The 2007 Subprime Market Crisis Through the Lens of European Central Bank Auctions for Short-Term Funds*

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Abstract

We study European banks' demand for short-term funds (liquidity) during the summer 2007 subprime market crisis. We use bidding data from the European Central Bank's auctions for one-week loans, their main channel of monetary policy implementation. Our analysis provides a high-frequency, disaggregated perspective on the 2007 crisis, which was previously studied through comparisons of collateralized and uncollateralized interbank money market rates which do not capture the heterogeneous impact of the crisis on individual banks. Through a model of bidding, we show that banks' bids reflect their cost of obtaining short-term funds elsewhere (e.g., in the interbank market) as well as a strategic response to other bidders. The strategic response is empirically important: while a naïve interpretation of the raw bidding data may suggest that virtually all banks suffered an increase in the cost of short-term funding, we find that for about one third of the banks, the change in bidding behavior was simply a strategic response. We also find considerable heterogeneity in the short-term funding costs among banks: for over one third of the bidders, funding costs increased by more than 20 basis points, and funding costs vary widely with respect to the country-of-origin. The funding costs we estimate using bidding data are also predictive of market- and accounting-based measures of bank performance, reinforcing the usefulness of "revealed preference" information contained in bids.

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1 Introduction

The "subprime credit crisis of 2007" is widely thought to have hit the European money markets after the August 9, 2007, when the French bank BNP Paribas announced its decision to freeze three investment funds with exposure to the U.S. subprime home-loan market.[1] The announcement was accompanied by a jump in uncollateralized lending rates in the interbank money market. In Figure 1, we follow Taylor & Williams (2009) and plot the spread between the (1-week) EURIBOR[2], a measure of the interbank uncollateralized rate, and the (1-week) EUREPO, the rate for fully collateralized loans on the interbank market. After the second week of August 2007, the gap between these rates significantly widened: the premium a lender required for an unsecured loan to a prime bank in the interbank market after August 2007 increased from around 4 basis points to well over 10 basis points for loans with a one-week maturity.

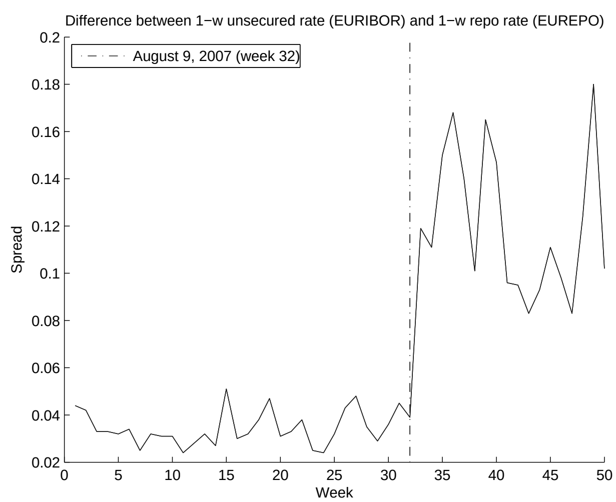


Figure 1: Spread between the unsecured and secured lending rates

[1]The combined value of the funds was €1.59 billion ($2.19 billion) (Wall Street Journal, August 10-12, 2007).

[2]EURIBOR, Euro Interbank Offer Rate, is a survey based daily reference rate based on the reports of panelist banks which provide information regarding the rates at which they expect to lend unsecured funds to other banks in the euro interbank market.

While yield spreads are useful indicators of aggregate credit market conditions, the heterogeneity of the impact of the crisis across system banks is also a vital input into many policy analyses. By understanding which banks were impacted more than others, one can gain more insight into the drivers of risk in the financial system.[3] Unfortunately, obtaining high-frequency data on individual banks' borrowing/lending rates is difficult, because most interbank transactions take place on an over-the-counter basis, or through anonymized trading. Therefore, the measures employed in most analyses are based on accounting/balance sheet information that is disclosed infrequently, or "market-based" information available from publicly-traded banks' share prices, credit-default swap (CDS) rates, or credit rating adjustments.

This paper utilizes recent developments in the analysis of multi-unit auctions to present a new source of "revealed preference" information on individual funding costs during the 2007 credit crisis. Our analysis is based on banks' bidding behavior in the European Central Bank's weekly refinancing operations. Every week in this period, the ECB auctioned loans with 1-week maturity to banks who offered the highest interest rates and were willing to put up the appropriate collateral to be repurchased after the loan matures. This is a funding channel that is utilized by a large number of banks in Europe, and one that became even more popular during the liquidity crisis, as the ECB's collateral requirements were not as stringent as the interbank market's.

A quick glance at the aggregate bids, which are just horizontal sums of individual bids submitted by all participants in an auction, reveals a significant change in bidding behavior for auctions before and after August 9, 2007 . Figure 2 shows the aggregate bids (normalized by subtracting the EONIA swap rate[4]). Before August 9, 2007 all aggregate bids (depicted with solid lines) were highly concentrated around the EONIA swap rate (i.e., around 0 on the vertical axis in the graph). After August 9, a significant upward shift and increased (both across and within auction) heterogeneity in aggregate bids is quite evident.

[3] We should emphasize that, unlike the Fed, the ECB does not have supervisory/regulatory authority over European banks. Such powers are exercised by national central banks and/or regulation agencies. However, the ECB can advise national central banks with regards to the "stresses" in the financial system.

[4] An "EONIA swap" is an interest rate swap transaction, where one party agrees to receive/pay a fixed rate to another party, against paying/receiving a floating rate termed EONIA (Euro OverNight Index Average), which is an average of all actual overnight unsecured transactions. The swap rate is viewed as an indicator of industry expectations of the relevant market interest rates because it can be used with overnight borrowing as an alternative to bidding in the repo auctions.

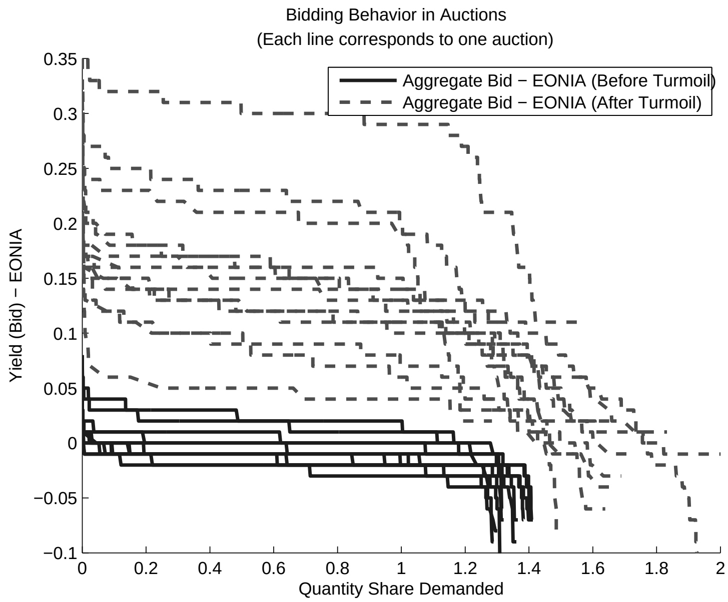


Figure 2: Aggregate bids (horizontal sum of individual bids in an auction)

While the dramatic shift in aggregate bids in ECB's liquidity auctions parallels developments in interbank markets, our analysis shows that the distinction between "bids" and "willingness-to-pay" is very important in this market. As we illustrate in Section 4 and Section 6, although virtually all banks' bidding behavior changed dramatically after August 9, this does not necessarily indicate a shift in all banks' *willingness-to-pay* for ECB provided liquidity. Even if some bidders did not experience a change in their costs of short-term funds from alternative sources, presumably because of their solid balance sheets and lack of exposure to problematic assets, these bidders rationally would have to adjust their bids as a best-response to a subset of "distressed" competitors' higher willingness-to-pay for ECB provided liquidity. Indeed, in Section 6 we show that for about one third of the participants, the observed change in bidding behavior was simply a strategic response: while their costs of obtaining short-term funds stayed the same (and thus willingness-to-pay also did not change), they increased their bids in order to best-respond to the higher bids of their rivals.

As for the bidders whose willingness-to-pay for ECB-provided liquidity increased significantly after August 2007, it is important to understand the determinants of this shift. We first demonstrate that the increase in liquidity demand was much more severe on some banks than others: for over $\frac{1}{3}$

of banks participating in the primary liquidity auctions willingness to pay for ECB loans increased by more than 20 basis points. There is also heterogeneity in the incidence of the crisis with respect to banks' country-of-origin. Some of these country-specific woes may have been predictable: in Section 6.3.1, we show that banks from member countries that relied less on ECB funding before August 2007 appear to have suffered less from the crisis.

To further investigate what led to the shifts in demand for liquidity at the bank level, we use in Section 6.4 an auxiliary dataset on a smaller subset of banks' credit default swap (CDS) rates and their reserve requirements with the ECB. We demonstrate that this increase in willingness-to-pay for ECB liquidity is linked to a deterioration in credit/default ratings (as measured by CDS rates), and to banks' worries about satisfying the reserve requirements. There is also some substitution to the ECB-provided loans with longer maturities.

Although "market-based" measures of banks' financial health such as CDS rates and stock prices are closely monitored by market participants and policymakers, the majority of banks in Europe do not have credit-default swaps traded on their bonds, and/or are not publicly traded themselves. Most of the information that is made available by such non-publicly traded banks is limited to balance sheets that are disclosed quarterly and sometimes annually. A natural question to ask, therefore, is whether the individual short-term liquidity demands we estimate using the auction data are at all related to the performance measures reported in bank balance sheets. Indeed, in Section 6.4.2, we find that the estimated marginal valuations of banks are predictive of several widely used performance measures (return-on-equity, return-on-assets, cost-to-income ratio) that are reported at the end of 2007 (i.e. the end of the auction sample we study). Moreover, we find that marginal values are much better predictors of these performance measures than the bids themselves. This suggests that extracting away the "strategic" component of bids leads to much improved measures of banks' liquidity costs, and eventually profits. Moreover, the latter finding can also be interpreted as a test of strategic behavior in the ECB auctions.

As we indicate in Section 5, banks' willingness-to-pay for ECB loans in the repo auctions should be closely linked to their outside options of procuring liquidity through the (unsecured and/or secured) interbank markets. Thus, banks bids provide a useful "lens" through which we can analyze developments in the largely opaque interbank credit market. Specifically, banks' willingness to pay for ECB loans (which are collateralized) should be between their fully collateralized and uncollateralized borrowing in the interbank market. Our data indicates that while such a relationship between banks' revealed willingness-to-pay and *reported* borrowing rates existed in the pre-crisis period, it broke down in the post-crisis period. As the starkest demonstration of this point, on several occasions after the turmoil, the market clearing interest rate for *collateralized* loans issued through the primary auctions (which constitutes a lower bound on the willingness-to-pay for the marginal bank under normal circumstances) was *higher* than the reported interest rate for the *unsecured* loans issued in the interbank market. In section 6.3, we present detailed evidence that the reported unsecured interest rates (EURIBOR in the EURO context) failed to reflect the "actual" unsecured borrowing rates that were faced by a large number of banks in the EURO area, a finding echoed in the recent settlement by Barclays with US and UK regulators regarding manipulations of the LIBOR and EURIBOR (Barclays 2012).

Our results suggest that studying the evolution of banks' willingness-to-pay for liquidity may be useful for studying the state of individual banks and interbank lending markets. While many questions may be answered with balance sheet data, its low frequency and the fact that it is based on disclosures rather than observed actions of the banks make the readily available data from bidding in weekly liquidity auctions more attractive. Moreover, we show that even the relatively high-frequency "market" based performance measures such as CDS or stock price data do not seem to explain much of the contemporaneous variation in the willingness-to-pay for liquidity. Recent advances in multi-unit auction theory and in empirical methods for modelling auction markets allow us to recover the willingness-to-pay directly from the bids.[5] That said, before using this or similar data for explicit regulatory purposes, one should be wary of the "gaming" incentives that may be induced by such a move.

[5] See Athey & Haile (2009) or Hendricks & Porter (2007) for surveys of recent advances in empirical methods and Milgrom (2004) for an excellent auction theory overview.

2 Turmoil in the Literature

The significance of the 2007 financial crisis for the evolution of the world economy is widely recognized, with numerous leading economists providing their thoughts on the crisis in the winter 2009 issue of the Journal of Economic Perspectives.[6] Painting an aggregate picture of the crisis in an influential series of papers, (Taylor & Williams 2008, Taylor & Williams 2009) have argued that the increase in the spread between the term swap rates used to proxy the expectations of overnight lending rates of financial market participants and the rates for unsecured term loans is probably caused by an increase in the counter-party risk.[7] In particular, after the news about the extent of highly risky subprime loans among securities with highest ratings held by many banks in their portfolios, there was a sudden shift in the probability of default. Looking at the difference between the secured and unsecured loan rates, Taylor and Williams argue that the increase in spread indeed seems to be due to this effect.[8] Afonso, Kovner & Schoar (2011) use data from the overnight interbank market to argue that counterparty risk seemed to play a much larger role than liquidity hoarding in the time period following Lehman Brothers' bankruptcy.

In a short article, Chari, Christiano & Kehoe (2008) argue that, while there is clear evidence of a financial crisis, some of the often cited sources of this crisis, including the tougher access to liquidity in the interbank market, are not consistent with publicly available aggregate data. Cohen-Cole, Duygan-Bump, Fillat & Montoriol-Garriga (2008) point out that the aggregate figures may be missing a lot of details, but Christiano (2008) disagrees on the whole with their arguments. In this paper we show that by looking at aggregate data a researcher indeed might miss the relevant changes in the structure of liquidity demands: while the aggregate demand may have stayed the same, many banks substituted from the secondary (interbank) market to the primary one, and the collapse of the secondary market may have important implications for allocative efficiency and

[6] See e.g., Brunnermeier (2009) and Cecchetti (2009).

[7] In contrast, some papers (e.g. Wu 2008) argue that the increased spread is due to "liquidity risk" stemming from increased uncertainty about future liquidity needs of each bank, which in turn increases banks' reluctance to lend long term.

