunity costs. Data on individual bank collateral holdings, however, is very hard to obtain.

Another important issue is how the effects we have uncovered would play out during a crisis period. For example, that small banks are more adversely affected by increases in the liquidity imbalance in the banking sector, *ceteris paribus*, suggests that small banks would be more vulnerable in a crisis. On the other hand, since small banks tend to be less short than large banks, it is possible that the net effect of a crisis may be worse for large banks than small ones. Thus, while our findings are consistent with the view that large banks have better access to the interbank market for liquidity than smaller banks, it is not clear how they would fare if this market would seize up.

Finally, our findings that there are imperfections in the market for liquidity even during times of normalcy leaves us with the hypothesis that the recent crisis represents a flaring up of these imperfections. Also, our findings on the impact of poor financial health suggests that system wide tightness in the market for liquidity could result from a general deterioration in banks' financial health. These are important issues to settle for future research.

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Appendix 1: Tables

Table 1: Bank Characteristics: Bidders
Descriptive statistics on bank characteristic variables for six types of banks as classified by the Deutsche Bundesbank: Private banks, savings banks, cooperatives, branches of foreign banks, Landesbanks, and cooperative central banks. "Bidders" are all banks that participated in at least one main refinancing operation during the sample period. The liquidity variables (fulfillment, normalized gross and net excess reserves are calculated for each bank the day before each auction. Asset size and the equity ratio are calculated for each bank each calendar month and reserve requirements each maintenance period. Writeoffs and provisions and return on assets are obtained annually. See Section 3.1 for definitions of the variables. For each bank, the mean of each variable is calculated (unconditionally, i.e., not conditional on bidding decisions), thus yielding a sample of individual bank means for each variable. The table reports summary statistics of these means across banks within each bank type.

	units	mean	median	std	s.e.	min	max	N
Panel (a): Private Banks								
Assets	mill	22794	4149	52774	5472	62	267591	93
Reserve requirement (daily)	mill	132.43	20.25	438.16	45.44	0.20	2901.60	93
Fulfillment	%	100.25	101.81	15.53	1.61	50.85	157.03	93
Norm gross excess reserves	%	14.55	9.42	41.83	4.34	-77.78	244.37	93
Norm net excess reserves	%	-243.82	-83.39	530.25	54.98	-3739.82	212.39	93
Writeoffs & provisions	%	0.35	0.21	0.48	0.05	0.00	3.08	93
Return on assets	%	0.34	0.21	0.47	0.05	-0.98	2.27	93
Equity ratio	%	4.96	4.06	3.90	0.40	0.81	24.04	93
Panel (b): Savings Banks								
Assets	mill	2092	1307	2754	144	170	31385	366
Reserve requirement (daily)	mill	22.06	14.31	27.48	1.44	1.26	314.89	366
Fulfillment	%	102.65	101.36	6.08	0.32	84.22	133.01	366
Norm gross excess reserves	%	7.48	6.05	9.35	0.49	-35.88	40.76	366
Norm net excess reserves	%	-81.53	-34.98	126.12	6.59	-1187.84	25.81	366
Writeoffs & provisions	%	0.36	0.32	0.22	0.01	0.00	1.48	366
Return on assets	%	0.22	0.21	0.11	0.01	-0.04	0.93	366
Equity ratio	%	4.12	4.01	0.79	0.04	2.46	8.08	366
Panel (c): Cooperatives								
Assets	mill	678	350	1380	77	26	18582	324
Reserve requirement (daily)	mill	7.81	4.04	13.25	0.74	0.24	127.10	324
Fulfillment	%	102.94	101.49	8.15	0.45	74.05	159.71	324
Norm gross excess reserves	%	9.42	5.69	13.17	0.73	-48.10	70.77	324
Norm net excess reserves	%	-31.90	-9.14	66.10	3.67	-585.01	44.27	324
Writeoffs & provisions	%	0.45	0.39	0.46	0.03	0.00	7.22	324
Return on assets	%	0.17	0.19	0.23	0.01	-1.53	0.77	324
Equity ratio	%	4.94	4.85	1.11	0.06	1.67	11.63	324

Table 1: (cont.)

	units	mean	median	std	s.e.	min	max	N
Panel (d): Foreign Banks								
Assets	mill	2256	1135	2586	564	31	8009	21
Reserve requirement (daily)	mill	17.09	8.94	18.91	4.13	0.02	62.31	21
Fulfillment	%	142.30	99.40	139.77	30.50	71.77	685.95	21
Norm gross excess reserves	%	103.94	12.67	278.41	60.75	-14.55	965.91	21
Norm net excess reserves	%	-206.53	-24.12	663.91	144.88	-1950.78	968.01	21
Writeoffs & provisions	%	0.26	0.09	0.60	0.13	0.00	2.18	21
Return on assets	%	0.28	0.15	0.53	0.12	-0.68	1.45	21
Equity ratio	%	7.86	5.02	9.19	2.01	1.09	34.09	21
Panel (e): Landesbanks								
Assets	mill	96918	73940	68435	19755	12539	228659	12
Reserve requirement (daily)	mill	351.98	266.25	265.26	76.57	21.09	854.93	12
Fulfillment	%	82.44	83.95	9.37	2.70	69.08	100.17	12
Norm gross excess reserves	%	-11.86	-11.60	12.04	3.47	-38.78	6.88	12
Norm net excess reserves	%	-217.10	-162.26	166.75	48.14	-596.13	-60.01	12
Writeoffs & provisions	%	0.13	0.09	0.12	0.03	0.02	0.49	12
Return on assets	%	0.10	0.12	0.10	0.03	-0.15	0.24	12
Equity ratio	%	2.66	2.71	0.77	0.22	1.33	3.69	12
Panel (f): Cooperative Central Banks								
Assets	mill	60320	39921	53767	26884	22081	139357	4
Reserve requirement (daily)	mill	241.17	113.85	277.29	138.64	80.54	656.42	4
Fulfillment	%	99.00	98.22	10.29	5.15	87.33	112.22	4
Norm gross excess reserves	%	6.76	-0.11	18.00	9.00	-6.10	33.36	4
Norm net excess reserves	%	-261.95	-157.97	268.94	134.47	-660.64	-71.21	4
Writeoffs & provisions	%	0.24	0.18	0.15	0.08	0.13	0.46	4
Return on assets	%	0.20	0.16	0.18	0.09	0.05	0.44	4
Equity ratio	%	2.83	3.01	0.59	0.30	1.99	3.33	4

