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## MRO bidding in the presence of LTROs: an empirical analysis of the pre-crisis period

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## WORKING PAPER SERIES

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# MRO BIDDING IN THE PRESENCE OF LTROS AN EMPIRICAL ANALYSIS OF THE PRE-CRISIS PERIOD

Edgar Vogel

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**NOTE:** This Working Paper should not be reported as representing the views of the European Central Bank (ECB). The views expressed are those of the authors and do not necessarily reflect those of the ECB.

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### **Abstract**

Using individual data from the Eurosystem's liquidity providing tenders for the pre-crisis period we investigate banks' joint bidding behaviour in Main Refinancing Operation (MRO) and Longer Term Refinancing Operations (LTRO). We test whether banks bid at lower rates in MROs before the LTRO and at higher rates after the LTRO, compared to other operations.

We offer two main findings. First, we find that in general banks bid in the MRO before the LTRO at lower rates as compared to "other" MROs. Moreover, MRO participants which also bid in the following LTRO bid at even lower rates, compared to peers not bidding in the LTRO. These findings support the hypothesis that banks view obtaining liquidity from the two operations as substitutes and bid strategically. Second, we find that banks generally bid more aggressively in the MRO after the LTRO. Even more striking, banks which participated also in the LTRO preceding the MRO bid at substantially higher rates. These findings reflect that "short" banks, with potentially large net liquidity needs after the LTRO bid more aggressively. Other counterparties with liquidity needs in that particular operation are forced, as a best response reaction, to bid also at higher rates. Although size plays a considerable role for bidding behaviour, the conclusions are valid for banks of different size.

*JEL classification: D44, D53, D84, E43, E50, G10, G21*

*Keywords: repo auctions, open market operations, strategic bidding, central bank operations, monetary policy*

## Non-technical Summary

Using individual bidder data from the Eurosystem’s liquidity providing tenders for the pre-crisis period, we investigate banks’ joint bidding behaviour in Main Refinancing Operation (MRO) and Longer Term Refinancing Operations (LTRO). The Eurosystem’s instrument to manage its operational target are collateralized refinancing operations of two different maturities: short term money with a maturity of one week is auctioned weekly in MROs while term money with a maturity of three months is auctioned once a month in LTROs. Via adjusting the amount of loans given to the banks, the ECB can steer liquidity in the overnight interbank market and the overnight interest rate.

While research has investigated bidding behavior for MROs and LTROs separately, it has so far not explicitly focused on the interdependencies of joint bidding plans in these two operation types. We contribute to this literature by directly addressing this gap. This is the first paper which derives and formulates hypotheses about how the sequence of operations might affect bidding behavior in ECB liquidity auctions, and brings these tests to the data in an otherwise standard econometric framework.

As theoretical auction literature has shown, auction participants usually take a longer sequence of operations into account when deciding about their bidding plans. In other words, banks consider bidding in the MROs and LTROs as a joint optimization problem and do not develop their bidding plans in isolation only for the MROs. To reflect this, we test whether banks bid differently in the MROs before and after the LTROs. More specifically, we first test whether banks bid in general at lower rates in the MRO before the LTRO. Furthermore, we hypothesize that banks which plan to bid in the MRO and LTRO will bid at even lower rates. This is because in the sequence of operations, the MRO takes place shortly before the LTRO. Hence, banks can split their bids between two operations and make up for a potential shortfall within a short period of time. Second, we test whether banks bid at higher rates after the LTRO. The motivation underlying this question is that the two preceding operations leave potentially more banks with a liquidity situation below their expectations. While data gaps do not allow for a direct test of this hypothesis, proxies for banks’ net demand confirm this conjecture. Hence, those bank have an incentive to bid at higher rates in order to make up for the liquidity shortfall.

As regards the first hypothesis, we find that in general, banks bid in the MRO before the LTRO at lower rates as compared to “other” MROs. Moreover, MRO participants which also bid in the following LTRO bid at even lower rates, compared to peers not bidding in the LTRO. These findings support the conjecture that banks view obtaining liquidity from the two operations as (asymmetric) substitutes and bid at lower rates before the LTRO as they split their demand between two operations. The relatively high discount in the MRO before the LTRO can be explained by both, bidders which participated in more operation types and ones which only bid in the MRO before the LTRO. Second, we find that banks generally bid more aggressively in the MRO after the LTRO. Even more striking, counterparties which participated also in the preceding LTRO bid at substantially higher rates. These findings reflect that “short” banks, with potentially large net liquidity needs after the LTRO, must bid more aggressively. In addition, counterparties which happen to have liquidity needs in that particular operation are forced, as a best response reaction, to adjust their bids up to obtain sufficient amounts of liquidity. These results hold for the whole sample and for banks of different size.