[8] As is the case of the U.S., the secured (EUREPO) and overnight swap rates (EONIA swap) are highly correlated in the Euro area. Taylor & Williams (2009) argue that both rates are close to being riskless, and could be considered close to perfect substitutes. Although it is a collateralized rate, there is some risk in EUREPO due to potential problems in the delivery or return of collateral. EONIA swaps are subject to some risk, in that one of the parties may default and the remaining party is subject to the differential in the fixed and overnight components of swap. In our data, EURIBOR-EUREPO spreads and the EURIBOR-EONIA spread are almost perfectly correlated.

credit availability. The increased heterogeneity of willingness-to-pay for liquidity in the post-turmoil period, and the failure of the interbank market to lead to an efficient allocation of liquidity among banks render the primary auctions (or open market operations) of the central banks crucial in improving the performance of the liquidity markets by correcting the misallocation.

Bidding data from repo auctions of the ECB have been studied previously in Bindseil, Nyborg & Strebulaev (2009). They describe many interesting details of this market and compare these auctions to those of Treasury bills by studying auctions between June 2000 and June 2001. Among other things, they argue that the common value component seems much less important in the central bank repo auction than in T-bill auctions, which substantiates our using the private-values framework. A similar approach was used in Hortaçsu & Kastl (forthcoming) to analyze Canadian T-bill auctions or in Chapman, McAdams & Paarsch's (2007) analysis of Canadian Receiver General auctions of cash. While the setting Chapman et al. analyze is the closest to ours, the objective of their analysis is quite different. Their main interest lies in investigating whether bidders' behavior in these auctions is consistent with best-response assumptions. They find that violations of best-responses are frequent, but the extent of these violations is small and that bidders' strategies are close to the best-responses. Our approach is to assume that bidders play best-responses and our goal is to use the estimated model to analyze the forces behind bidders' choices and to analyze the impact of the financial turmoil by studying the link between the willingness-to-pay in the repo auctions and alternative sources of funding.

3 Primary Auctions of Liquidity in the EURO Area

In this paper we focus on the auctions of liquidity, which are part of the Main Refinancing Operations (MROs)[9] of the ECB. They are auctions of collateralized loans with one-week maturity, conducted every week. The main function of the MROs (at least before the turmoil period) is to provide liquidity to the market. They are pivotal in steering interest rates (through the minimum bid rate), to manage liquidity in markets, and to signal the stance of monetary policy.

Before each auction, a bank that wants to participate will submit bids specifying the rate and

[9] See Section B.2.2 in the appendix for more details.

the quantity it is willing to transact with the ECB to the national central bank of the member state where the institution is located (has a head office or branch). The bids of an institution may be submitted by only one establishment in each member state. Banks may submit bids for up to ten different interest rate levels; hence, a bid in these auctions can be thought of as a demand function. The ECB then collects the bids and determines the maximum rate at which the demand weakly exceeds the supply. All bids for higher rates are satisfied and demands at the marginal rate are rationed proportionally. During the time span of our dataset the ECB has used only the discriminatory auction format, but it has the right to change the mechanism at any time. All winning bidders thus had to pay their full bids (i.e., rates) for the allocated liquidity.

After each auction, the ECB publicly reveals the following about the outcome: % marginal (market clearing) bid rate, allotment at marginal rate, total amount allotted, weighted average allotment rate, total number of participating bidders, minimum rate of all bids, and maximum rate of all bids. No additional data that would provide information on demands by individual banks are revealed.

The loans obtained in these auctions have to be collateralized. In particular, banks are expected to cover the amounts allotted to them with a sufficient level of eligible assets (collateral) discussed in more detail in section B.2.3. Penalties can be applied by the national central banks in case of a failure to deliver the collateral. The eligible collateral is broader than collateral generally accepted for loans at the EUREPO rate on the interbank (secondary) market, even more so after the turmoil. Nevertheless, the ECB applies valuation haircuts as risk control measures.

Table 1 shows the relative weight for the categories of eligible assets used by Eurosystem counterparties. It illustrates that banks substitute illiquid collateral (uncovered bank bonds, asset-backed securities) for highly liquid collateral (central government securities).[10] This trend accelerated after the turmoil with a sharp increase in asset-backed securities; however, it reflects a medium-term development that has been ongoing for a while and is not strictly related to the turmoil.

With this relevant background, we are ready to describe our dataset in detail and go on to estimate a model of bidding in the repo auctions.

[10] See also Ewerhart & Tapking (2008).

Table 1: Structure of Collateral Pledged Against the MROs

	2004	2005	2006	2007	2008
Central government securities	0.52	0.50	0.48	0.46	0.42
Regional government securities	0.03	0.03	0.03	0.03	0.03
Uncovered bank bonds	0.12	0.14	0.16	0.17	0.20
Covered bank bonds	0.16	0.15	0.14	0.12	0.11
Corporate bonds	0.09	0.09	0.09	0.09	0.08
Asset-backed securities	0.04	0.05	0.06	0.08	0.09
Other marketable assets	0.04	0.04	0.04	0.04	0.05
Non-marketable assets	0.01	0.01	0.01	0.01	0.02

4 Data

Our unique dataset consists of all submitted bids in 50 regular discriminatory (pay-your-bid) repo auctions of liquidity provided via collateralized loans with 1-week maturity conducted as part of the regular MROs of the ECB between January 4, 2007 and December 11, 2007.

In the full sample, there are, on average, 341 participating bidders (banks) in an auction. There are 733 unique bidder-identities, which suggests that only about one half of potential bidders participate in any given auction. Participants submit bids with very few steps (price-quantity pairs): only 1.66 on average. The banks demand is about 1 billion EUR at 3.94%, which is, on average, about 4 basis points higher than the EONIA rate.

Table 2 illustrates the change in means and standard deviations following the turmoil of August 2007. There are several interesting differences: the increase in the number of steps in each bid (from 1.47 to 2.02), the decrease in the amount of liquidity offered for sale (from 292.34 to 202.19 billions EUR) and, perhaps most importantly, the increase in the spread between the bids and the EONIA rate (from 0 to 10 basis points). Recall that in a discriminatory auction, a bidder would do best if she knew the market clearing rate beforehand and thus was able to submit a single bid equal to that rate for an amount at which her marginal value equaled that interest rate. Figure 3 shows that there is a clear first-order stochastic dominance relationship between the empirical cumulative distribution functions before and after the turmoil. A potential explanation for this phenomenon might be that some bidders simply needed to make sure that they received at least some minimal level of liquidity in the primary market; therefore, they submitted inframarginal bids for which they were willing to pay a premium over the market clearing rate.

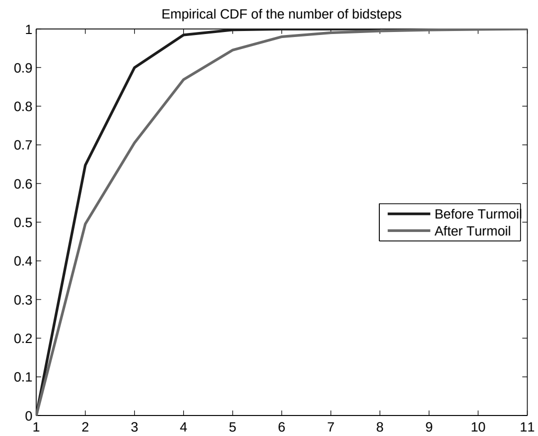


Figure 3: Distribution of the number of steps in a bid before and after the turmoil

Table 2: Data Summary: Before and After August 2007

Summary Statistics				
	Mean		Std Dev	
	Before	After	Before	After
Bidders	348.6	328.1	20.88	34.37
Submitted steps	1.47	2.02	0.73	1.34
Price bid	3.80	4.13	0.20	0.06
Price bid spread[a]	0.00	0.10	0.02	0.08
Quantity bid	0.004	0.005	0.009	0.014
Issued Amount (billion €)	292.34	202.19	1.42	4.51

[a] Spread against EONIA rate.

After August 2007 the bids become much more dispersed, as shown by the aggregate bids depicted with dashed-dot lines (-.) in Figure 2. In each auction the aggregate bid also becomes much steeper relative to the aggregate bids before the turmoil, which are depicted as solid lines. As we noted in the introduction, however, bids are determined in equilibrium as a function of the willingness-to-pay, and a strategic effect due to competition from other bidders. Therefore, we now build a model that will allow us to uncover the unobserved willingness-to-pay from the bids.

5 Model and Estimation Framework

Our analysis is based on the share auction model of Wilson (1979) with private information.[11] We first discuss the setup of the model of a discriminatory auction relevant for our setting, and next characterize its equilibrium.

5.1 Setup

The following assumptions describe the setup of our model.

Assumption 1 *(Bidders) There are N_t potential bidders who may participate in auction t.*

This assumption is reasonable in the present context as all bidders register with the ECB before the auction and the list of registered participants is publicly available.

Assumption 2 *(Information) Bidder i's information set at the time of auction t consists of (ω_t, θ_{it}). ω_t is a vector of valuation-relevant variables observed by all potential bidders, but not necessarily by the econometrician, and θ_{it} is a vector of private signals observed by bank i.*

In our context, ω_t contains publicly available information observed by bidders prior to the auction, including relevant market rates, the number of potential bidders (N_t), economic indicators and announcements. θ_{it} could include a bank's private information about its reserve/funding requirements, collateral availability, and the funding rates it faces in the secondary markets, which affect the bank's willingness-to-pay for ECB liquidity.

Assumption 3 *(Conditional Independence) Conditional on ω_t, θ_{it} are independent across potential bidders i.*

Assumption 4 *(Private Values) Bank i's ex-post willingness-to-pay for ECB liquidity in auction t is given by a marginal valuation function of the form $v_{it}(q, \theta_{it}, \omega_t)$. $v_{it}(.)$ is weakly decreasing in q.*

[11] The discriminatory auction version of Wilson's model with private values has been studied in Hortaçsu & McAdams (2010) in the context of Turkish treasury bill auctions. Kastl (2011) and Kastl (2012) extend this model to an empirically relevant setting, in which bidders are restricted to use step functions with limited number of steps as their bidding strategies. The estimation of this model is described in detail in Hortaçsu & Kastl (forthcoming). Several related theoretical papers on divisible good auctions, such as Ausubel & Cramton (2002), Back & Zender (1993) or Wang & Zender (2002) focus on the properties of equilibria.

The above two are the most restrictive assumptions we will impose on the data. Importantly, *conditional* on ω_t and θ_{it}, bidders' marginal valuations do not depend on the private information of other bidders. One motivation for this specification is that since after the crisis the interbank markets dried out, the speculative reasons for obtaining liquidity in the ECB's auctions motivated by potential resale opportunities were not likely present. Moreover, Bindseil et al. (2009) provide some econometric evidence that private values might be appropriate in case of repo auctions in the pre-crisis period.[12]

In the pre-turmoil period the actual amount of liquidity allocated in the auction by the ECB differed only slightly from the pre-announced supply, but as Figure 15 illustrates the deviations became quite substantial in the post-turmoil period. We assume that bidders rationally expected the ECB to deviate from the announced benchmark. We thus assume that the supply of liquidity available in a given week, Q_t, is uncertain from the perspective of each bidder. For notational convenience, we also define the per-rival supply as $\tilde{Q}_t \equiv \frac{Q_t}{N_t - 1}$.

Assumption 5 *(Supply Uncertainty) The total amount of liquidity being auctioned at time t, Q_t is a random variable from the perspective of any bidder. Amount of liquidity per rival, $\tilde{Q}_t$, is therefore also random and follows a distribution $M\left(\tilde{Q}_t|\omega_t\right)$, which is common knowledge among the bidders and which has a strictly positive density $m\left(\tilde{Q}_t\right)$ on $\left[\underline{Q}, \overline{Q}\right]$. Conditional on ω_t, $\tilde{Q}_t$ is independent of θ_{it}.*

With this setup, we define bidders' pure strategies as mappings from private signals to the set of allowable *bid functions* $\mathcal{Y}$. Since in most divisible good auctions in practice, including the liquidity auctions of the ECB, the bidders' choice of bidding strategies is restricted to non-increasing step functions with an upper bound on the number of steps, $K = 10$, we also impose the following assumption:

[12] If the cost of funding for each bank would be observable to the researcher ex post, one could attempt a formal test of private values. Employing a strategy similar to Hendricks, Pinkse & Porter (2003) or using deconvolution methods as in Bonhomme & Robin (2010) to gauge the relative importance of the common value component might be an interesting direction for future research.

Assumption 6 *(Actions) Each player $i = 1, ..., N$ has an action set:*

$$A_i = \left\{ \begin{array}{c} \left(\vec{b}, \vec{q}, K_i\right) : \dim\left(\vec{b}\right) = \dim\left(\vec{q}\right) = K_i \in \{1, ..., 10\}, \\ b_{ik} \in B = [0, \infty), \ q_{ik} \in [0, 1], \ b_{ik} > b_{ik+1}, q_{ik} < q_{ik+1} \end{array} \right\}.$$

where a bid of 0 denotes non-participation.