Table 2: Bank Characteristics: Non-Bidders

Descriptive statistics on bank characteristic variables for four types of banks as classified by the Deutsche Bundesbank: Private banks, savings banks, cooperatives, and branches of foreign banks. "Non-bidders" are all banks that did not participate in any main refinancing operation during the sample period. There is no Landesbank or cooperative central bank non-bidder. All variables are as described in Table 1, but note that for non-bidders, there is no difference between gross and net excess reserves as there never is a maturing repo.

	units	mean	median	std	s.e.	min	max	N
Panel (a): Private Banks								
Assets	mill	1477.72	242.03	6847.49	665.09	11.11	69252.90	106
Reserve requirement (daily)	mill	6.99	1.71	16.73	1.62	0.01	131.21	106
Fulfillment	%	169.61	108.13	279.13	27.11	26.84	2073.32	106
Norm net excess reserves	%	210.83	24.93	808.20	78.50	-141.97	5584.70	106
Writeoffs & provisions	%	0.73	0.31	1.03	0.10	0.00	5.37	106
Return on assets	%	0.89	0.25	1.97	0.19	-4.61	12.51	106
Equity ratio	%	13.80	8.58	13.35	1.30	1.35	67.42	106
Panel (b): Savings Banks								
Assets	mill	894.65	682.85	748.57	55.34	61.38	4573.03	183
Reserve requirement (daily)	mill	10.10	7.60	8.59	0.63	0.61	43.16	183
Fulfillment	%	102.67	101.32	6.24	0.46	88.77	135.04	183
Norm net excess reserves	%	8.30	6.21	12.77	0.94	-10.25	129.95	183
Writeoffs & provisions	%	0.43	0.39	0.25	0.02	0.00	1.28	183
Return on assets	%	0.24	0.22	0.15	0.01	0.02	1.35	183
Equity ratio	%	4.31	4.19	0.88	0.07	2.28	8.02	183
Panel (c): Cooperatives								
Assets	mill	234.38	148.17	302.07	8.46	11.52	4220.17	1275
Reserve requirement (daily)	mill	2.86	1.84	3.58	0.10	0.01	40.26	1275
Fulfillment	%	105.93	101.06	79.51	2.23	74.53	2476.16	1275
Norm net excess reserves	%	25.33	5.98	325.48	9.12	-233.86	9219.97	1275
Writeoffs & provisions	%	0.44	0.38	0.38	0.01	-0.24	5.35	1275
Return on assets	%	0.21	0.22	0.29	0.01	-4.52	3.97	1275
Equity ratio	%	5.28	5.11	1.20	0.03	1.82	19.75	1275
Panel (d): Foreign Banks								
Assets	mill	1474.30	423.37	2976.73	405.08	12.39	15486.32	54
Reserve requirement (daily)	mill	9.61	2.06	27.29	3.71	0.00	191.84	54
Fulfillment	%	535.17	114.50	1414.76	192.52	52.87	8213.70	54
Norm net excess reserves	%	1697.84	54.23	5726.84	779.32	-15.89	35075.25	54
Writeoffs & provisions	%	0.20	0.06	0.27	0.04	0.00	0.91	54
Return on assets	%	0.88	0.27	1.65	0.22	0.03	6.72	54
Equity ratio	%	4.11	1.42	7.24	0.99	-1.05	35.42	54

Table 3: Pricing and Bidding Statistics for Individual Banks by Type

Descriptive statistics on bidding and performance variables for six types of banks as classified by the Deutsche Bundesbank: Private banks, savings banks, cooperatives, branches of foreign banks, Landesbanks, and cooperative central banks. The variables are defined in the itemized list in Section 3.3. Averaging by bank: Means of each variable are calculated first for each bank. The reported statistics are then calculated across banks for each bank type. Conditional on bidding.