# 1 Introduction

The Eurosystem's instrument to manage its operational target are collateralized refinancing operations of two different maturities: short term money with a maturity of one week is auctioned weekly in the Main Refinancing Operations (MROs) while term money with a maturity of three months is auctioned once a month in Longer Term Refinancing Operations (LTROs). Via adjusting the amount of loans given to the banks, the ECB can steer liquidity in the overnight interbank market and can control the overnight interest rate.

By offering operations with different maturities the banks are also given the opportunity to diversify their portfolios. This is not only an opportunity but also a challenge: bidding in different operations with different maturities at different times under uncertainty is a non-trivial task. MROs and LTROs have been separately analyzed in a number of papers. However, there is only limited and indirect evidence on the interdependencies of joint bidding plans in these two operation types. We contribute to this literature by directly addressing this gap. This is the first paper which derives and formulates hypotheses about how the sequence of operations might affect bidding behavior in ECB liquidity auctions, and brings these tests to the data in an otherwise standard econometric framework. We motivate this line of research by findings from the auction literature suggesting that agents' bidding plans (strategies) take entire sequences of auctions into account.

We use individual bidding data from the Eurosystem's tender operations from the pre-crisis period with competitive bidding to examine banks' joint bidding behaviour in MROs and LTROs. We focus on this period as for the majority of the crisis period the ECB adopted a fixed rate full allotment strategy.<sup>1</sup> More specifically, we analyze bidding patterns in MROs preceding and following LTROs.

We offer two main findings. First, we find that in general, banks bid in the MRO before the LTRO at lower rates as compared to "other" MROs. Moreover, MRO participants which also bid in the following LTRO bid at even lower rates, compared to peers not bidding in the LTRO. These findings support the conjecture that banks view obtaining liquidity from the two operations as (asymmetric) substitutes and bid lower before the LTRO as they split their demand between two operations. The relatively high discount in the MRO before the LTRO can be explained by both, bidders which participated in more operation types and ones which only bid in the MRO before the LTRO. Second, we find that banks generally bid more aggressively in the MRO after the LTRO. Even more striking, counterparties which participated also in the preceding LTRO bid at substantially higher rates. These findings reflect that "short" banks, with potentially large net liquidity needs after the LTRO, must bid more aggressively. In addition, counterparties which happen to have liquidity needs in that particular operation are forced, as a best response reaction, to adjust their bids up to obtain sufficient amounts of liquidity. These results hold for the whole sample and for banks of different size.

The rest of the paper is organized as follows. The next section describes the institutional framework of the Eurosystem. The third section introduces the data and provides a preliminary descriptive analysis. In section 4 we summarize the literature and provide the theoretical motivation for the empirical work which is presented in section 5. The last section concludes. Additional material can be found in the appendix.

## 2 Institutional Framework

The operational framework of the ECB – similar to other major central banks – targets the short term interest rate on the interbank market.<sup>2</sup> By steering the overnight interest rate the ECB pins down the origin of the

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<sup>1</sup>Unless otherwise stated, the modalities in the operational framework refer to the pre-crisis period.

<sup>2</sup>We will use ECB and Eurosystem interchangeably. On a more technical level, the ECB's operational target is to keep EONIA (Euro OverNight Index Average) close to the minimum bid rate which serves in non-crisis times as the main policy rate (e.g. ECB (2001) or

yield curve and transmits its policy stance to the economy. For banks with access to the Eurosystem standing facilities, this rate can fluctuate between the rate of the deposit facility and the marginal lending facility.