Therefore, the set $\mathcal{Y}$ includes all non-decreasing step functions with at most 10 steps, $y : \mathbb{R}_+ \to [0, 1]$, where $y_i(p) = \sum_{k=1}^{K} q_{ik} I(p \in (b_{ik+1}, b_{ik}])$ where I is an indicator function. A bid function for type θ_i specifies for each price p, how big a share $y_i(p|\theta_i)$ of the securities offered in the auction (type θ_i of) bidder i demands.[13]

Because bidders' strategies are step functions, the residual supply will be a step function and hence but for knife-edge cases any equilibrium will involve rationing with probability one. Consistently with our application, we assume rationing pro-rata on-the-margin, under which the auctioneer proportionally adjusts the marginal bids so as to equate supply and demand.[14]

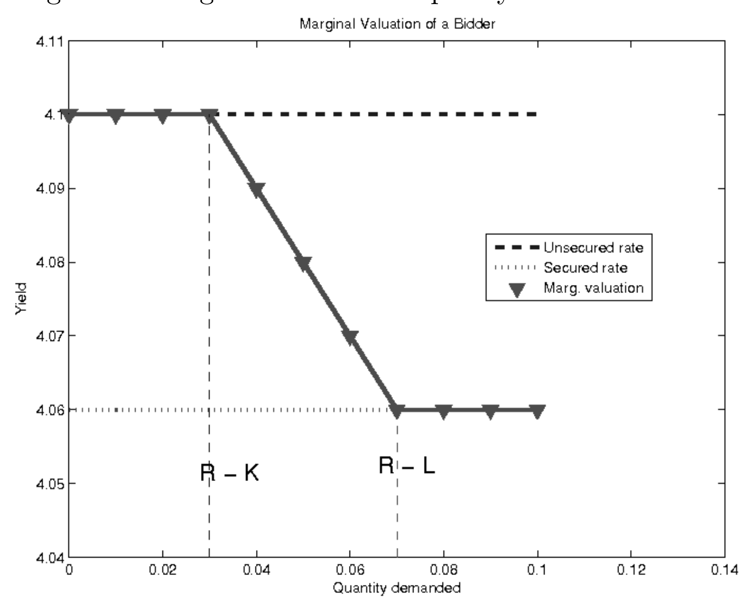
We note that while our model specifies banks' marginal valuations for ECB liquidity as the main economic primitive, due to the substitutable nature of ECB and interbank loans, these demand functions are very much dependent on a bank's outside funding opportunities. Specifically, consider the following stylized model in which bank i has a liquidity need (possibly due to a reserve requirement, to improve its balance sheet, or to close a funding gap) of R_{it} at time t. This must be fulfilled through three alternative channels: 1) ECB primary auctions, 2) unsecured interbank lending, which is done through over-the-counter deals, or 3) secured interbank lending, which is also done over-the-counter. These channels are substitutes, but access to them is limited based on collateral availability. In particular, assume that bank i has L_{it} units of "liquid", high-quality collateral acceptable by secured interbank lending counterparties. The bank also has $K_{it} - L_{it}$ units of securities that are acceptable by the ECB and perhaps by other counterparties as collateral, but are subject to "haircuts." The haircuts applied to this set of securities effectively increase the interest

[13] To ease notation, we will later surpress the conditioning on ω_t.

[14] Under rationing pro-rata on-the-margin the rationing coefficient at market clearing price P^C satisfies $R(P^c) = \frac{Q - TD_+(P^c)}{TD(P^c) - TD_+(P^c)}$ where $TD(P^c)$ denotes total demand at price P^c, and $TD_+(P^c) = \lim_{p \downarrow P^c} TD(p)$. Also, since bidders use step functions, a situation may arise in which multiple prices would clear the market. If that is the case, we assume consistently with our application that the auctioneer selects the most favorable price from his perspective, i.e., the highest price.

rate at which the bank can borrow against these securities; these rates are bounded below by the "secured" interbank lending rate, s_{it}, that the bank faces, and bounded above by the "unsecured" interbank lending rate, u_{it}, which requires no collateral. The marginal value for obtaining liquidity in the auctions run by the ECB can therefore be represented as in Figure 4, where we assume the bank's total collateralized borrowing capacity, K_{it}, to be less than its liquidity need R_{it}. The bank's willingness-to-pay for the first $R_{it} - K_{it}$ euros of funding, thus, is equal to its unsecured funding rate, u_{it}. Between the $R_{it} - K_{it}$ and $R_{it} - L_{it}$, the bank faces different haircut rates depending on its portfolio of securities it can post as collateral. The last L_{it} euros of funding can be obtained from the "secured" interbank market, thus the bank's willingness-to-pay for these units is s_{it}. In our model, we will assume that $\{R_{it}, K_{it}, L_{it}, u_{it}, s_{it}\}$ are independent across banks conditional on ω_t.

Figure 4: Marginal Value for Liquidity in ECB Auctions



5.2 Equilibrium

Our solution concept is Bayesian Nash Equilibrium, which is a collection of functions $y_i(\cdot|\theta_i)$ such that almost every type θ_i of bidder i is choosing his bid function so as to maximize his expected utility from participating in the auction. The expected utility of type θ_i of bidder i who employs a strategy $y_i(\cdot|\theta_i)$ given that other bidders are using $\{y_j(\cdot|\cdot)\}_{j\neq i}$ can be written as:

$$EU_i(\theta_i) = E_{Q,\theta_{-i}|\theta_i}\left[\begin{array}{c} \int_0^{q_i^c(Q,\theta,\mathbf{y}(\cdot|\theta))} v_i(u,\theta_i)\,du \\ -\sum_{k=1}^{K} \mathbf{1}\left(q_i^c(Q,\theta,\mathbf{y}(\cdot|\theta)) > q_k\right)(q_k - q_{k-1})\,b_k \\ -\sum_{k=1}^{K} \mathbf{1}\left(q_k \geq q_i^c(Q,\theta,\mathbf{y}(\cdot|\theta)) > q_{k-1}\right)\left(q_i^c(Q,\theta,\mathbf{y}(\cdot|\theta)) - q_{k-1}\right) b_k \end{array}\right] \tag{1}$$

where $q_i^c(Q,\theta,\mathbf{y}(\cdot|\theta))$ is the (market clearing) quantity bidder i obtains if the state (bidders' private information and the supply quantity) is (θ, Q) and bidders bid according to strategies specified in the vector $\mathbf{y}(\cdot|\theta) = [y_1(\cdot|\theta_1), ..., y_N(\cdot|\theta_N)]$, and similarly $P^c(Q,\mathbf{s},\mathbf{y}(\cdot|\theta))$ will denote the market clearing price associated with state (θ, Q). The distribution of this random variable is an important ingredient in the bidder's optimization problem. The first term in (1) is the gross utility the type θ_i enjoys from his allocation, the second term is the total payment for all units allocated at steps at which the type θ_i was not rationed and the final term is the payment for units allocated during rationing.

Part (i) of the following proposition, which is proved in Kastl (2012), provides necessary conditions characterizing the equilibrium in discriminatory auctions with private values when marginal valuation function is continuous in q. These conditions are derived by ruling out profitable deviations in quantity demanded, and are described in part (i) of Proposition 1 below. Since the continuity of the marginal valuation function might be questionable at the last step (in particular for bidders who submit just one step), we make use of a different necessary condition for optimality with respect to the bid, which is described in part (ii).[15]

Proposition 1 *Under assumptions 1-6 in any Bayesian Nash Equilibrium of a Discriminatory Auction, for almost all θ_i, with a bidder of type θ_i submitting $K_i(\theta_i) \leq 10$ steps, every step k in the equilibrium bid function $y_i(\cdot|\theta_i)$ satisfies the following necessary conditions for optimality:*

(i) $\forall k < K_i(\theta_i)$ and $v(q,\theta_i)$ is continuous in a neighborhood of q_k

$$v(q_k,\theta_i) = b_k + \frac{\Pr(b_{k+1} \geq P^c)}{\Pr(b_k > P^c > b_{k+1})}(b_k - b_{k+1}) \tag{2}$$

[15]It is easy to show that as $K \to \infty$, i.e., as the submitted bid becomes a continuous function, the necessary conditions for the choice of q_k and b_k converge to the same optimality condition, which was characterized by Wilson (1979).

and at the final step $K_i(\theta_i)$*:*

$$b_K = v(\overline{q}, \theta_i)$$

where $\overline{q} = \sup_{(Q,\theta_{-i})} q_i^c(Q, \theta, \mathbf{y}(\cdot|\theta))$*, i.e., the largest quantity allocated to type* θ_i *in equilibrium.*

(ii) $\forall k \leq K_i(\theta_i)$ *such that* $v(q, \theta_i)$ *is a step function in* q *at step* k *such that* $v(q, \theta_i) = v_k$ $\forall q \in (q_{k-1}, q_k]$*:*

$$v_k = b_k + \frac{\Pr(b_k > P^c)}{\frac{\partial \Pr(b_k > P^c)}{\partial b_k}} \tag{3}$$

In our setup, Proposition 2 of Kastl (2012) guarantees that an equilibrium (in distributional strategies) exists. The main goal of our econometric analysis is to estimate banks' marginal valuations for ECB liquidity. Equation (2) is our main identification equation; it describes the equilibrium relationship between bids and values. Using these necessary conditions, we obtain point estimates of the marginal values at submitted quantity-steps nonparametrically using a resampling method proposed in our earlier work (Hortaçsu & McAdams 2010, Hortaçsu & Kastl forthcoming). We extend this method in this paper to control for factors commonly observed by bidders but not the econometrician, i.e. ω_t. To do this, we show how the estimation method proposed in our earlier work can be used on data from a *single* auction to obtain consistent estimates of marginal valuations.

To review how the resampling method works, suppose there are N potential bidders that are (ex ante) symmetric and the supply is certain.[16] Then, fixing a bidder's bid, we draw (with replacement) $N-1$ actual bid functions from observed data. This simulates one possible state of the world from the perspective of the fixed bidder – a possible vector of private information – and thus results in one potential realization of the residual supply. Intersecting this residual supply with the fixed bid, we obtain a market clearing price. Repeating this procedure many times, we obtain an estimate of the full distribution of the market clearing price conditional on the fixed bid. Using this estimated distribution of market clearing price, we can obtain our estimates of marginal values at each submitted step using (2).

In the present context, it is quite conceivable that bids condition on a large number of factors

[16] Additional observed ex-ante heterogeneity among bidders (such as size) is easily incorporated by introducing additional groups. The cost of adding more dimensions is the lower number of observations used for resampling.

that are commonly observable to bidders, but not to the econometrician – i.e. the component of ω_t that the econometrician does not observe may play a very important role, especially after August 2007. To account for ω_t, we conduct our estimation auction-by-auction, utilizing the fact that there are a large number of bidders per auction. In doing so, we need to require, as above, that bidders' private signals are *conditionally* independent where the conditioning is on all public information available at the time of the auction. We now discuss the consistency of the resampling method used within an auction, i.e. as the number of bidders grows large.

5.3 Consistency

We will prove consistency of our estimator for the symmetric case where all bidders play a symmetric Bayesian Nash equilibrium strategy, and where the number of bidders N goes to infinity. Focusing on a price p, let random variable Y_i satisfy $Y_i = y(p|\theta_i)$ at the limiting game as $N \to \infty$. It thus denotes the quantity demanded by type θ_i in the limiting game at price p. The asymptotic properties (as the number of bidders grows large) of private value discriminatory auction games have been studied by Swinkels (2001), whose Corollary 6.5 states that the limiting equilibrium strategies are essentially unique since the probabilities of winning a certain quantity with a bid b are well approximated by the probability of winning efficiently. The most important condition needed for Swinkels' argument is asymptotic environmental similarity (AES), which is guaranteed in our context by the exogenous supply uncertainty. Hence Y_i is essentially unique as well. Let $\mu = EY_i$.

Define an indicator of excess supply at price p given bidder i's demand being x at that price and given the rivals' demands $Y_1, ..., Y_{N-1}$ at price p (note that these demands are random from i's perspective) and per-bidder supply $\tilde{Q}$ as follows:

$$\Phi\left(Y_1, \ldots, Y_{N-1}, \tilde{Q}; p, x\right) = 1\left((N-1)\tilde{Q} - \sum_{j=1}^{N-1} Y_j - x \geq 0\right)$$

Recall that per Assumption 5 the (per-bidder) supply, $\tilde{Q}$, follows a distribution $M\left(\tilde{Q}|\omega_t\right)$ and, conditional on ω_t, Y_i and $\tilde{Q}$ are independent.

Our parameter of interest is the probability that the market clearing price is below p; i.e. that there is excess supply at price p. Letting ξ be the parameter of interest:

$$\begin{aligned}\xi &= \lim_{N\to\infty} \xi_N \\ &= \lim_{N\to\infty} E_{\tilde{Q}} \Pr\left(x + \sum_{i=1}^{N-1} Y_i \leq (N-1)\,\tilde{Q}\right)\end{aligned}$$

Define the following *V-statistic* estimator of ξ, given a sample of size N: $\{Y_1, \ldots, Y_N\}$).

$$\begin{aligned}V_N &= E_{\tilde{Q}} \frac{1}{N^{N-1}} \sum_{r\in\mathcal{N}} \Phi\left(Y_1^{(r)}, \ldots, Y_{N-1}^{(r)}, \tilde{Q}; p, x\right) \\ &= \int_{\underline{Q}}^{\overline{Q}} \frac{1}{N^{N-1}} \sum_{r\in\mathcal{N}} \Phi\left(Y_1^{(r)}, \ldots, Y_{N-1}^{(r)}, \tilde{Q}; p, x\right) dM\left(\tilde{Q}|\omega_t\right)\end{aligned}$$

where $\mathcal{N}$ denotes the set of $N-1$ element resamples, with replacement, from $\{Y_1, \ldots, Y_N\}$).

Note that the resampling estimator described in the previous section is a Monte-Carlo approximation of V_N, where instead of evaluating the average over all N^{N-1} possible resampled $(N-1)$-tuples, we evaluate it over $B(N)$ randomly selected set of resamples. Denote this resampling estimator by $V_N^{B(N)}$.Our main proposition, proved in Appendix A.1, is that $V_N^{B(N)}$ is a consistent estimator of ξ as the number of bidders and the number of resamples grow large.

Proposition 2 *Under Assumptions 1-5 above,* $plim_{N,B(N)\to\infty} V_N^{B(N)} = \xi$.

5.3.1 Asymmetric bidders

As pointed out in Hortaçsu & Kastl (forthcoming), the resampling method can be extended to allow for ex-ante observable asymmetries between bidders, by essentially performing the resampling within ex-ante symmetric groups of bidders. In our setting, we may have the additional complication that while bidders may be informed about asymmetries (i.e. which banks were hit hard by the crisis, which were not), the econometrician is not. For example, the distributions from which the private information is drawn may differ between the banks that suffered from the crisis (group indexed with b for "bad" banks) and those that did not (group indexed with h for "healthy" banks). Performing the resampling method assuming that this kind of an asymmetry does not exist may lead to erroneous estimates of marginal values. In our context, however, the distributions of market clearing price from perspective of a bidder from group b or h submitting the same bid are virtually indistinguishable since with large N_b and N_h, whether we are drawing $N_b, N_h - 1$ or $N_b - 1, N_h$ makes very little difference. We will therefore present out estimates of marginal valuations under the assumption that the bidders are ex-ante symmetric.[17]

5.3.2 Supply Uncertainty

To incorporate this feature into our estimation framework, we use the empirical distributions of deviations from the pre-announced supply in the pre- and post-turmoil period. At each iteration of our resampling algorithm, we resample independently from the corresponding empirical distribution of supply deviations. Appendix B.3 provides more details about the way supply is determined in the weekly repo auctions.