	units	mean	std	s.e.	min	max	N
Panel (a): Private Banks							
Underpricing	bp	1.24	1.75	0.19	-5.50	5.58	89
Relative underpricing	bp	0.07	0.86	0.09	-3.47	1.65	89
Discount	bp	3.04	2.07	0.21	-4.50	9.69	93
Relative discount	bp	0.14	1.57	0.16	-4.89	5.92	93
Stopout deviation	bp	1.63	0.94	0.10	0.70	5.40	93
Award ratio	%	54.90	23.75	2.46	0.00	100.00	93
Demand to reserve req	%	909.07	1749.32	182.38	15.07	12124.14	92
Award to total award	%	0.63	1.69	0.18	0.00	11.58	93
Bidding frequency	%	48.95	32.40	3.36	1.28	98.72	93
Number of bids		2.18	0.72	0.07	1.00	4.57	93
Panel (b): Savings Banks							
Underpricing	bp	1.66	1.90	0.10	-5.75	9.25	352
Relative underpricing	bp	-0.01	1.09	0.06	-7.71	3.46	352
Discount	bp	3.32	2.81	0.15	-5.50	17.50	366
Relative discount	bp	-0.09	1.76	0.09	-8.14	12.10	366
Stopout deviation	bp	1.73	1.28	0.07	0.00	11.00	366
Award ratio	%	57.41	23.62	1.23	0.00	100.00	366
Demand to reserve req	%	285.41	228.18	11.93	21.38	1503.59	366
Award to total award	%	0.09	0.17	0.01	0.00	1.97	366
Bidding frequency	%	44.43	32.47	1.70	1.28	100.00	366
Number of bids		2.29	0.88	0.05	1.00	5.13	366
Panel (c): Cooperatives							
Underpricing	bp	0.78	2.55	0.15	-14.00	8.25	308
Relative underpricing	bp	-0.87	1.80	0.10	-14.13	3.88	308
Discount	bp	3.47	4.09	0.23	-14.00	31.25	324
Relative discount	bp	-0.18	2.91	0.16	-14.24	21.37	324
Stopout deviation	bp	2.80	2.20	0.12	0.00	21.00	324
Award ratio	%	58.97	26.29	1.46	0.00	100.00	324
Demand to reserve req	%	249.83	280.80	15.60	13.26	3062.99	324
Award to total award	%	0.03	0.06	0.00	0.00	0.77	324
Bidding frequency	%	27.51	25.41	1.41	1.28	100.00	324
Number of bids		2.05	1.09	0.06	1.00	9.00	324

Table 3: (cont.)

	units	mean	std	s.e.	min	max	N
Panel (d): Foreign Banks							
Underpricing	bp	0.69	1.94	0.44	-4.75	3.29	19
Relative underpricing	bp	-0.18	1.42	0.33	-5.71	1.02	19
Discount	bp	2.84	4.24	0.93	-4.75	13.25	21
Relative discount	bp	-0.15	2.35	0.51	-7.45	4.64	21
Stopout deviation	bp	1.94	1.57	0.34	0.40	7.00	21
Award ratio	%	58.34	28.36	6.19	0.00	100.00	21
Demand to reserve req	%	939.11	1218.19	272.40	73.36	4721.26	20
Award to total award	%	0.17	0.32	0.07	0.00	1.15	21
Bidding frequency	%	34.68	27.90	6.09	1.28	97.44	21
Number of bids		1.87	0.84	0.18	1.00	4.22	21
Panel (e): Landesbanks							
Underpricing	bp	1.48	1.14	0.33	-0.54	3.87	12
Relative underpricing	bp	0.53	0.36	0.10	0.02	1.19	12
Discount	bp	2.83	1.31	0.38	1.21	5.61	12
Relative discount	bp	0.50	0.77	0.22	-0.51	2.31	12
Stopout deviation	bp	1.04	0.22	0.06	0.70	1.46	12
Award ratio	%	48.54	14.42	4.16	27.15	73.42	12
Demand to reserve req	%	520.64	342.03	98.74	190.36	1087.91	12
Award to total award	%	1.68	1.39	0.40	0.24	4.58	12
Bidding frequency	%	80.45	19.41	5.60	29.49	100.00	12
Number of bids		2.42	0.40	0.12	1.84	3.15	12
Panel (f): Cooperative Central Banks							
Underpricing	bp	2.82	1.60	0.80	1.53	5.16	4
Relative underpricing	bp	0.51	0.57	0.29	-0.15	1.24	4
Discount	bp	4.27	2.23	1.12	2.38	7.50	4
Relative discount	bp	0.45	0.61	0.30	-0.11	1.28	4
Stopout deviation	bp	1.17	0.31	0.15	0.83	1.55	4
Award ratio	%	42.34	16.93	8.46	18.34	56.57	4
Demand to reserve req	%	1221.95	1181.01	590.51	205.75	2711.00	4
Award to total award	%	1.45	0.90	0.45	0.53	2.64	4
Bidding frequency	%	49.36	31.97	15.98	3.85	75.64	4
Number of bids		3.51	1.49	0.74	2.43	5.67	4

Table 4: Cross-Sectional Regressions

Each column represents a separate regression. Standard errors (in brackets) are adjusted for heteroscedasticity by using the Huber/White estimate of variance. a, b, c denote significance (two-tailed) at the 1%, 5%, and 10% level, respectively.