To implement its operational target, the ECB has to set the appropriate liquidity conditions in the interbank market. This happens via loans to banks against eligible collateral (repos). If liquidity is too abundant, the overnight rate on the interbank market will drop while overly tight liquidity conditions will let the interest rate rise. Liquidity needs of banks are in principle beyond the control of the central bank. They are composed of liquidity absorbing items like government deposits, banknotes, or minimum reserves. Reserve requirements are determined as a share of short term liabilities<sup>3</sup> and are intended to serve as a mandatory liquidity buffer held at accounts with the central bank. Their operational role is to increase the (structural) liquidity shortage and to smooth movements of short term interest rates. As banks have to hold a pre-specified amount of reserves on average over a maintenance period (MP), there is a substantial variation in the fulfillment pattern (front- or backloading) which depends on the expected path of interest rates. The length of the MPs varies slightly but is approximately four weeks. Minimum reserves are remunerated at the average policy rate over the respective period. Funds deposited with the central bank over and above what is required are not remunerated. Given this setup, banks have an incentive not to hold more reserves than necessary.

As in the pre-crisis period the banking system suffered by construction from an *aggregate* liquidity deficit, the “appropriate” (i.e. neutral) liquidity conditions were implemented via three different types of operations: main refinancing operations (MRO), longer-term refinancing operations (LTRO), and fine-tuning operations (FTO). MROs and LTROs were liquidity providing while FTOs were used for both, liquidity providing and absorbing purposes.<sup>4</sup> The timing of these operations was subject to a change which was implemented in March 2004 (see ECB (2003) for more details). The main features of the updated operational framework are that the MPs now start on the settlement day of the MRO following the monthly policy rate meeting of the Governing Council. Given the timing of the meeting, the MP usually starts between the 10th and 15th of any calendar month.<sup>5</sup> Further, the maturity of the weekly MROs was shortened from two weeks to one week. The other relevant change for the banks’ decision making process is that now MROs do not overlap with the day when rate changes become effective and banks do not have liquidity buffers from previous week’s auction. Hence, over- or underbidding due to expected changes in the interest rate should not play any role for bidding behavior in MROs. Moreover, if the overnight rate is expected to be close to the minimum bid rate on the last day of the MP, then it should, by invoking the martingale hypothesis, also be close to the policy rate on all other days during the MP (Hamilton 1996) and a violation would indicate the existence of arbitrage possibilities.<sup>6</sup>

In both frameworks, the timing of the MRO within the week is identical. The MRO auction is gener-

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<http://www.ecb.int/mopo/implementation/intro/html/index.en.html>). EONIA is a volume weighted index of overnight unsecured transactions computed from the contributions of panel banks in the Euro area. Other central banks target an array of benchmark rates: the Swiss National Bank targets the 3-months LIBOR (Jordan and Kugler 2004) or the Fed targets the federal funds rate (Meulendyke 2008).

<sup>3</sup>The reserve ratio was initially 2% (starting from January 1999) and lowered to 1% in January 2012 with a lump-sum deduction of EUR 100.000 which exempts small banks from holding reserves. As the ECB sets the reserve ratio, it is partly able to control this liquidity absorbing factor.

<sup>4</sup>Within its operational framework (described in the General Documentation), the ECB can also use reverse transactions (repos), the issuance of central bank debt instruments or outright transactions for the implementation of monetary policy. During the financial crisis, the ECB abandoned the strategy to operate with zero excess liquidity at any point in time. At the beginning of the crisis, it shifted liquidity provision towards the beginning of the MP (frontloading with liquidity absorbing FTO at the end of the MP) and later switched to unlimited liquidity provision at a fixed rate (“full allotment”). In addition, it introduced additional monthly LTROs with a maturity of one month and carried out two LTROs with a maturity of three years (the so-called VLTROs, settled on 22 December 2011 and 1 March 2012). Furthermore, it engaged in outright purchases of covered bonds (Covered Bond Purchase Programmes 1 and 2) and of government debt (Securities Market Programme). All these operations left the banking system with liquidity in excess of the mandatory minimum reserves.

<sup>5</sup>In the old framework, the start was always on the 23rd of a month.

<sup>6</sup>This is because the MRO rate is kept constant over the MP and the ECB guarantees to exactly fulfill banks’ aggregate liquidity needs (i.e. to smooth out any positive or negative liquidity shock). In such an environment, banks have no incentive to keep more liquidity than needed to fulfill reserve requirements, and the short term interbank rates (i.e. a substitute to central bank financing) can be expected to stay very close to the MRO rate with a high degree of certainty. Consequently, the expected interest rate is tightly linked to the deterministic MRO rate and rate expectations play only a minor role.

ally announced on Monday at 15:30. Counterparties can place bids until Tuesday 9:30.<sup>7</sup> Bids are up to 10 rate/volume-bundles with the main policy rate being the floor. The ECB also announces the liquidity neutral benchmark allotment volume. This is the volume which is needed to exactly fulfill the banking sector's aggregate liquidity needs. The allotment decision (total bid amount, total allotment amount, lowest, highest, weighted average, and marginal rate) is announced at 11:20.