6 Results

Having laid out the model and the estimation method in the previous sections, we now move on to discuss the results. In Sections 6.1 and 6.2, we use the estimated willingness-to-pay for each bank in each auction to analyze the impact of the crisis on the individual banks. We find that while marginal valuations shifted with the turmoil, there was wide variation in levels of distress across individual banks. Moreover, as we note in Section 6.1, the level and especially the dispersion of bid shading across banks also shifted during the turmoil, in response to the rise in uncertainty. In Section 6.2, we show that accounting for the "strategic" component of bids significantly affects our inference regarding which banks' marginal valuations shifted, and whose did not. In Section 6.3, we investigate how the marginal valuations can be interpreted in terms of banks' outside collateralized and uncollateralized funding opportunities. Finally, in Section 6.4, we investigate the validity of our marginal valuation estimates by showing that they are highly correlated with other measures of bank distress/performance.

[17]We have, however, experimented with an iterative procedure to classify bidders when their group membership is not ex-ante observable. We discuss this method in Appendix B.1.

6.1 Bid Shading Before and After the Crisis

As we see in Figure 2 and Table 2, the turmoil in the financial markets increased the variability of bids. Because there was more variation in bidding strategies, uncertainty about where the primary market would clear also increased. We now examine how the turmoil affected the degree of shading, where shading is defined as the difference between the marginal value and the bid. Using our estimates, the average amount of shading over the entire sample period was about 6.6 basis points with a standard deviation of 20 basis points. Looking at shading before and after the turmoil provides a different picture, however. In particular, the mean shading before the turmoil was only about 4 basis points with a standard deviation of 11.5 basis points. After the turmoil, the mean shading increased to 11.2 basis points with a standard deviation of 30.5 basis points.

The increased variability of shading supports our finding that some bidders likely were affected by the subprime crisis significantly more than others. Regressing estimated shading for each bidder on the turmoil dummy reveals that the turmoil resulted in a significant change in the amount of shading for 99 bidders. For 7 bidders, shading decreased by an average of 2 basis points, while for the remaining 92 bidders, it increased by over 18 basis points on average.

6.2 Identification of "Distressed" Bidders

Having estimated the marginal values for each bidder before and after the turmoil, we now can look for the effect of the turmoil on these values. Figure 5 shows that while before the turmoil the average willingness-to-pay for liquidity amounted to few basis points, after turmoil it kept increasing exceeding a 30 basis points premium over EONIA by the end of 2007.

Focusing now on the effects on individual banks, for 482 bidders who participate at least once before and after the turmoil, we regress the quantity-weighted estimates of marginal values for each bidder on a turmoil dummy.[18] Figure 6 plots the histogram of the significant coefficients from these

[18] Quantity-weighted marginal value is constructed as follows: $v_i = \frac{\sum_{k=1}^{K}(q_k - q_{k-1})v_{ik}}{q_K}$ where we let $q_0 = 0$. This weighting gives the most weight to the marginal value at the "largest" step of the bid function. This one-dimensional measure captures the main features of the marginal valuation function: for banks that have weak balance sheets (and hence their outside option is more-or-less to borrow unsecured), most weight should be given to the highest marginal values (and thus approximately to the rates at which this bank would borrow unsecured due to the collateral accepted by the ECB being much wider than that acceptable on the private repo market), with the opposite being true for a healthy bank.

regressions. For almost 100 bidders, the (normalized) marginal values have risen by more than 20 basis points in the post-turmoil period. This exercise reveals another interesting point: the turmoil seemed to be accompanied by an increase in marginal value for liquidity in the primary market for about two thirds of the participants, whereas the remaining one third experienced no significant increase.

Our conclusions would be quite different if we based the analysis solely on bids and hence we believe that using a model to separate out the strategic effect is quite important. Running the same type of regressions, but using quantity-weighted bids (again normalized by EONIA) rather than marginal values would result in a significantly positive relationship for virtually all bidders. Table 3 shows that the predictions differ for over 20% of the banks. Given the amounts of money that often are mentioned in connection with helping the struggling banking sector, whether 20% of banks seem to be healthy or not might potentially be quite important.

Table 3: Predicting Potential Problems

Based on		**Bids**	
		Yes	No
Values	Yes	326	5
	No	96	55

As a placebo test of the last exercise, we also tried focusing exclusively on the time period before the turmoil (we observe 32 auctions before the turmoil in our data) and splitting this subset of data into two halves, before and after auction 16.[19] Regressing bids and values, respectively, on a dummy for auctions $16 - 32$ results in data on both bids and values showing no effect for 398 banks; exhibiting a significant effect for 6 banks; and for 19 and 20 banks, respectively, they seem to have been significantly affected based either on bids or on values data, but not both. This exercise suggests that the difference in predictions based on values and bids reported in Table 3 appears likely not to be by chance. In fact, it suggests that the turmoil had an important effect, causing significant changes in bids for most banks, but with the underlying values actually changing only

[19] Once again we obtained virtually the same results initializing our algorithm with symmetric bidders or with random assignment of bidders into two groups.

for a smaller subset of banks.

Figures 7 and 8 provide another illustration of why accounting for the strategic effect maybe very important in identifying banks whose demand for liquidity was affected by the crisis. In Figure 7, we plot the density of the average difference in quantity-weighted price bids in the post vs. pre-crisis period auctions. We plot the densities separately for the banks that we identified as being "hard-hit" (i.e. experienced a significant shift in marginal valuations after the crisis) vs. "not hard-hit." As can be seen, although there are some visible differences across the two densities, the means are very similar, and the supports of the two densities largely overlap. In contrast, when we plot the densities of the difference in estimated marginal values across the post vs. pre-crisis auctions, we see a much more visible difference across the "hard-hit" vs. "not hard-hit" groups; while the mean marginal value change for the not hard-hit group is at zero, the mean of the "hard-hit" group, indeed the entire density, has shifted to the right.

6.3 Marginal Valuations and Banks' Outside Funding Opportunities

In Section 5.1, we argued that banks' marginal valuations in the ECB auctions can be linked closely to their outside funding opportunities, especially in the interbank market. In particular, we showed that a bank's (revealed) marginal valuation for ECB loans should be bounded above by the unsecured lending rate it faces, and below by the "risk free" rate (which is available through the provision of very high quality collateral). Furthermore, if a bank's marginal valuation of ECB loans is close to the prevailing EUREPO (our proxy for the risk-free rate) this indicates high-quality collateral availability, and thus access to collateralized funding opportunities in the interbank market.

To analyze how the turmoil affected banks' access to outside funding, we first need to summarize the information contained in the estimated marginal valuations. To do this, we first calculate, for each bank and each auction, the quantity-weighted average of the marginal valuations. We then project these on the EUREPO and EURIBOR rates. If all banks could access the EURIBOR as their unsecured rate, the estimated quantity-weighted marginal valuation would be a convex combination of the EUREPO (with weight α_i) and EURIBOR (weight $1-\alpha_i$), with the α between

0 and 1. Higher α corresponds to better collateral (marginal values closer to the EUREPO rate) and vice versa.

The distribution of α's in our sample summarizes the heterogeneity in banks' ability to access the "reported" EUREPO and EURIBOR rates. In the pre-turmoil period, taking the mean of α_i across all bidders, we get 0.16, with a median of 0.29. That is, the median bank's marginal valuations in the pre-turmoil period was consistent with the EUREPO and EURIBOR being available to this bank. That said, there was quite a bit of heterogeneity, with some banks' α_i being negative. This suggests that even in the pre-turmoil period, the unsecured interest rate which would rationalize these bank's marginal value in the primary auction lay above the EURIBOR, and hence that these banks could not borrow unsecured at the EURIBOR.

In the post-turmoil period, the average α decreased to -0.14, and the median to -0.10. This suggests that, post-turmoil, the average bank did not have usable collateral in the interbank market, and that more than half of the banks could not borrow unsecured at EURIBOR. Note also that in Figure 9, several auctions in the latter part of our sample cleared above the EURIBOR. Since ECB loans are collateralized, this suggests that there must have been excess demand for uncollateralized loans at the reported EURIBOR rate.

Since the EURIBOR (or its counterpart, LIBOR) plays a crucial role in anchoring most of the consumer loans, such as mortgages, it is important to note when this rate fails to reflect market clearing prices and the increase in the heterogeneity of funding costs among market participants. A first potential explanation is that the EURIBOR is not based on actual transactions, but rather on a survey of a subset of banks that is subject to misreporting. The recent settlement (Barclays 2012) agreed to by Barclays provides direct evidence that banks were understating the EURIBOR quotes due to inside pressures from their trading desks and from the desire of the management to make the bank's borrowing costs look lower than they are. A second explanation is that of a market failure due to increased informational asymmetries (credit rationing a la Stiglitz & Weiss (1981), or perhaps due to precautionary hoarding by banks (Brunnermeier 2009).

We next look at the implied outside funding opportunities across the banks that we labeled as financially distressed after the turmoil (because of a significant increase in marginal values), and the banks that were classified as not distressed. For the distressed group, we see a sharp fall in mean α_i from 0.18 to -0.19, and the median α_i decreases from 0.19 to -0.19. This suggests that the bidders who we label as distressed suffered from a big decline in the valuation of collateral in the interbank market. In contrast, the "non-distressed" bidders' mean α decreased much less – from 0.14 to -0.02, and the median decreases from 0.11 to 0.01.[20] To further illustrate the stark difference between the two groups of banks, suppose we interpret the non-participation in a given week as a signal of healthy balance sheet (i.e., $\alpha = 1$), then while the mean and median of hardhit banks before and after turmoil barely change, the mean (median) α of the healthy banks are 0.42 (0.53) before the turmoil and 0.27 (0.36) after the turmoil suggesting that either the "healthy" banks possessed balance sheets with collateral of sufficient size and quality or, unlike their hardhit counterparts, they were able to obtain loans at or close to EURIBOR.

6.3.1 Cross-country differences in banks' marginal values

Summarizing the marginal valuation information by projecting it onto secondary market rates also allows us to investigate the nature of heterogeneity across banks at the level of their country-of-origin. In Figure 10, we plot the mean α values across bidders before and after the crisis by country. Recall that α is close to 1 if a bidder's marginal value for ECB loans is close to EUREPO, the interbank secured interest rate, and close to 0 if the bidder's marginal value is the EURIBOR, the interbank unsecured interest rate. An α value that is negative indicates that the bidder has marginal value above the reported EURIBOR; i.e. the bidder cannot satisfy its funding needs at the EURIBOR rate.

In the figure, we see that there is considerable heterogeneity across countries, both pre and post-crisis. First notice that pre-crisis, some countries' banks have α values close to 1, while others' banks have α values close to zero (and, in one case, slightly negative). There is high positive correlation between pre- and post-crisis αs; the Pearson correlation coefficient is 0.9. After the crisis, α values appear to have declined across the board, with the low α countries' banks being

[20] Recall that we were able to classify only 482 bidders (out of the total of 733 identities appearing throughout our sample). While we have estimated α_i for the remaining bidders and estimated their marginal values whenever they submitted a bid, they did not submit bids both pre- and post-turmoil, and therefore our procedure cannot classify them. This explains why the reported means of the insignificantly and significantly affected may not translate directly into the overall mean of α across all bidders.

pushed into the negative α zone.

Because of non-disclosure requirements, we cannot investigate how country characteristics, especially attributes of their respective financial systems, are correlated with the funding costs of their banks. However, the exercise above may be instructive, in that α values are quite highly correlated before and after the crisis: the countries whose banks are likely to suffer are those whose banks had high liquidity funding costs to begin with.

6.4 The determinants of banks' willingness-to-pay for liquidity

We motivated our model with private values by arguing that banks' values for liquidity obtained in the primary market likely are driven to a large extent by the collateral value of each bank's asset portfolio and by the private information each bank has about its liquidity position, i.e., its need to satisfy the prescribed reserve requirements. To test these assumptions, we complement our dataset and our estimates of marginal values with additional detailed bank-level data for a subsample of banks. We conduct two different analyses. In our first analysis, we use data that is available at the weekly frequency of the auctions. This allows us to run panel regressions; though the availability of such "high frequency" data is quite limited. In our second analysis, we use data on bank balance sheets from Bankscope, which reports data for a much larger subset of the banks in our sample. Since Bankscope data is only available annually, this analysis is conducted cross-sectionally.

6.4.1 Marginal valuations and "high frequency" indicators of distress

In our first exercise we use three types of data: (1) data that is common to all banks and specific to each tender – the one-week Eurepo rate[21]; (2) bank-specific data that is publicly available, for example bank's CDS and asset sizes; and (3) non-public bank-specific data, including volumes allotted at ECB's long-term refinancing operations (LTRO), banks' current accounts with the national central banks, and reserve requirements.[22] Unfortunately, the intersection of banks for whom there are publicly traded CDSs and banks for whom we have data on reserve requirements leaves us with only 20 banks to work with.

[21] See Piazzesi (forthcoming) for an argument about why it is important to control for the levels of interest rates.

[22] The source for these data are: Bloomberg (bank assets); ECB (DG-M/MOA: current accounts; DG-M/FO: LTROs and MROs bidding data); Reuters (Eurepo rate); and KMV (CDS).

Let us briefly summarize which effects we expect from each variable included in the analysis that follows. As mentioned earlier, the *one-week Eurepo rate* normally sets a floor for bid rates (if it is above the minimum bid rate) and marginal values because it measures the cost of "alternative" funding in the secondary market against highly liquid collateral. Thus this rate sets the common floor level for the bids and marginal values for all banks.

The (relative) *CDS premium* captures the impact of credit risk premia in the inter-bank market; higher values of this variable should lead to an increase in the bids and marginal values of liquidity at the central bank auctions.[23]

Volumes allotted at the LTROs captures the impact of term liquidity funding pressure. With a liquid interbank lending market, the term-liquidity that a bank receives from the central bank (LTROs) should have little or no impact on the marginal value for liquidity in the short-term auction (MRO). However, if the ECB becomes the primary funding source for a bank, then we might expect a noticeable link between the two auctions. Accordingly, our $LTROout_{it}$ variable measures the outstanding volume of loans obtained in LTROs that bank i owns in week t (in billion €).