	units	Underpricing bp	Relative Underpricing bp	Discount bp	Relative Discount bp	Stopout Deviation bp	Award Ratio %	Demand to Res. Req. %
Constant		0.479	-1.477^{a}	6.064^{a}	1.885^{b}	4.642^{a}	43.016^{a}	612.741^{a}
		(0.63)	(-3.05)	(5.52)	(2.38)	(8.58)	(4.78)	(3.19)
ln(assets)	ln(mill)	0.149^{b}	0.186^{a}	-0.201^{c}	-0.125^{c}	-0.320^{a}	0.381	-17.898
		(2.00)	(3.84)	(-1.93)	(-1.66)	(-6.13)	(0.46)	(-0.90)
norm net excess reserves	%	4.4E-04	-1.7E-04^{b}	0.002^{a}	0.001^{b}	0.001^{a}	-0.015^{b}	-2.036^{a}
		(1.43)	(-2.02)	(2.71)	(2.09)	(3.34)	(-2.39)	(-4.91)
Small x nex	%	1.8E-05	-3.0E-05	1.8E-05	-2.4E-05	6.0E-05^{b}	4.6E-05	0.040^{c}
		(0.32)	(-0.71)	(0.23)	(-0.43)	(2.44)	(0.10)	(1.85)
Writeoffs & provisions	%	1.841	2.250	39.643	23.692	-8.038	-306.382	-1,690.775
		(0.07)	(0.16)	(1.31)	(1.49)	(-0.88)	(-1.32)	(-0.38)
Return on assets	%	-0.473	27.874	-27.050	-17.738	-25.988	-123.625	-9,746.481
		(-0.01)	(1.49)	(-0.36)	(-0.30)	(-0.56)	(-0.35)	(-1.21)
Equity ratio	%	-0.067^{c}	-0.034	-0.178^{a}	-0.114^{a}	0.001	1.237^{b}	-1.575
		(-1.72)	(-1.42)	(-2.63)	(-2.71)	(0.03)	(2.45)	(-0.09)
Savings Bank		0.411^{c}	0.169	-0.498	-0.604^{a}	-0.456^{a}	6.742^{b}	-329.178^{a}
		(1.68)	(1.33)	(-1.60)	(-2.60)	(-3.00)	(2.10)	(-3.55)
Cooperative Bank		-0.240	-0.395^{b}	-0.608	-0.830^{a}	0.153	8.770^{b}	-282.166^{a}
		(-0.76)	(-2.24)	(-1.44)	(-2.65)	(0.73)	(2.27)	(-3.14)
Foreign Bank		-0.181	0.055	-0.240	-0.391	-0.275	5.361	-153.049
		(-0.37)	(0.27)	(-0.21)	(-0.68)	(-0.69)	(0.66)	(-0.70)
Landesbank		-0.405	-0.056	-0.157	0.428	0.203	-4.651	-316.369^{c}
		(-1.02)	(-0.32)	(-0.31)	(1.24)	(1.08)	(-0.92)	(-1.78)
Coop Central Bank		1.043	-0.026	1.284	0.357	0.251	-11.095	296.862
		(1.38)	(-0.08)	(1.31)	(1.15)	(0.80)	(-1.51)	(0.58)
R^2		0.054	0.120	0.033	0.020	0.156	0.037	0.562
N		777	777	812	812	812	812	811

Table 5: Market Condition and Interaction Variables

Descriptive statistics of explanatory market condition and interaction variables. Imbalance is the standard deviation of the normalized net excess reserves of all banks before a given auction. Imbalance×nex and imbalance×ln(assets) are interaction variables for which imbalance is multiplied by the normalized net excess reserves and log of assets, respectively, for each bidder in a given auction. (Note: nex denotes normalized net excess reserves.) Size ratio is the ratio of the expected auction size in auction t and the realized auction size in auction t-2. Expected auction size is the liquidity neutral amount, which is computed from the liquidity figures announced by the ECB the afternoon on the day prior to the auctions. Swap spread is the difference between the two week swap rate and the minimum bid rate at 9:15 a.m./ on the auction day. Volatility of swap rate is the conditional volatility of the two week swap rate on auction days (see Appendix 2).

	Units	mean	median	std	s.e.	min	max	N
imbalance	%	1,144	400	3,331	382	86	26,997	76
imbalance×nex	%×%	-208,065	-42,118	2,770,774	18,022	-9.79E+07	3.67E+08	23,635
imbalance×ln(assets)	%×ln(mill)	7,543	2,945	21,128	137	282	339,127	23,673
size ratio	100%	1.238	0.977	1.747	0.200	0.200	15.800	76
expected auction size	bill	84.256	83.000	28.829	3.264	5	177	78
swap spread	bp	5.913	4.250	8.658	0.980	-9.000	48.250	78
volatility of swap rate	bp	5.322	5.776	1.332	0.151	0.194	9.304	78

Table 6: Panel Regressions

Each column represents a separate regression, all run with maintenance period fixed effects. Standard errors (in brackets) are clustered on each auction and adjusted for heteroscedasticity by using the Huber/White estimate of variance. a, b, c denote significance (two-tailed) at the 1%, 5%, and 10% level, respectively. Note: nex denotes normalized net excess reserves.