In the period considered, LTROs were carried out on a monthly basis. They have a maturity of three months and were originally introduced because they provide “a good opportunity for smaller counterparties, which have limited or no access to the interbank market, to receive liquidity for a longer period” (ECB (2002), p. 5). The change in the operational procedures affected the position of the LTRO within the MP: the allotment was moved from the first to the last Wednesday of the month. Similarly to the MROs, the exact details of the three-month operation are announced on (usually) Tuesday 15:30 inviting banks to submit bids until Wednesday 9:30 and results are published at 11:20. Contrary to the MROs, there is no binding minimum bid rate. There is also no benchmark allotment but a pre-announced fixed volume with rather infrequent changes. Hence, in these auctions the Eurosystem acts as a pure price taker without the intention to signal any monetary policy stance. For these operations, interest rate expectations over the life of the operation may play a role.

FTOs can be liquidity providing or absorbing (with the policy rate then serving as a ceiling) and are used on an ad-hoc basis to smooth out unexpected aggregate liquidity shocks to the system. These shocks can be truly unexpected (exogenous) but were at several occasions endogenous in the sense that banks' total demand in refinancing operations fell short of the banking system's aggregate liquidity needs. This underbidding was mainly driven by interest rate expectations (Bindseil, Nyborg, and Streubulaev 2009). In such cases, the ECB has to inject liquidity into the system if it wants to prevent the overnight rate to drift to the rate of the marginal lending facility. More generally, FTOs were carried out on the last day of the MP to re-establish neutral liquidity conditions on that day.

## 2.1 Literature Review

The MRO and LTRO auctions of the ECB were analyzed in a series of separate papers. Linzert, Nautz, and Bindseil (2007) focus on bidding behavior in the LTROs. They investigate how a set of exogenous variables (interest rates, costs of collateral, etc.) but also variables like banks' size or country of origin affect banks' bidding behavior and success. In line with expectations they find that costs of collateral and market financing costs are important determinants of banks' behavior. Small banks bid generally at higher rates and obtain hence higher allotments. Further, small banks react stronger to interest rate expectations but react less to changes in the costs of collateral. In contrast to the MROs, they find evidence for the winner's curse effect in the LTROs as banks reduce participation, bid rates and bid volumes when interest rate uncertainty increases. This effect is especially pronounced for larger banks indicating that they have a more active money market desk.

Complementing the analysis from above, Bindseil, Nyborg, and Streubulaev (2009) focus on the MROs. In contrast to the LTROs, banks bid more aggressively when interest uncertainty increases. This suggests that the fear of going out empty-handed from the auction is more important than the winner's curse and is in line with the hypothesis that banks do not possess (private) information. If they had information about the post-auction market, banks should bid opportunistically and the winner would “overpay” relative to the post-auction value (Milgrom and Weber 1982).

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<sup>7</sup>This description is valid for weeks without bank holidays. With holidays the weekdays might differ but the MRO was still allotted before the LTRO. Yet another change is that in the old framework, the ECB only announced its forecast of the autonomous factors and the market had to calculate a proxy for the subsequent allotment. This left some room for speculation whether the allotment decision was liquidity neutral or not.



Eisenschmidt, Hirsch, and Linzert (2009) compare banks' MRO bidding behavior before and during the crisis. Their main finding is a polarization of banks' bidding behaviour during the crisis: while more banks place bids above the marginal rate in order to avoid rationing, the share of very low bids also increases. They interpret this as a signal that financially strong banks bid opportunistically as they had access to the interbank market. Stressed banks were more risk averse and wanted to secure ECB funding even if they had to pay – relative to the pre-crisis period – a higher price for liquidity. This is indirect evidence for the hypothesis that the risk of being short-squeezed incentivizes banks to bid at higher rates (Nyborg and Strebulaev 2004). Similar to the other two papers evaluating the ECB operations, it is found that large banks underbid small banks. Cassola, Hortaçsu, and Kastl (2013) estimate the willingness of banks to pay at ECB auctions and find that before the crisis, auction outcomes were closely linked to published (traded) market rates (EUREPO and EURIBOR). During the crisis, ECB auction and market rates become increasingly decoupled. They view this as a sign that some banks were not able to obtain market funding at market rates. These stressed banks pushed up bid rates, forcing financially sound banks to also adjust their bid rates reinforcing the upward spiral.<sup>8</sup>