The *reserve deficiency* is calculated from banks' current accounts with the national central banks: the marginal value of liquidity should increase in the amount that a bank has to accumulate until the end of the reserve maintenance period.[24] To account for the potential non-linearity around 1, where Deficiency=1 means that a bank needs exactly to average exactly its daily reserve requirement for the rest of the monitoring period to satisfy the monhly requirement, we also introduce a dummy variable for "Small Deficiency" and we interact it with the our Deficiency measure. Banks with Deficiency below 1 should value liquidity from the ECB less on the margin.

Finally, *Turmoil* is a dummy variable equal to 1 in the post-turmoil period. We also included interactions of all variables with this dummy.

We estimated the model with fixed effects.[25] The estimates for the specification with Eurepo

[23] We use the price of a (5-year) CDS contract on the day before each auction, and define a relative credit default swap variable as the bank's CDS minus the average of all banks' CDS, in order to remove any possible trends that are correlated with the other variables used, i.e. $RCDS_{it} = CDS_{it} - \frac{\sum_{j \neq i} CDS_{jt}}{N_{j \neq i}}$.

[24] See Appendix B.4 for details on how we calculated the reserve deficiency measure.

[25] The estimates from a Random Effects and Fixed Effects models are qualitatively and quantitatively very similar.

1-week and the alternative interest rate measures as explanatory variables are reported in Table 4 below.[26]

The estimates show that the Euribor 1-week rate does very well at explaining the level of marginal values before the turmoil. Marginal values increased significantly after the crisis (and so do EONIA and EUREPO). Deficiency has no statistically significant impact on marginal values, but banks which accumulated excessive reserves before the auction (with Deficiency< 1) value liquidity less than the other banks, significantly so after the turmoil. The impact of the outstanding volumes in LTROs is not statistically significant for marginal values either before or after the crisis in the pooled regressions (columns (1)-(3)). Nevertheless, column (6) suggests that in the post-turmoil period LTROs and MROs are substitutes since the value for MRO-provided liquidity seems to be declining with the amount allocated in the LTROs. The credit risk variable (measured by the relative CDS) is statistically significant after the turmoil. A bank with CDS above the average tends to have higher marginal valuations for liquidity.

In order to assess the economic significance of the results, we calculated the predicted difference between the marginal valuations for two banks under the following assumptions: Eurepo rate 1-week at its highest in-sample value (4.15%); one bank with CDS differential at highest in-sample value (46.09); the other bank at the minimum sample value (-31.1); one bank with the highest outstanding long-term loan from the LTROs (40.44) and one bank at zero. The values are intended to contrast "good" and "bad" banks in the sample. The model predicts a marginal value of 3.94% for the "good" bank and a marginal value of 4.57% for the "bad" bank, that is over 60 basis points difference in short-term funding costs across these two banks.

6.4.2 Marginal valuations and balance sheet indicators

We now investigate the connection between our estimated marginal valuations and balance sheet variables obtained from Bankscope. Most of the bidders in our data set are not publicly traded, thus publicly available information on these institutions is largely limited to quarterly or sometimes annual financial statements that are disclosed by these firms. Using Bankscope, we construct

[26]Since not all banks participate in every auction, we also used a two-step Heckman selection model (Heckman 1976, Heckman 1979). The estimates obtained with correction for sample selection are very similar to those obtained with FE and RE and can be obtained upon request.

Table 4: Analysis of Marginal Values

	Marginal Value					
	(1)	(2)	(3)	(4)	(5)	(6)
EURIBOR	1.02			1.03	1.02	1.08
	(0.03)***			(0.03)***	(0.02)***	(0.01)***
EURIBOR*Turmoil	-.59			-.57	-.18	-.47
	(0.13)***			(0.12)***	(0.1)*	(0.04)***
EUREPO		1.03				
		(0.03)***				
EUREPO * Turmoil		-.68				
		(0.16)***				
EONIA			1.02			
			(0.03)***			
EONIA*Turmoil			-.82			
			(0.13)***			
Turmoil	2.50	2.87	3.46	2.39	0.8	2.00
	(0.55)***	(0.63)***	(0.54)***	(0.48)***	(0.4)**	(0.18)***
RCDS	-.0007	-.0007	-.0006	-.001		
	(0.001)	(0.001)	(0.001)	(0.001)		
RCDS * Turmoil	0.008	0.008	0.008	0.008		
	(0.001)***	(0.001)***	(0.001)***	(0.001)***		
Deficiency	-.0000938	-.0004	-.0008		0.002	
	(0.003)	(0.004)	(0.004)		(0.004)	
Deficiency * Turmoil	-.005	-.006	-.005		-.008	
	(0.006)	(0.006)	(0.006)		(0.007)	
Small Deficiency (less than 1)	-.01	-.01	-.01		0.01	
	(0.01)	(0.01)	(0.01)		(0.01)	
Small Deficiency * Turmoil	-.05	-.05	-.05		-.03	
	(0.03)*	(0.03)*	(0.03)*		(0.018)*	
LTROOut	0.004	0.004	0.005			0.002
	(0.006)	(0.006)	(0.006)			(0.004)
LTROOut * Turmoil	-.005	-.006	-.007			-.008
	(0.006)	(0.006)	(0.006)			(0.003)***
Obs.	736	736	736	843	1793	17010
Bank FE	20	20	20	22	56	704
R^2	0.79	0.78	0.78	0.79	0.69	0.57

* Significant at 10% level.
** Significant at 5% level.
*** Significant at 1% level.

measures of return-on-equity (ROE) and return-on-assets (ROA),[27] which are standard performance indicators in the banking literature (Madura 2008). We also compute the cost-to-income ratio (CTI), and net-interest margin (NIM), which are proxies for the profit generation ability of the bank.[28] These widely-used ratios are of course not immune to criticism (European Central Bank 2010), but can be constructed for a large number of banks for whom market-based performance measures (based on traded securities) are not available.

[27] ROE is defined as net income / average total equity, and ROA is defined as net income / average total assets, where the averages are taken yearly.

[28] CTI is calculated as the ratio of operating expenses to operating revenues; thus a higher CTI proxies for lower profitability. NIM is the ratio of the net interest income over interest bearing assets.

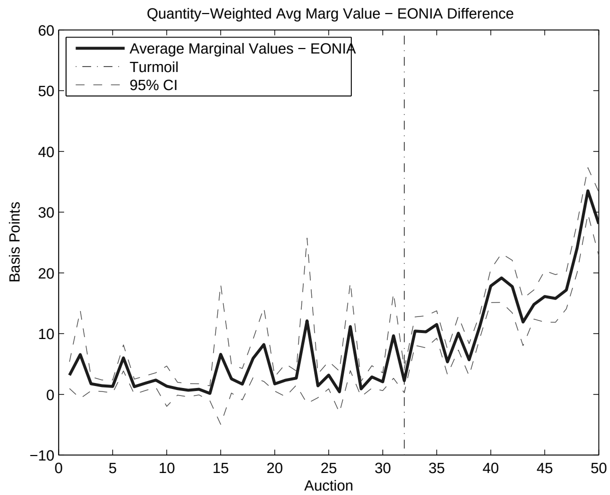


Figure 5: Average Willingness-to-pay

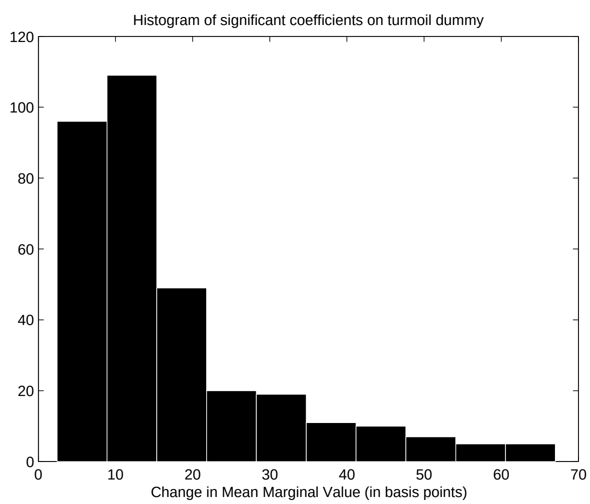
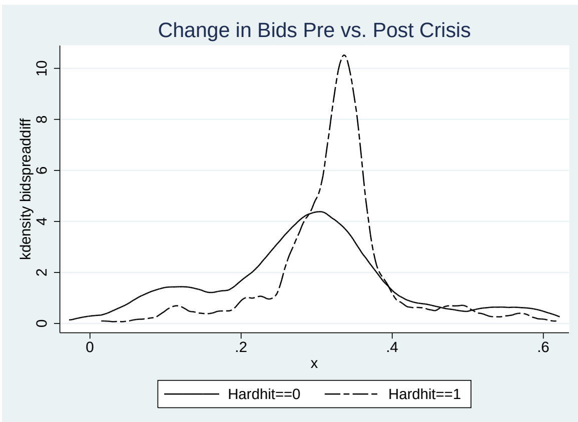


Figure 6: Histogram of Significant Turmoil Effects



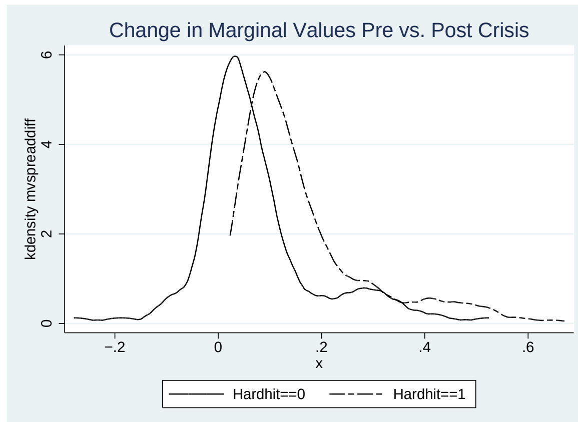


Figure 7: Distributions of the change in quantity-weighted bids pre- vs. post-crisis

Figure 8: Distributions of change in quantity-weighted marginal values pre- vs. post-crisis

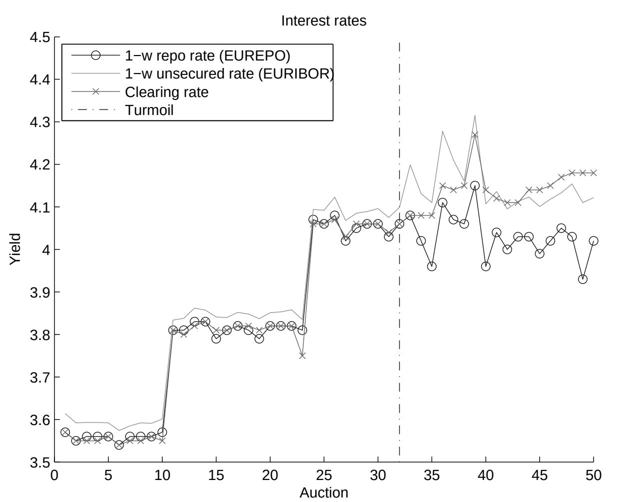


Figure 9: EUREPO, EURIBOR and primary auction clearing rates

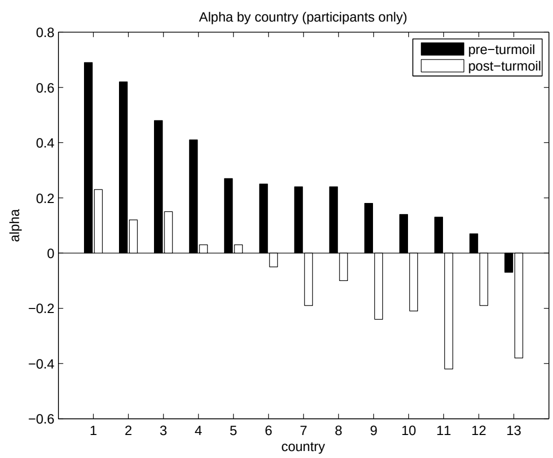


Figure 10: Pre and Post-Crisis Alphas across Euro-zone Countries

Table 5: Correlation between bank performance ratios and marginal values/bids

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	ROA'07	ROA'07	ROA'07	ROE'07	ROE'07	ROE'07	CTI'07	CTI'07	CTI'07	NIM'07	NIM'07	NIM'07
Δ bids	0.0520		0.126	-0.00613		0.0156	0.0734		-0.0370	0.0138		-0.000176
	(0.133)		(0.140)	(0.0288)		(0.0302)	(0.150)		(0.157)	(0.103)		(0.109)
Δ marginal values		-0.156	-0.188*		-0.0514**	-0.0553**		0.274**	0.283**		0.0357	0.0357
		(0.107)	(0.113)		(0.0230)	(0.0242)		(0.119)	(0.126)		(0.0832)	(0.0877)
ROA'06	0.561***	0.562***	0.564***									
	(0.0260)	(0.0259)	(0.0260)									
ROE'06				0.240***	0.241***	0.242***						
				(0.0299)	(0.0297)	(0.0298)						
CTI'06							0.568***	0.568***	0.569***			
							(0.0860)	(0.0853)	(0.0855)			
NIM'06										0.916***	0.916***	0.916***
										(0.0114)	(0.0114)	(0.0115)
Constant	0.0782*	0.116***	0.0798*	0.0399***	0.0450***	0.0407***	0.299***	0.284***	0.294***	0.0628	0.0626**	0.0627
	(0.0457)	(0.0225)	(0.0456)	(0.00974)	(0.00474)	(0.00969)	(0.0716)	(0.0585)	(0.0712)	(0.0410)	(0.0276)	(0.0411)
Observations	390	390	390	390	390	390	386	386	386	390	390	390
R-squared	0.546	0.549	0.550	0.143	0.154	0.155	0.104	0.116	0.116	0.943	0.943	0.943

The dependent variables in this table are bank performance ratios (ROA, ROE, CTI and NIM) reported year-end 2007. The independent variables are the pre- vs. post-crisis (Aug. 9, 2007) change in a bank's quantity-weighted average price bids (Δ bids) and estimated marginal valuations (Δ marginal values). We also control for the year-end 2006 performance ratios. Standard errors are in parentheses, with (***) indicating $p<0.01$, (**) $p<0.05$, and (*) $p<0.1$

We construct these measures for both the end of 2006, and the end of 2007, which comprise the endpoints of our auction data set. In Table 5, we regress the end-of 2007 performance indicators on their lagged values in 2006, along with the changes in the banks quantity-weighted average bids and marginal valuations across the pre- vs. post-crisis periods; i.e. we investigate whether any of the change in the profitability of the bank from 2006 to 2007 can be explained using our auction-based measures of the short-term funding costs faced by these banks.