	units	Underpricing bp	Relative Underpricing bp	Discount bp	Relative Discount bp	Stopout Deviation bp	Award Ratio %	Demand to Res. Req. %
Constant		-0.292	-1.259[a]	1.774	-1.021[c]	1.110[b]	23.654[b]	641.080[a]
		(-0.28)	(-4.51)	(1.57)	(-1.91)	(2.45)	(2.56)	(12.06)
ln(assets)	ln(mill)	0.174[a]	0.162[a]	0.029	0.017	-0.191[a]	-0.241	-6.055
		(10.34)	(9.12)	(0.71)	(0.40)	(-7.61)	(-0.73)	(-1.27)
norm net excess reserves	%	-3.8E-05	1.9E-06	2.3E-04[a]	2.3E-04[a]	8.9E-05[b]	-0.006[a]	-1.053[a]
		(-0.85)	(0.06)	(3.65)	(4.19)	(2.59)	(-6.70)	(-19.18)
Small x nex	%	1.9E-05[a]	1.8E-05[a]	2.2E-05[a]	2.2E-05[a]	-7.9E-06[c]	-2.8E-05	0.004[a]
		(3.41)	(3.16)	(2.82)	(2.82)	(-1.82)	(-0.34)	(3.36)
Writeoffs & provisions	%	-17.258[a]	-16.817[a]	-6.611	-6.642	16.859[a]	227.456[a]	-9,741.073[a]
		(-3.44)	(-3.80)	(-0.94)	(-0.96)	(3.78)	(3.22)	(-8.98)
Return on assets	%	6.228	8.335[b]	17.402[a]	17.625[a]	4.487	-59.745	-8,770.781[a]
		(1.62)	(2.29)	(2.75)	(2.83)	(1.29)	(-0.84)	(-5.72)
Equity ratio	%	0.025[a]	0.020[a]	-0.014	-0.020	-0.021[a]	0.590[a]	-9.754[a]
		(3.63)	(2.82)	(-1.15)	(-1.54)	(-2.76)	(3.91)	(-4.18)
imbalance	%	-9.8E-06[a]	-5.6E-06[a]	-1.5E-05[a]	-9.4E-06[a]	4.7E-06[a]	1.3E-04[a]	0.002[a]
		(-6.28)	(-6.40)	(-6.85)	(-5.57)	(3.83)	(3.03)	(9.42)
imbalance x nex	% x %	7.3E-10[a]	5.4E-10[a]	-3.9E-10	-4.4E-10[c]	-8.2E-10[a]	1.3E-08[a]	5.0E-06[a]
		(3.62)	(4.09)	(-1.39)	(-1.81)	(-5.31)	(2.91)	(20.61)
imbalance x ln(assets)	% x ln(mill)	4.2E-07[a]	5.1E-07[a]	-9.5E-07[a]	1.0E-06[a]	-2.0E-07	-6.7E-08[b]	-1.4E-04[a]
		(3.22)	(4.43)	(4.06)	(4.76)	(-1.33)	(-2.60)	(-4.92)
size ratio	100%	0.098[b]	-0.021[b]	0.069	0.015	-0.039[b]	-0.026	13.237[a]
		(2.23)	(-2.32)	(1.48)	(0.92)	(-2.03)	(-0.08)	(3.69)
swap spread	bp	0.138[a]	0.015[c]	0.277[a]	0.035	0.089[a]	-0.780[b]	3.064[a]
		(3.43)	(1.98)	(5.55)	(1.44)	(10.47)	(-1.99)	(3.99)
neg. swap spread		-2.716[a]	-0.124	-2.829[a]	-0.047	0.096	24.180[a]	-74.517[a]
		(-5.47)	(-1.32)	(-5.21)	(-0.21)	(0.48)	(5.08)	(-4.72)
volatility	bp	-0.319[c]	0.012	-0.336[c]	0.045	0.087	0.950	4.756
		(-1.83)	(0.48)	(-1.78)	(0.73)	(1.49)	(0.71)	(1.07)
exp. auction size	bill	0.022[a]	-0.001	0.016[b]	0.004	0.004	0.253[a]	-0.417[c]
		(3.95)	(-0.44)	(2.38)	(1.12)	(1.43)	(3.67)	(-1.87)
Savings Bank		0.034	0.019	-0.458[a]	-0.463[a]	-0.229[a]	9.070[a]	-373.028[a]
		(0.54)	(0.34)	(-4.29)	(-4.38)	(-3.02)	(8.17)	(-12.45)
Cooperative Bank		-0.415[a]	-0.407[a]	-0.477[a]	-0.460[a]	0.167[a]	6.541[a]	-359.546[a]
		(-7.08)	(-7.68)	(-5.35)	(-5.59)	(3.24)	(5.58)	(-11.77)
Foreign Bank		-0.141	-0.121	-0.721[a]	-0.693[a]	-0.061	13.537[a]	-169.276[a]
		(-1.41)	(-1.44)	(-5.46)	(-5.43)	(-0.64)	(6.23)	(-3.44)
Landesbank		-0.012	-0.071	0.189	0.220	0.249[a]	-4.289[a]	-279.538[a]
		(-0.19)	(-1.27)	(1.13)	(1.29)	(3.48)	(-2.86)	(-7.53)
Coop Central Bank		-0.153	-0.141	0.028	0.047	0.217[b]	-4.989[c]	-216.660[a]
		(-1.30)	(-1.47)	(0.16)	(0.28)	(2.55)	(-1.77)	(-3.59)
R^2		0.6055	0.0681	0.5715	0.0445	0.2274	0.2261	0.4132
N		19,088	19,088	23,461	23,461	23,461	23,461	23,461

Table 7: Heckman Sample Selection Regressions

Each column represents a separate regression. Standard errors are clustered on each auction and adjusted for heteroscedasticity by using the Huber/White estimate of variance. t-statistics are in brackets. a, b, c denote significance (two-tailed) at the 1%, 5%, and 10% level, respectively. Note: nex denotes normalized net excess reserves. The selection equation (Panel b) is run on the full sample of bidding and non-bidding banks.