Work on the substitutability of MROs and LTROs has so far been limited; bidding behavior was mostly analyzed without explicitly taking interactions into account. Indirect evidence on a link between bidding behavior in MROs and LTROs is provided e.g. by Cassola, Hortaçsu, and Kastl (2013). They find that MROs and LTROs were substitutes before the crisis but find that after August 2007 bidding behavior in both operations was more aligned (suggesting complementarity). After (before) the outbreak of the crisis, outstanding volumes in an LTRO led to more (less) aggressive bidding in MROs. The reason for the change is that during the crisis, increasing LTRO borrowing signalled stress which in turn increased also bid rates in the MROs. Linzert, Nautz, and Bindseil (2004) conclude with a mixed result. They find that banks which frequently bid in the MROs bid for higher amounts and also more often in the LTROs but the effect on bid rates and bid rate dispersion is not significant. Banks which had an increasing allotment over the past two MROs prior to the LTRO bid for lower volumes and at lower rates. The effects are rather small and (depending on the specification) statistically only marginally significant. Lastly, Eisenschmidt, Hirsch, and Linzert (2009) test the substitutability hypothesis with a natural experiment by exploiting changes in the share of funds allotted in the LTROs and MROs while keeping aggregate liquidity provision unchanged at the neutral amount. They find that in the pre-crisis period a change in relative allotment volumes did not lead to any significant change in bidding behaviour while during the crisis bid rates in the MROs increased if the MRO allotment share decreased. This indicates that banks were not willing to shift into the LTRO but rather bid at higher rates in the MRO. Their interpretation is that banks want to retain flexibility instead of being locked in for three months. However, they also find that bidding success in the LTROs induces banks to bid at lower rates in the MRO as some of their funding needs have been satisfied already.

### 3 Data

We use individual bidder data from the ECB's tender operations with competitive bidding starting with the MRO allotted on 16th October 2001 and end with the MRO allotted on the 8th August 2007. The first cutoff is motivated by data availability: we use the 2 week EURIBOR – which was quoted first on 15th October 2001 –

<sup>8</sup>There is also a large literature on the period with fixed rate tender and heavy overbidding (before June 2000), e.g. Nautz and Oechssler (2006), Nautz and Oechssler (2003), Ayuso and Repullo (2001) or Ehrhart (2001). While there is no consensus, the most frequently cited explanations for overbidding are an overly tight liquidity policy due to an asymmetric loss function of the ECB, expectations of rising rates and, on a more theoretical basis, an inherent instability or even non-existence of an equilibrium in fixed rate tenders. Furthermore, a large literature also evaluated bidding behavior in government bond auctions; e.g. Nyborg, Rydqvist, and Sundaresan (2002) for Sweden, Elsinger and Zulehner (2007) for Austria, Bjønnes (2001) for Norway, Cammack (1991) for the US, and Hortaçsu and McAdams (2010) for Turkey. The predominant findings is that higher uncertainty induces bidders to bid at lower rates, demand less, and increase the dispersion of their bids (i.e. bidders react to the winner's curse).

for computing forward rates. The second date we consider to be the beginning of the financial crisis in the Euro area: on August 9 and the following days, the ECB used a series of – rather unusual – fine-tuning operations (FTOs) to inject overnight liquidity. This choice ensures that we exclude any potential anticipation effects.<sup>9</sup> We are able to follow individual bidders over time via unique bidder codes. Unless otherwise stated, bidding aggressiveness refers to bidding behaviour in terms of prices (i.e. bid rates).

We also exclude operations which were underbid: within the specified period banks bid in 10 MROs less than the ECB was willing to allot (measured by the benchmark allotment). This “bidder strike” was mainly due to expectations of falling interest rates and hence a preference to shift refinancing to the next MRO (Bindseil, Nyborg, and Streubulaev 2009). Lastly, we throw away data from the old operational framework with MPs without an LTRO, or, where the first and/or last operation is an LTRO. This has to be done as identification relies on having MROs before and after an LTRO within a MP (more details are given in section 5.1). This leaves in total 259 MROs and 63 LTROs.