The results (in columns 1,4, 7, and 10) indicate that the change in the bidding behavior of the banks across the pre- vs. the post-crisis periods in our sample is not significantly correlated with the change in the bank's performance measure from the end of 2006 to the end of 2007. However, for ROE and CTI, the change in the marginal valuations do show significant correlations. Indeed, when we include both bids and marginal valuations in the regressions, the change in marginal valuations are significant at 5% for ROE and CTI, and at 10% for ROA. The effects are also economically significant – based on the coefficient estimates, a 1 percentage point (100 basis point) increase in the bank's marginal value for liquidity is associated with an 18.8% drop in ROA, 5.6% drop in ROE, and a 28% increase in CTI. Among the four measures we consider, only the net-interest margin does not display a significant association with the changes in bids or marginal values, which could perhaps be attributed to its extreme persistence.

These regressions suggest that not only auction-based measures of short-term funding costs, which are observable at high-frequency by the ECB, may be an important predictor of bank profitability, but that accounting for the strategic component of the auctions by estimating the marginal valuations helps provide more accurate predictions. Since bank balance sheets are available only at quarterly or sometimes annual frequencies, this suggests that auction data could be very useful for policymakers when assessing the health of the financial system.

7 Conclusion

We used an economic model of bidding in the ECB's main refinancing operations to recover participant banks' marginal valuations for ECB provided short-term loans, which also can be linked to the banks' outside funding opportunities in the interbank market. Our econometric approach allows us to decompose into two main effects the dramatic upward shift in banks' bids beginning in August 2007: a "fundamental" effect linked to a genuine increase in the willingness-to-pay for ECB loans because of dwindling funding opportunities elsewhere, and a "strategic" effect, in which banks without a shift in their willingness-to-pay best-respond to their competitors' more aggressive bidding behavior. We showed that the "strategic" effect is non-negligible: while a naïve analysis of bids would indicate that all bidders' willingness-to-pay for short-term ECB funding increased because of the subprime crisis, accounting for the strategic effect reveals that one third of the bidders did not experience such a statistically significant shift.

Our results also shed light on the linkages between primary and secondary money market rates, and the shortcoming of "survey" based market rate reporting. We showed that before August 2007, participant banks' marginal valuations were in close agreement with the EUREPO and EURIBOR: published secured and unsecured lending rates reported based on surveys of money-center banks. After August 2007, though, we find that banks' marginal valuations and, sometimes their bids for secured ECB loans, far exceed the EURIBOR. That suggests that a large number of banks were not able to borrow at published rates. Recent legal proceedings against some of the panel banks provide further evidence (Barclays 2012). These results together suggest that monitoring primary market activity may allow policymakers and market observers to gain a more detailed understanding of the depth of similar financial crises.

The primary market activities of banks also allowed us to paint a more disaggregated picture of the 2007 subprime crisis. We noted that there was considerable heterogeneity in banks' willingness-to-pay for ECB loans across different Eurozone countries. Perhaps more significantly, banks from member countries that relied less on ECB funding before August 2007 appear to have suffered less from the crisis. We also find that our estimates for the short-term funding costs of the banks during the crisis are correlated with more "conventional" measures of banks' financial health, whenever such measures are available. This suggests that our method of measuring short-term funding costs of Euro-system banks may be useful in constructing high-frequency indicators of financial distress with very broad coverage of system banks.

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A Appendix

A.1 Proof of Proposition 2

We first define the following *U-statistic* estimator of ξ, given a sample of size N: $\{Y_1, \ldots, Y_N\}$).

$$
\begin{aligned}
U_N &= E_{\tilde{Q}} \frac{1}{N} \sum_r \Phi\left(Y_{1,r}, \ldots, Y_{N-1,r}, \tilde{Q}; p, x\right) \\
&= \int_{\underline{Q}}^{\overline{Q}} \frac{1}{N} \sum_r \Phi\left(Y_{1,r}, \ldots, Y_{N-1,r}, \tilde{Q}; p, x\right) dM\left(Q \tilde{|} \omega_t\right)
\end{aligned}
$$

where r denotes the set of all $N-1$ element subsets of the N draws of Y_i's. U_N and V_N have the probability limit and asymptotic distribution by Theorem 6.2.2 (p.388) of Lehmann (1999).

Consider $E_Y U_{N_d}$:

$$
\begin{aligned}
E_Y U_N &= E_Y \frac{1}{N} \sum_r E_{\tilde{Q}} \Phi\left(Y_{1,r}, \ldots, Y_{N-1,r}, \tilde{Q}; p, x\right) \\
&= \frac{1}{N} \sum_r E_{\tilde{Q}} E_Y \Phi\left(Y_{1,r}, \ldots, Y_{N-1,r}, \tilde{Q}; p, x\right) \\
&= E_{\tilde{Q}} \Pr\left(x + \sum_{i=1}^{N-1} Y_{r_i} \leq (N-1)\tilde{Q}\right) \\
&\equiv \zeta_N
\end{aligned}
$$

where the first equality follows from Tonelli's theorem (Billingsley 1995, p.234) since the integrand is non-negative.

Futhermore, let $\mu \equiv E\left(Y_i\right)$.

$$
\begin{aligned}
\lim_{N \to \infty} \zeta_N &= E_{\tilde{Q}} 1 \left\{\mu \leq \tilde{Q}\right\} \\
&= \Pr\left(\tilde{Q} \geq \mu\right) \\
&= \zeta
\end{aligned}
\tag{A-1}
$$

where the first equality follows from $\bar{Y} \equiv \frac{\sum_{i=1}^{N-1} Y_i}{N-1} \to \mu$ (by LLN), $\lim_{N \to \infty} \frac{x}{N-1} = 0$ and dominated convergence theorem.

Let us consider $Var(U_N)$.

$$Var(U_N) = E_Y\left[U_N^2\right] - \left[E_Y(U_N)\right]^2$$

$$\begin{aligned}
E_Y\left[U_N^2\right] &= \frac{1}{N^2}E_Y\left[E_{\tilde{Q}}\left[\sum_r 1\left\{x+\sum_{i=1}^{N-1}Y_{r_i}\leq(N-1)\tilde{Q}\right\}\right]E_{\tilde{Q}}\left[\sum_s 1\left\{x+\sum_{i=1}^{N-1}Y_{s_i}\leq(N-1)\tilde{Q}\right\}\right]\right]\\
&= \frac{1}{N^2}E_Y\left[N\left[\left(E_{\tilde{Q}}1\left\{x+\sum_{i=1}^{N-1}Y_i\leq(N-1)\tilde{Q}\right\}\right)^2\right]+\right.\\
&\left. N(N-1)E_{\tilde{Q}}\left[1\left\{x+\sum_{i\neq s,r}Y_i+Y_s\leq(N-1)\tilde{Q}\right\}\right]E_{\tilde{Q}}\left[1\left\{x+\sum_{i\neq r,s}Y_i+Y_r\leq(N-1)\tilde{Q}\right\}\right]\right]\\
&\leq \frac{1}{N^2}N*1+E_{Y_{i\neq r,s}}\left[E_{Y_r,Y_s}\left(E_{\tilde{Q}}1\left\{Y_s\leq(N-1)\tilde{Q}-\sum_{i\neq r,s}Y_i-x\right\}E_{\tilde{Q}}1\left\{Y_r\leq(N-1)\tilde{Q}-\sum_{i\neq r,s}Y_i-x\right\}\right)\right]\\
&= \frac{1}{N^2}N*1+E_{Y_{i\neq r,s}}\left[E_{Y_s}\left(E_{\tilde{Q}}1\left\{Y_s\leq(N-1)\tilde{Q}-\sum_{i\neq r,s}Y_i-x\right\}\right)E_{Y_r}\left(E_{\tilde{Q}}1\left\{Y_r\leq(N-1)\tilde{Q}-\sum_{i\neq r,s}Y_i-x\right\}\right)\right]\\
&= \frac{1}{N^2}N*1+E_{Y_{i\neq r,s}}\left[E_{Y_r}E_{\tilde{Q}}1\left\{Y_r\leq(N-1)\tilde{Q}-\sum_{i\neq r,s}Y_i-x\right\}\right]^2\\
&= \frac{1}{N^2}N*1+E_{Y_{i\neq r,s}}\left[E_{\tilde{Q}}\Pr\left(Y_r\leq(N-1)\tilde{Q}-\sum_{i\neq r,s}Y_i-x\right)\right]^2
\end{aligned}$$

where the inequality obtains since the diagonal terms are bounded by 1 and for the off-diagonal terms. We then decompose the expectation over Y to an outer expectation over $Y_{i\neq r,s}$ and an inner expectation over Y_r and Y_s. Since Y_s and Y_r are iid, the product inside the inner expectation becomes a product of expectations, which in turn is the square of the expectation (with respect to $\tilde{Q}$) of one of the marginals (where we switched the order of integration with respect to Y_r and $\tilde{Q}$.

Next, adding and subtrating μ in order to have $N-1$ elements in the sum, taking the limit and applying the dominated convergence theorem together with the LLN, we obtain:

$$\begin{aligned}
\lim_{N\to\infty} E_Y\left[U_N^2\right] &= \lim_{N\to\infty} E_{Y_{i\neq r,s}}\left[\left(E_{\tilde{Q}}\Pr\left\{Y_r \le (N-1)\,\tilde{Q} - \sum_{i\neq r,s} Y_i - \mu + \mu - x\right\}\right)^2\right] \\
&= \lim_{N\to\infty} E_{Y_{i\neq r,s}}\left[\left(E_{\tilde{Q}}\Pr\left\{Y_r - \mu + x \le (N-1)\left(\tilde{Q} - \frac{\sum_{i\neq r,s} Y_i + \mu}{N-1}\right)\right\}\right)^2\right] \\
&= \left(\Pr\left(\tilde{Q} \ge \mu\right)\right)^2
\end{aligned}$$

where the last equality follows since $\lim_{N\to\infty}\frac{\sum_{i\neq r,s} Y_i+\mu}{N-1} = \mu$, Y_r has bounded support by Assumption 6 and hence probability is 1 if and only if $\tilde{Q} > \mu$ and zero otherwise, and hence the expectation with respect to $\tilde{Q}$ becomes simply $\Pr\left(\tilde{Q} \ge \mu\right)$.

Therefore,

$$\begin{aligned}
\lim_{N\to\infty} Var\left(U_N\right) &\le \lim_{N\to\infty}\left[\frac{1}{N} + \left(\Pr\left(\tilde{Q} \ge \mu\right)\right)^2 - \left(\Pr\left(\tilde{Q} \ge \mu\right)\right)^2\right] \\
&\le 0
\end{aligned}$$

This implies consistency of U_N.

B NOT FOR PUBLICATION: Appendix

B.1 An iterative algorithm to classify bidders when their group membership is not observed

We adopt an iterative procedure and estimate an asymmetric model with two groups of banks as follows: in the first step, we start the algorithm by arbitrarily allocating bank identities across two groups: banks that suffered from the crisis (group indexed with b for "bad" banks) and those that did not (group indexed with h for "healthy" banks).[29]. The resampling method is modified to allow for two groups of bidders that are symmetric within a group, but not necessarily across the groups. This is achieved by drawing with replacement from observed bids from each group separately. We thus obtain estimates of the marginal values of each bidder in every auction. In the second step, we use these estimated values to find a subset of bidders who experienced a stochastic increase in their estimated values for liquidity in the post-turmoil period. We assume that experiencing financial distress in our model translates into a shift in the distribution of marginal values in the sense of first-order stochastic dominance. There are many alternatives to check for this shift, and the test we use is based on comparing means of the distributions before and after turmoil for each bidder. This test is operationalized by regressing the quantity-weighted average of the marginal value estimates (normalized by EONIA to take out the level effect of interest rates[30]) on the turmoil dummy for each bidder separately. If the estimated coefficient on the turmoil dummy is significant at 5% level – i.e., if the mean marginal value increased – we classify this bidder as one who experienced financial distress in the post-turmoil period. In the third step of our algorithm, we re-estimate the model using the newly obtained two groups of bidders.[31] In the fourth step, we again estimate the subset of bidders that experienced an increase in their values by using the estimates from the asymmetric model. If this subset coincides with the two groups used in step 3, then we stop; otherwise, we

[29] In practice, we started both with allocating all banks into the Healthy Group and with a random allocation, both of which led to statistically indistinguishable estimates.

[30] See Piazzesi (forthcoming) for a thorough discussion of the recent literature on the structure of interest rates.

[31] Bidders are treated asymmetrically in all auctions. That is, we fix the two groups even before turmoil. Had the bidders been actually symmetric before turmoil, our approach would result only in loss of efficiency, but the estimates of the distribution of the market clearing price would still be consistent.

repeat step 3.[32] In practice, we stop the algorithm when weakly less than 5 bidder identities switch groups. We are able to classify 482 bidder identities out of the 733 in our data. The remaining bidder identities do not submit bids both before and after the turmoil.

As we indicate in Section 5.3.1, that the initial assignment of banks into groups does not seem to matter in our application is due to the fact that we have a large number of banks in each group. This in turn results in virtually the same estimates of marginal values (whether a bidder was assigned to b or h) and hence essentially unique allocation of bidders into the two groups. We conjecture that the impact of the asymmetry on the estimates of marginal values and thus on the identification of the latent types would likely be much more profound with small number of bidders in each group.

B.2 Institutional Background

B.2.1 Objectives and Tools of the ECB

The operational framework for monetary policy implementation by the ECB has three main objectives: signalling of the monetary policy stance, steering of very short-term interest rates, and provision of refinancing to the banking system in an efficient way and under all circumstances. The ECB has three main tools to implement its objectives: minimum reserve requirements with averaging provision, standing facilities, and open market operations. The main focus of this paper is on open market operations, but below we briefly describe each of the three components because all are quite relevant for banks' behavior in the open market operations .