Panel a: Bidding and Performance	units	Underpricing bp	Relative Underpricing bp	Discount bp	Relative Discount bp	Stopout Deviation bp	Award Ratio %	Demand to Res. Req. %
Constant		-1.530	-1.575^{a}	0.216	-1.461^{b}	1.220^{b}	51.053^{a}	-456.629^{c}
		(-1.25)	(-5.08)	(0.16)	(-2.35)	(2.29)	(3.84)	(-1.72)
ln(assets)	ln(mill)	0.131^{a}	0.180^{a}	0.055	0.089^{b}	-0.167^{a}	-1.691^{a}	75.240^{a}
		(4.67)	(9.78)	(1.03)	(2.03)	(-6.95)	(-4.20)	(3.29)
norm net excess reserves	%	-3.1E-05	-2.6E-05	1.4E-04^{b}	1.4E-04^{a}	4.0E-05	-0.003^{a}	-1.155^{a}
		(-0.77)	(-1.01)	(2.53)	(2.98)	(1.57)	(-4.63)	(-19.86)
Small x nex	%	1.8E-05^{a}	1.6E-05^{a}	1.5E-05^{c}	1.3E-05^{c}	-1.1E-05^{b}	1.3E-04	-0.007^{b}
		(2.58)	(2.75)	(1.79)	(1.77)	(-2.48)	(1.55)	(-2.33)
Writeoffs & provisions	%	-36.261^{a}	-13.612^{a}	-13.088	1.826	16.329^{b}	20.880	-10,172.330^{a}
		(-3.40)	(-3.07)	(-1.11)	(0.22)	(2.37)	(0.17)	(-9.02)
Return on assets	%	7.373	8.399^{b}	18.599^{a}	17.700^{a}	4.680	-64.452	-10,002.490^{a}
		(1.63)	(2.28)	(2.76)	(2.71)	(1.37)	(-0.91)	(-6.55)
Equity ratio	%	0.011	0.022^{a}	-0.028^{b}	-0.016	-0.020^{a}	0.581^{a}	-8.556^{a}
		(1.15)	(3.23)	(-2.38)	(-1.27)	(-2.65)	(4.00)	(-3.89)
imbalance	%	-1.0E-05^{a}	-5.1E-06^{a}	-1.3E-05^{a}	8.0E-06^{a}	4.3E-06^{a}	6.1E-05^{b}	0.003^{a}
		(-4.54)	(-5.72)	(-5.03)	(-4.42)	(3.27)	(2.55)	(8.23)
imbalance x nex	% x %	7.3E-10^{a}	6.3E-10^{a}	-1.1E-10	-1.2E-10	-6.4E-10^{a}	5.3E-09	5.3E-06^{a}
		(3.60)	(5.83)	(-0.41)	(-0.61)	(-5.32)	(1.32)	(22.68)
imbalance x ln(assets)	% x ln(mill)	5.5E-07^{a}	4.9E-07^{a}	9.6E-07^{a}	9.4E-07^{a}	-2.4E-07^{c}	-5.2E-06^{b}	-2.2E-04^{a}
		(4.02)	(4.60)	(3.83)	(4.41)	(-1.69)	(-2.24)	(-4.79)
size ratio	100%	0.104^{a}	-0.008	0.094^{a}	0.004	-0.031^{a}	-0.498^{b}	1.455
		(4.54)	(-1.47)	(3.19)	(0.21)	(-2.62)	(-2.08)	(0.50)
swap spread	bp	0.148^{a}	0.011	0.285^{a}	0.031	0.079^{a}	-0.836^{c}	5.015^{a}
		(2.81)	(1.02)	(4.13)	(0.98)	(13.79)	(-1.89)	(2.68)
neg. swap spread		-2.938^{a}	-0.065	-2.965^{a}	0.167	0.168	25.268^{a}	-110.244^{a}
		(-4.59)	(-0.65)	(-4.11)	(0.62)	(1.11)	(4.38)	(-3.51)
volatility	bp	-0.345^{c}	0.004	-0.300	0.020	0.066	-0.777	-2.870
		(-1.90)	(0.13)	(-1.54)	(0.33)	(1.13)	(-0.52)	(-0.48)
exp. auction size	bill	0.030^{a}	-0.001	0.018^{b}	0.003	0.006^{c}	0.332^{a}	0.097
		(3.63)	(-0.45)	(2.02)	(1.01)	(1.82)	(3.85)	(0.24)
Savings Bank		0.021	0.051	-0.375^{a}	-0.354^{a}	-0.177^{b}	6.717^{a}	-203.948^{a}
		(0.33)	(0.93)	(-3.15)	(-3.30)	(-2.33)	(5.60)	(-5.35)
Cooperative Bank		-0.365^{a}	-0.408^{a}	-0.465^{a}	-0.480^{a}	0.167^{a}	6.731^{a}	-347.479^{a}
		(-5.67)	(-7.59)	(-4.75)	(-5.39)	(2.97)	(5.39)	(-12.17)
Foreign Bank		-0.144	-0.088	-0.577^{a}	-0.587^{a}	-0.039	11.092^{a}	-87.065^{c}
		(-1.20)	(-1.05)	(-4.06)	(-4.72)	(-0.39)	(5.21)	(-1.93)
Landesbank		-0.019	-0.068	0.166	0.228	0.248^{a}	-4.392^{a}	-267.867^{a}
		(-0.27)	(-1.19)	(1.05)	(1.37)	(3.48)	(-2.97)	(-7.38)
Coop Central Bank		-0.021	-0.183^{b}	0.096	-0.077	0.194^{b}	-3.370	-255.259^{a}
		(-0.14)	(-1.96)	(0.52)	(-0.47)	(2.23)	(-1.20)	(-4.01)
N uncensored		19,088	19,088	23,461	23,461	23,461	23,461	23,461

Panel b: Selection	units	Underpricing bp	Relative Underpricing bp	Discount bp	Relative Discount bp	Stopout Deviation bp	Award Ratio %	Demand to Res. Req. %
Constant		-3.779^{a}	-3.778^{a}	-3.525^{a}	-3.529^{a}	-3.525^{a}	-3.528^{a}	-3.406^{a}
		(-28.62)	(-28.44)	(-31.68)	(-31.20)	(-31.81)	(-31.44)	(-36.51)
ln(assets)	ln(mill)	0.244^{a}	0.244^{a}	0.264^{a}	0.264^{a}	0.265^{a}	0.263^{a}	0.273^{a}
		(25.82)	(25.77)	(28.53)	(28.30)	(28.64)	(28.49)	(25.96)
norm net excess reserves	%	-1.4E-06	-1.4E-06	-8.6E-07	-8.5E-07	-8.6E-07	-8.9E-07	-1.3E-05
		(-0.19)	(-0.19)	(-0.12)	(-0.12)	(-0.12)	(-0.13)	(-0.77)
Small x nex	%	-1.6E-05^{a}	-1.6E-05^{a}	-1.8E-05^{a}	-1.8E-05^{a}	-1.7E-05^{a}	-1.8E-05^{a}	-2.0E-05^{a}
		(-6.17)	(-6.14)	(-6.68)	(-6.65)	(-6.67)	(-6.64)	(-7.00)
Writeoffs & provisions	%	-3.767^{a}	-3.733^{a}	-3.125^{a}	-3.006^{a}	-3.160^{a}	-2.957^{a}	-5.122^{a}
		(-2.79)	(-2.79)	(-2.88)	(-2.79)	(-2.89)	(-2.74)	(-4.33)
Return on assets	%	-8.221^{a}	-8.219^{a}	-7.762^{a}	-7.748^{a}	-7.780^{a}	-7.708^{a}	-9.740^{a}
		(-6.24)	(-6.22)	(-6.94)	(-6.94)	(-7.01)	(-6.87)	(-8.03)
Equity ratio	%	0.006^{a}	0.006^{a}	0.003	0.003	0.003	0.003	-1.6E-04
		(2.68)	(2.67)	(1.45)	(1.44)	(1.47)	(1.47)	(-0.09)
imbalance	%	1.6E-06^{a}	1.6E-06^{a}	2.0E-06^{a}	2.0E-06^{a}	2.0E-06^{a}	1.9E-06^{a}	1.9E-06^{a}
		(2.93)	(2.92)	(3.24)	(3.25)	(3.22)	(3.28)	(3.12)
imbalance x nex	% x %	9.6E-11	9.7E-11	8.7E-11	8.7E-11	8.6E-11	9.1E-11	3.9E-10
		(0.55)	(0.56)	(0.48)	(0.48)	(0.47)	(0.51)	(1.16)
imbalance x ln(assets)	% x ln(mill)	-6.0E-08	-5.9E-08	-1.5E-07^{c}	-1.4E-07^{c}	-1.5E-07^{c}	-1.4E-07^{c}	-1.3E-07^{c}
		(-0.87)	(-0.85)	(-1.79)	(-1.77)	(-1.80)	(-1.77)	(-1.73)
size ratio	100%	0.018^{a}	0.018^{a}	0.019^{a}	0.020^{a}	0.019^{a}	0.019^{a}	0.017^{a}
		(5.89)	(5.92)	(6.80)	(6.82)	(6.74)	(6.78)	(4.91)
swap spread	bp	0.008^{a}	0.009^{a}	0.016^{a}	0.016^{a}	0.016^{a}	0.016^{a}	0.016^{a}
		(2.64)	(2.69)	(7.16)	(7.24)	(7.18)	(7.30)	(7.18)
neg. swap spread		-0.118^{c}	-0.117^{c}	-0.240^{a}	-0.239^{a}	-0.244^{a}	-0.235^{a}	-0.233^{a}
		(-1.92)	(-1.90)	(-4.09)	(-4.08)	(-4.15)	(-4.02)	(-4.25)
volatility	bp	0.027^{b}	0.027^{b}	0.027^{b}	0.028^{b}	0.027^{b}	0.028^{b}	0.022^{b}
		(2.02)	(2.03)	(2.35)	(2.37)	(2.37)	(2.39)	(2.29)
exp. auction size	bill	0.002^{a}	0.002^{a}	-7.6E-05	-3.0E-05	-7.4E-05	-2.9E-05	-2.2E-05
		(2.88)	(2.86)	(-0.10)	(-0.04)	(-0.09)	(-0.04)	(-0.03)
Savings Bank		0.207^{a}	0.208^{a}	0.166^{a}	0.166^{a}	0.165^{a}	0.166^{a}	0.117^{a}
		(7.09)	(7.09)	(6.92)	(6.89)	(6.84)	(6.91)	(5.96)
Cooperative Bank		-0.091^{a}	-0.091^{a}	-0.117^{a}	-0.117^{a}	-0.117^{a}	-0.117^{a}	-0.172^{a}
		(-3.24)	(-3.24)	(-4.88)	(-4.87)	(-4.85)	(-4.84)	(-7.82)
Foreign Bank		0.062	0.062	-0.022	-0.022	-0.022	-0.020	-0.055
		(1.14)	(1.16)	(-0.44)	(-0.43)	(-0.43)	(-0.39)	(-1.14)
Landesbank		0.062	0.063	0.156^{b}	0.153^{c}	0.156^{c}	0.143^{c}	0.029
		(0.77)	(0.78)	(1.96)	(1.93)	(1.95)	(1.82)	(0.38)
Coop Central Bank		-0.165	-0.164	-0.085	-0.087	-0.087	-0.094	-0.175
		(-1.21)	(-1.20)	(-0.67)	(-0.69)	(-0.69)	(-0.74)	(-1.55)
Maturing repo		2.431^{a}	2.431^{a}	2.352^{a}	2.351^{a}	2.351^{a}	2.351^{a}	2.047^{a}
		(58.41)	(58.36)	(60.20)	(60.01)	(60.28)	(59.55)	(14.57)
Last auction		2.439^{a}	2.491^{a}	1.807^{b}	1.940^{b}	1.722^{b}	1.999^{a}	1.503^{b}
		(2.86)	(2.90)	(2.23)	(2.41)	(2.17)	(2.66)	(2.14)
N		164,746	164,746	169,119	169,119	169,119	169,119	169,119