Reserve requirements have two main functions. They contribute to stabilise money market interest rates and enlarge the structural liquidity shortage of the banking system. Euro area banks have to keep minimum reserves (current accounts with national central banks[33]). They are computed on a lagged accounting basis by applying a reserve ratio (currently at 2%) to the

[32]While we do not have a formal proof of whether this method converges, if it does, it is easy to see that the resulting estimates are consistent estimates of the primitives of the asymmetric model. In the actual application, it turns out that after very few iterations, the two groups of bidders are very stable – both in terms of size and in terms of identities of bidders contained in each. The asymmetry therefore seems not to play as important a role in the estimation stage, which is probably due to the large number of participants. We experimented with a random initial assignement of bidders into the two groups; after very few iterations, we obtained virtually the same bidder groups as those arrived at when starting with the symmetric model.

[33]National Central Banks

reserve base. The reserve base includes short-term liabilities of banks (deposits and debt securities with maturity below or equal to two years). Reserves must be kept on average over a maintenance period (averaging mechanism) which has approximately one month duration. Required reserves are remunerated - at a rate linked to the marginal rate of the Main Refinancing Operations (MROs) described below. Current account holdings beyond the minimum requirement are not remunerated (excess reserves).

There are two types of *standing facilities*, one providing liquidity (against collateral), which is a marginal lending facility and another, absorbing liquidity, which is a deposit facility. Both are overnight facilities taken at the discretion of the banks, and, in general, there are no limits set by the ECB to their recourses by banks. Standing facilities have penalty rates: marginal lending +100 basis points above the Minimum Bid Rate (henceforth MBR, which is a policy rate, see below for more details) and deposit facility -100 basis points below the MBR.[34] These two rates set a corridor for the interbank market overnight interest rate.

There are three main types of *open market operations*. The Main Refinancing Operations (MROs), which are the main focus of our analysis, The Longer Term Refinancing Operations (LTROs) are liquidity providing reverse transactions, with three-month maturity, conducted once a month, every month. The main function of the LTROs is to provide additional longer-term liquidity to the market. They are not intended to signal the (future) stance of monetary policy. Fine Tuning Operations (FTOs) provide or absorb liquidity. They have neither fixed frequency nor maturity. Provision of liquidity is made via reverse transactions or foreign exchange swaps, and absorption of liquidity is normally achieved via collection of fixed term deposits or foreign exchange swaps. The main function of the FTOs is to smooth the effects on interest rates caused by unexpected liquidity fluctuations in the market. Since 2005 the ECB conducts (almost) systematically an FTO on the last day of each reserve maintenance period.

[34] The interest rate corridor was narrowed to ± 50 basis points as of October 9, 2008.

B.2.2 More Details on the Main Refinancing Operations

MROs are executed weekly according to an indicative calendar published by the Eurosystem. Normally, the announcement of the operation is on Monday[35], the execution on Tuesday[36] and settlement on Wednesday. On the announcement day (Monday) the ECB publishes an estimate of the average autonomous factors[37] from the announcement day until the maturity of the operation (9 days ahead forecast) as well as the benchmark allotment. On the execution day (Tuesday) the ECB publishes a revised estimate of the average autonomous factors and benchmark amount.

As we mentioned earlier, a bid may consist of up to ten interest rates and associated quantities a bank is willing to transact with the ECB. The interest rate bid must be expressed as multiples of a basis point, i.e., of 0.01 percentage points. The minimum bid amount is EUR 1,000,000. Bids exceeding this amount must be expressed as multiples of EUR 100,000. The ECB may impose a maximum bid limit in order to prevent disproportionately large bids.

In the allotment, bids are listed in descending order of offered interest rates. Bids with the highest interest rate levels are satisfied first and subsequently bids with successively lower interest rates are accepted until the total liquidity to be allotted is exhausted. If at the lowest interest rate level accepted (i.e., the marginal interest rate), the aggregate amount bid exceeds the remaining amount to be allotted, the remaining amount is allocated pro rata among the bids according to the ratio of the remaining amount to be allotted to the total amount bid at the marginal interest rate (a.k.a. rationining rule pro-rata on-the-margin). The amount allotted to each bank is rounded to the nearest euro.

The ECB may apply either single rate (uniform price) or multiple rate (discriminatory) auction procedures. So far only the latter has been used, and thus our data includes only discriminatory auctions. In a discriminatory auction, the allotment interest rate is equal to the interest rate offered by each individual bid. Since October 15 2008 the weekly main refinancing operations have been carried out with a fixed-rate tender procedure with full allotment.

[35]Info in Reuters page ECB16.

[36]Info in Reuters page ECB17.

[37]Defined as Autonomous factors (AF) = Net Foreign Assets (NFA) + Net Assets Denominated in Euro (NDA) - Banknotes (BN) - Government deposits (GOV) - Other (O).

B.2.3 Collateral (Eligible Assets)

All Eurosystem liquidity-providing operations (including marginal lending and intraday credit) are based on underlying assets that must fulfill certain criteria in order to be eligible. A European credit assessment framework (ECAF) has been set up in order to evaluate the eligible collateral. The collateral accepted by the Eurosystem is very broad. Two types of assets are included in the list: marketable and non-marketable. The ECB publishes daily a list of eligible marketable assets on its website.[38] Marketable assets must be debt instruments meeting high credit standards which are assessed by the ECAF rules. The issuers can be central banks, public sector, private sector, and international institutions; the place of issue must be EEA[39], the place of establishment of the issuer must be the EEA and non-EEA G10 countries, the currency must be EUR.[40] Both regulated and non-regulated markets are considered; the latter must be, however, accepted by the ECB. Non-marketable assets are credit claims and Retail Mortgage Backed Debt Instruments (RMBD). For credit claims the debtor/guarantor must meet high credit standards which are assessed by the ECAF rules. The debtor/guarantor can be public sector, non-financial corporations, and international institutions; the place of establishment of the debtor/guarantor must be the euro area and the currency must be EUR. Minimum size rules apply. For RMBD the asset must meet high credit standards which are assessed by the ECAF rules. The issuers can be credit institutions; the place of establishment of the issuer must be the euro area, and the currency must be EUR. A bank may not submit as collateral any asset issued or guaranteed by itself or by any other entity with which it has close links.

In the assessment of credit standard of eligible assets the Eurosystem takes into account the following sources: external credit assessment institutions (ECAIs), national central banks in-house credit assessment systems (ICAS exist in Deutsche Bundesbank, Banco de España, Banque de France and Oesterreichische Nationalbank), counterparties internal ratings-based systems (IRB) or third-party providers rating tools. The Eurosystems credit quality threshold is defined in terms

[38] Eligible assets are listed at: `https://mfi-assets.ecb.int/dla_EA.htm`

[39] European Economic Area

[40] Since November 14, 2008 the list of eligible marketable debt instruments was enlarged to include instruments denominated in US dollar, yen and sterling, issued by EEA issuers.

of a "single A" credit assessment (meaning "A-" by Fitch or S&P; or "A3" by Moody).[41] The Eurosystem considers a probability of default (PD) over a one-year horizon of 0.10% as equivalent to a "single A" credit assessment. Prudential information can be used by the Eurosystem as a basis for rejecting assets. In countries, in which RMBDs are mobilised, the respective national central bank must implement a credit assessment framework for this type of asset. The performance of the credit assessment systems is reviewed annualy. It consists of an ex post comparison of the observed default rate for the set of all eligible debtors and the credit quality threshold defined by the benchmark PD.

Risk control measures are applied to protect the Eurosystem against the risk of a financial loss if underlying assets have to be realised owing to the default of a counterparty. The following measures are applied: i) valuation haircuts (increasing with the maturity and illiquidity of the asset); ii) margin calls (i.e. marking to market): if the value of the underlying collateral falls below a certain level the national central bank will require the counterparty to supply additional assets or cash. The Eurosystem may apply limits to the exposure vis-a-vis issuers/debtors or guarantors and may exclude certain assets from use in its monetary policy operations. The last two are, however, currently not applied.[42]

In pooling systems the counterparty makes a pool of sufficient underlying assets available to the national central bank to cover the related credits thus implying that individual assets are not linked to specific credit operations. In an earmarking system each credit operation is linked to specific identifiable assets. Assets are subject to daily valuation.

B.3 Liquidity demand and supply

To put the liquidity auctions of the ECB into perspective and understand the supply policy of the ECB, let us first look at the simplified balance sheet of the Eurosystem, for example on June 29, 2007 (Table 6 and Table 7).

On the Liabilities side the main items are Banknotes and Current Accounts (together represent 77% of total Liabilities), the latter including the minimum reserve requirement. On the Assets side

[41] As of October 25 2008 and until December 2009 the ECB lowered the threshold to BBB- (except for asset-backed securities, which were still A-).

[42] Additional haircuts will be applied to all newly eligible marketable assets.

Table 6: Balance sheet of the Eurosystem on June 29, 2007

Assets		Liabilities	
1. Net Foreign Assets	325,703	5. Banknotes	630,777
2. Net Assets Denominated in EUR	282,041	6. Current Accounts	194,530
3. Liquidity Providing Open Market Operations	463,501	7. Government Deposits	69,621
4. Marginal Lending Facility	5	8. Deposit Facility	80
		9. Other	176,242
Total Assets	1,071,250	Total Liabilities	1,071,250

* Values in million EUR.

Table 7: Structure of the balance sheet of the Eurosystem on June 29, 2007

Assets	%	Liabilities	%
1. Net Foreign Assets	30	5. Banknotes	59
2. Net Assets Denominated in EUR	26	6. Current Accounts	18
3. Liquidity Providing Open Market Operations	43	7. Government Deposits	6
4. Marginal Lending Facility	0	8. Deposit Facility	0
		9. Other	16
Total Assets	100	Total Liabilities	100

there are two large items: Net Foreign Assets and Net Assets Denominated in Euro (representing 56% of total Assets). The former relates to foreign exchange reserve holdings of the Eurosystem (in gold and US Dollar) managed by the ECB. The latter reflects the investment portfolio holdings of national central banks (managed in a decentralised manner according to agreed rules). It is important to note that this is not a monetary policy portfolio. Liquidity providing OMO represent 43% of the Assets of the Eurosystem. This is the item that is adjusted/managed by the ECB and relevant for monetary policy implementation.

The liquidity needs of the banking system can be calculated from the balance sheet as follows:

+ Assets (other than 3 and 4) provide liquidity

- Liabilities (other than 8) create liquidity needs.

Thus:

Liquidity Deficit = Autonomous factors (AF) + Current Accounts (CA).

Where:

Autonomous factors (AF) = Net Foreign Assets (NFA) + Net Assets Denominated in Euro (NDA)

- Banknotes (BN) - Government deposits (GOV) - Other (O).

Current Accounts include the reserve requirement (RR) plus very small excess reserves (XR).

Example 1 *From the balance sheet data (Table 6) we can see that AF = -268,896 million EUR, and CA = -194,530 million EUR. Therefore the aggregate liquidity deficit in the euro area was AF+CA=-463,426 million EUR or approximately 463 billion EUR, of which 58% was due to the so-called autonomous factors and 42% was due to the reserve requirement (current accounts).*

Alternatively one could express the liquidity needs as follows (Table 8): Outright portfolio - Reserve Base - Other = -463,426 million EUR, where Reserve Base = Banknotes + Current Accounts and Outright Portfolio = NFA + NDA - GOV.

Table 8: Simplified balance sheet of the Eurosystem on June 29, 2007

Assets	%	**Liabilities**	%
1. Outright Portfolio	538,125	3. Reserve Base	825,307
2. Repo Operations	463,501	4. Net Standing Facilities	75
		5. Other	176,242
Total Assets	1,001,624	Total Liabilities	1,001,624

* Values in million EUR.

As shown in Table 6 (also Table 8) the ECB provides liquidity to the banking system mainly via its regular *open market operations*, which satisfy: [43]

OMO + ML - DF = AF + CA. And OMO = MRO + LTRO.

Before the turmoil the MROs represented about 70% of the refinancing and the LTROs only 30%. Thus, the bulk of the liquidity was provided by MROs on a short-term basis (weekly) and was rolled-over every week. For example, on June 29, 2007, the outstanding volumes in OMO consisted of: (i) Main refinancing operations (MROs: 313,499 million EUR) and (ii) Longer-term refinancing operations (LTROs: 150,002 million EUR).

In general, the liquidity policy of the ECB is quantity-oriented even if the objective is to steer the overnight interest rate. It is a rules-based approach where the benchmark allotment plays a central role.

[43] The provision of liquidity via the marginal lending facility is negligible.

The benchmark allotment in a MRO is the allotment amount which allows counterparties to smoothly fulfill their reserve requirements until the day before the settlement of the next MRO, when taking into account the following liquidity needs:

- Liquidity imbalances that have occurred previously in the same reserve maintenance period and which were not anticipated in the preceding MRO
- ECB's forecast of the autonomous factors
- ECB's forecast of excess reserves which are assumed to be the same on each day of the reserve maintenance period

The weekly benchmark allotment is (in simplified terms) given by:

$$MRO^{benchmark} = AF^{forecast} + \underline{RR} + XR^{forecast} + \{Forecast\ error\ of\ previous\ week\}$$

Assuming: $ML - DF = 0$. The reserve requirement is fixed as it is calculated on a lagged accounting basis.

The underlying idea of the benchmark allotment is that if the ECB's forecast errors are unbiased and the forecast error variance is small compared to the reserve requirement, then the overnight rate on the last day in the reserve maintenance period should be expected to be close to the middle of the interest rate corridor defined by the rates on the standing facilities. With a symmetric interest rate corridor this policy should keep the overnight rate close to the policy rate.

In fact, on the last day of the reserve maintenance period we get the aggregate liquidity imbalance equal to the forecast error made by the ECB, the former being either a net recourse to marginal lending (liquidity shortage) or to the deposit facility (liquidity surplus).

$$ML - DF = Forecast\ Error$$

.

If the overnight rate is expected to be close to the policy rate on the last day of the RMP, then on any other day in the reserve maintenance period it should also be close to the policy rate by applying the martingale hypothesis.