Panel c: Parameters. Standard errors are in italics and smaller font. b denotes significance (two-tailed) at the 5% level.

	Underpricing	Relative Underpricing	Discount	Relative Discount	Stopout Deviation	Award Ratio	Demand to Res. Req.
Log pseudolikelihood	-69721	-63710	-93279	-89687	-79036	-149881	-219179
Prob>chi2	0.372	0.021	0.027	0.000	0.002	0.000	0.000
rho	-0.034	0.049^{b}	0.083^{b}	0.129^{b}	0.071^{b}	-0.219^{b}	0.630^{b}
	0.038	*0.021*	*0.037*	*0.030*	*0.023*	*0.031*	*0.082*
sigma	2.352^{b}	1.717^{b}	3.235^{b}	2.784^{b}	1.762^{b}	36.490^{b}	714.128^{b}
	0.138	*0.139*	*0.321*	*0.302*	*0.155*	*0.965*	*68.027*
lambda	-0.080	0.085^{b}	0.268^{b}	0.360^{b}	0.125^{b}	-7.975^{b}	449.658^{b}
	0.091	*0.037*	*0.110*	*0.066*	*0.043*	*1.108*	*89.412*

Appendix 2: Volatility of Swap Rate

To estimate the conditional volatility of the two week swap rate, we apply a modified GARCH(1,1) model (Bollerslev, 1986) to daily rate changes. We have considered various calendar effects, as in Hamilton (1996), but not all are in the final specification. Our model is based on that in Nyborg et al (2002). However, our final specification has a somewhat better fit in the period we are studying as compared to their's.

Table 8: Conditional Volatility of Swap Rate

This table reports the results of the conditional volatility estimation of the two-week swap rate, using a modified GARCH(1,1) model. Panel (a) gives the coefficients of the mean equation, while panel (b) gives the coefficients of the variance equation.

Slope is the difference between 12 and 1 month Euribor. (-1) stands for the preceding day's observation Downswap takes the value 1 if the swap rate fell the previous day and 0 otherwise. ECBMEET(-1) is 1 if there was a meeting of the ECB Governing Council the previous day. Underbid(-1) is 1 if there was an underbid auction. (An auction is underbid if total demand is less than the liquidity neutral amount. For this purpose, total demand is the demand of all, not only German, bidders. See Nyborg et al (2002) for a discussion of underbid auctions.) Endmonth takes the value 1 if the day is the last business day of a month and 0 otherwise, Endres takes the value 1 if the day is the last business day of a reserve maintenance period and 0 otherwise. Endres(-1) is a dummy variable for the first business day in a maintenance period. Mainrepo takes the value 1 if the day is an auction day (main refinancing operation) and 0 otherwise.

	Coefficient	z-statistics
Panel (a): Mean equation		
Constant	-0.003	-1.181
Slope(-1)	0.015	2.686
Downswap(-1)×ECBMEET(-1)	0.023	2.289
Downswap(-1)×Underbid(-1)	-0.073	-12.91
Panel (b): Variance equation		
C	0.002	7.982
ARCH(1)	0.123	3.188
GARCH(1)	0.565	8.782
Endmonth	-0.003	-10.657
Endres(-1)	-0.002	-9.215
Endres	-0.002	-6.265
Mainrepo	-0.0005	-4.042