Empirical evidence before the turmoil matches these predictions very closely (figure 11).

Figure 14 shows that the liquidity needs of the banking system evolved very smoothly before the turmoil between 400 and 450 billion EUR. The MROs had a volume of around 300 billion EUR and the LTROs about 100-150 billion EUR. Deviations from benchmark were negligible as illustrated in figure 15.

Figure 14 further illustrates how the ECB managed liquidity during the turmoil. Four aspects are shown: i) the total volume of refinancing was kept on trend, albeit with somewhat more volatility; there was a significant increase at the end of the year mainly for seasonal reasons; ii) there was an increase in the absolute volume and relative weight of LTROs in total refinancing. However, the volume of MROs declined so that the total volume was kept on trend; iii) the ECB conducted more frequent and sizable fine-tuning operations (FTOs), both providing and draining liquidity; the latter (draining) were more frequent and sizable; A final aspect is illustrated in figure 15: iv) At the MROs deviations from benchmark became very sizable and time-varying (larger at the first MRO in the RMP and somewhat smaller in subsequent MROs in the same RMP).

B.4 Calculation of Reserve Deficiencies

A bank's reserve deficiency varies with unexpected liquidity shocks, which may be driven by unexpected mismatches between cash inflows and outflows from that bank's accounts; it may also reveal the failure to guarantee a targeted allotment at a previous auction. The *Deficiency* variable is calculated for each bank i as follows. First:

$$D_{it} = T * RR_i - \sum_{s=1}^{t} CA_{is}$$

where D_{it} is the accumulation of reserves needed to fulfill its requirement until the last day of the reserve maintenance period for bank i on day t. RR_i is the daily average reserve requirement of bank i (set by the ECB at the beginning of each reserve maintenance period) and T is the number of days in the maintenance period; $T - t$ is the number of days until the end of the reserve maintenance period. If a bank follows a smooth (linear) reserve fulfilment path, it targets as its daily current account the daily average reserve requirement D^*_{it}:

$$D^*_{it} = T * RR_i - t * RR_i \Leftrightarrow \frac{D^*_{it}}{RR_i} = T - t$$

Deficiency is therefore defined as:

$$Deficiency_{it} = \frac{D_{it}}{RR_i} - \frac{D^*_{it}}{RR_i} = \frac{D_{it}}{RR_i} - (T - t)$$

We use the $Deficiency$ value on the day before the MRO. To account for the potential non-linearity around 1 (Deficiency=1 means that a bank needs exactly its daily reserve requirement for the rest of the monitoring period to satisfy the monhly requirement.) we also introduce a dummy variable for "Small Deficiency" and we interact it with the our Deficiency measure.

B.5 Long Term Refinancing Operations

We also obtained data on ECB's LTROs. We have 19 auctions covering 10/2006 to 3/2008. As described in the institutional background, these auctions are run only once a month and they are for loans with 3-months maturity. These data are summarized in table 9 and the pre- and post-turmoil means and standard deviation in table 10. The patterns in general correspond to those from the main refinancing operations studied in the main body of this paper. The important differences are (i) the much starker increase the price bid spread against the EONIA rate following the turmoil (from 1 to 47 basis points) which is about five times the increase in the MROs and (ii) the number of participants is less than a half of those in MROs. This is probably mainly due to the overlapping maturities of the loans (monthly auction frequency and 3-month maturity) since the set of banks participating in both types of refinancing operations is very similar. This last observation allows us to perform the same exercise as in the case of MROs and use the estimated values to classify bidders into more and less distressed groups. Doing so, we obtain a similar pattern as in the MROs: only about $\frac{2}{3}$ of bidders experienced an increase in their mean (quantity-weighted) marginal value, while almost all banks significantly increased their bid spreads against EONIA suggesting more aggressive bidding strategy.

Table 9: Data Summary - LTROs

Summary Statistics				
Auctions	19			
	Mean	St.Dev.	Min	Max
Bidders	148	19	96	175
Submitted steps	2.29	1.68	1	10
Price bid	4.20	0.44	3.20	5.05
Price bid spread[a]	0.26	0.26	-0.48	1.02
Quantity bid	0.01	0.02	$1 * 10^{-5}$	0.28
Issued Amount (billions €)	49.74	8.58	40	75

[a] Spread against EONIA rate.

Following the same procedure as in MROs, we estimated the marginal values that would rationalize the observed bids in LTROs. We also repeated the same exercise as in the case of MROs to classify the bidders in LTROs into the distressed and not distressed groups. The results are summarized in table 11. Due to less participation frequency (we have only 11 auction pre-turmoil and

Table 10: Data Summary LTROs: Before and After August 2007

Summary Statistics	Mean		Std Dev	
	Before	After	Before	After
Bidders	150.6	143.4	10.66	26.53
Submitted steps	1.76	3.04	0.94	2.15
Price bid	3.78	4.55	0.26	0.16
Price bid spread[a]	0.01	0.47	0.02	0.17
Quantity bid	0.009	0.013	0.024	0.023
Issued Amount (billion €)	46.36	54.38	5.05	9.82

[a] Spread against EONIA rate.

8 auctions post-turmoil) we were able to classify only 200 bidder identities. Very similar pattern arises for those, however, as in the case of MROs. Virtually all participants significantly increased their bids, but for $\frac{49}{189}$ (or 26%) of those, this does not seem to have been accompanied by an increase in values.

Table 11: Predicting Potential Problems - LTROs

Based on		**Bids**	
		Yes	No
Values	Yes	140	4
	No	49	7

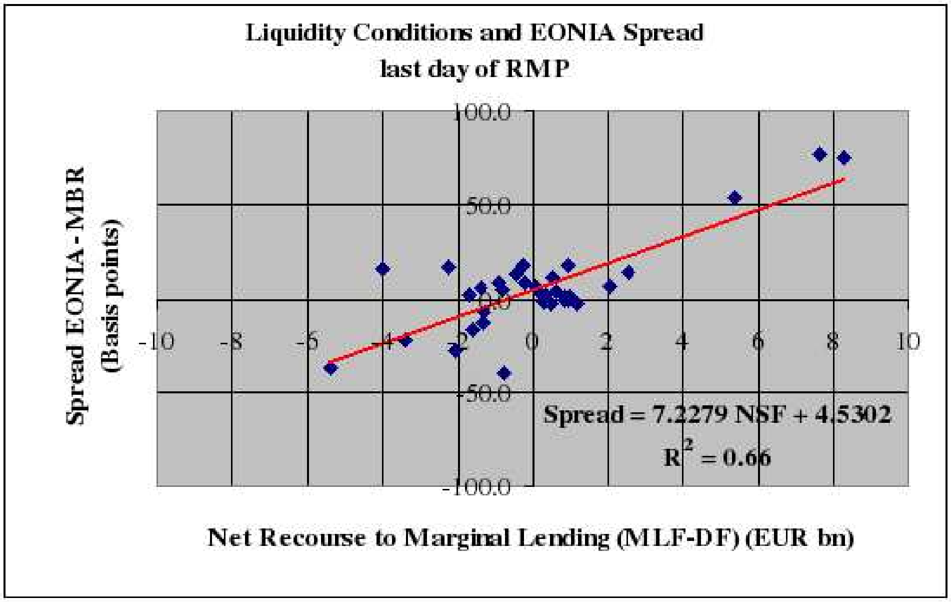

Figure 11: EONIA Spread and Liquidity Conditions on the Last Day of the RMP

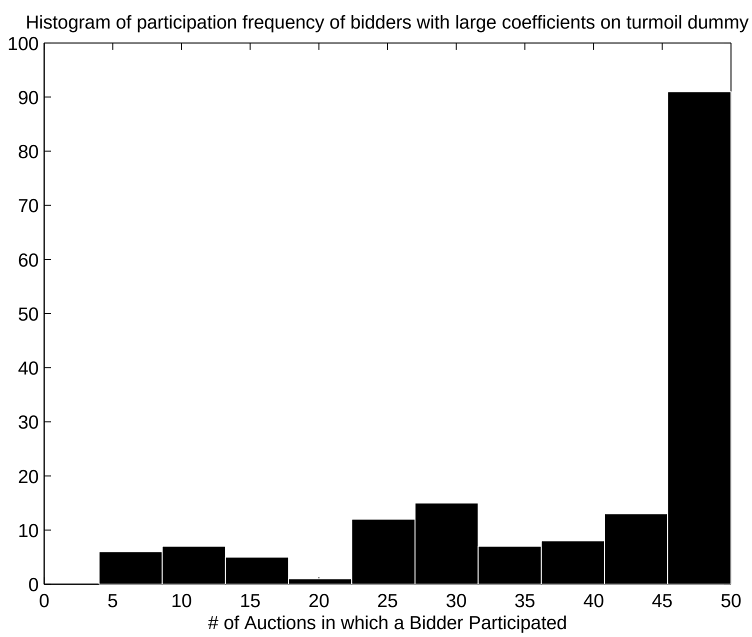

Figure 12: Histogram of Participation by Bidders with Large Significant Turmoil Effects

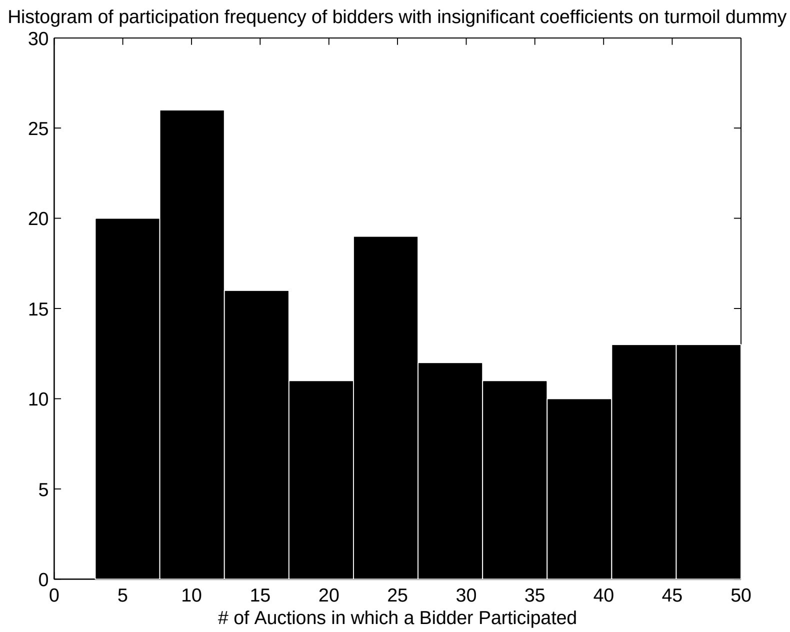

Figure 13: Histogram of Participation by Bidders with Insignificant Turmoil Effects

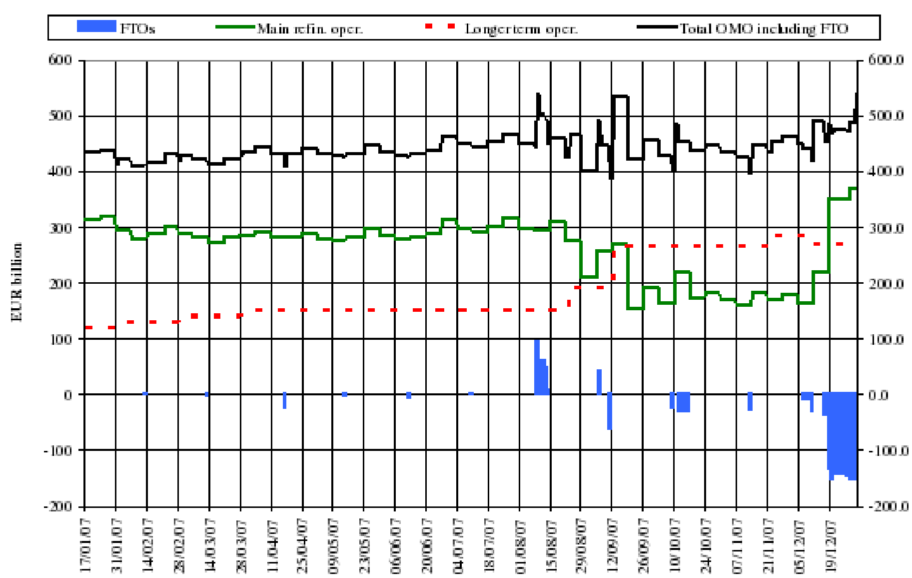

Figure 14: Liquidity Provision by the ECB in 2007

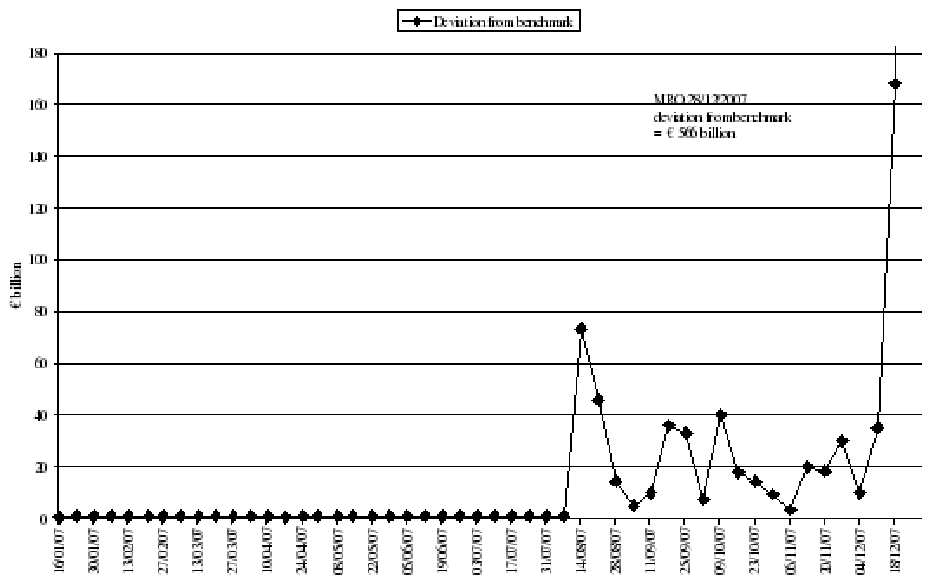

Figure 15: Deviation from Benchmark at the MROs in 2007