In section 3.1 we describe the definition and construction of the variables. Then, section 3.2 offers descriptive statistics of bidding in MROs, conditional on a) the position of the MROs relative to the LTRO and b) conditional on LTRO participation.

### 3.1 Variables

The variables are standard in the literature and divided into two categories: endogenous and exogenous. Endogenous variables are endogenous from banks’ perspective and reflect bidders’ individual decisions. Exogenous variables are market data (e.g. forward spreads) or the ECB benchmark and taken as given by individual banks.

#### 3.1.1 Endogenous Variables

The approach here follows the convention in the literature and condenses bank  $i$ ’s bid schedule in operation  $t$  into a tuple  $\{r_{i,t}, q_{i,t}\}$  with  $r_{i,t}$  being the weighted average rate computed as  $r_{i,t} = \sum_{k=1}^K b_{i,t,k} \times q_{i,t,k} / \sum_{k=1}^K q_{i,t,k}$  where  $q_{i,t,k}$  denotes the bid volume for bid  $k$ . We use this bid rate to compute

*discount* as the benchmark rate minus the bank specific weighted average bid rate, i.e.  $discount_{i,t} = R_t - r_{i,t}$  with  $R_t$  being the secondary market rate. We take the change in the length of the operations into account by accordingly adjusting the secondary market rate. For the MROs we use the one week swap rate (two week for the old operating framework). Although the underlying instrument (EONIA) is unsecured, the swap rate is considered to be – resembling the features of repos – almost risk free. The EONIA swap market is highly liquid and is hence likely to reflect accurately the prevailing market conditions (Hartmann and Valla (2008), Bindseil, Nyborg, and Streubulaev (2009)). Also, it is available for the whole sample period and tracks EUREPO – a European interbank repo rate – rather well for the overlapping period.<sup>10</sup> The discount gives us an indication by how much banks underbid the benchmark rate. Later, we will use the discount as a measure of “aggressiveness” in bidding with more aggressive bidding (i.e. higher bid rates) corresponding to lower discounts. Also, the discount will serve as the dependent variable in the econometric exercise. We further investigate bank bidding behavior in terms of bid volume by using the bank’s

<sup>9</sup>Other papers also spanning the time period around the crisis choose a similar cut-off date; e.g. Eisenschmidt, Hirsch, and Linzert (2009), Kraenzlin and Schlegel (2012) or Cassola, Hortaçsu, and Kastl (2013). Lastly, e.g. Eisenschmidt, Hirsch, and Linzert (2009) and Cassola, Hortaçsu, and Kastl (2013) focus on the effects of the crisis and show that this has changed the bidding behavior of banks quite substantially. As we do not want to “pollute” our sample by using data from that period, we exclude the time period after the cut-off date.

<sup>10</sup>We also tried the EUREPO and EURIBOR (an unsecured interbank rate) as alternatives. Both are fixed 11:05 and published at 12:00 and hence not contaminated by the publication of tender results (i.e. post-auction activity). In terms of levels, the swap rate is trading somewhat above EUREPO and below EURIBOR. However, given that the spreads between the different benchmarks are rather stable, the results (especially marginal effects) were essentially unchanged as the level differences are absorbed by a constant.

*relative bid quantity* defined as a bank's total bid amount relative to the benchmark on the announcement day. We measure success by the

*award ratio* defined as an individual bank's allotted volume relative to its total bid volume. However, as high award ratios can be achieved by bidding at high rates, an elevated award ratio is also an indication for aggressive bidding. The next three variables are derived from individual decisions but used as tender-level variables. An uneven distribution of the award ratio indicates that many banks missed their refinancing targets (in either direction) and have been taken by surprise. We measure this by the

*award imbalance* as the cross sectional (per tender) standard deviation of the individual award ratios. We will use the lagged value (i.e. from the last operation) of this variable to proxy for the uneven distribution of liquidity needs. According to Nyborg and Strebulaev (2004), a more dispersed liquidity situation implies more aggressive bidding. This is because more banks are "short" and try to avoid being short-squeezed in the post-auction secondary market. Further,

*participation* is computed as the number of participations in e.g. MROs of a MP divided by the total number of MROs of that period. This statistic will be a number between 0 and 1.

### 3.1.2 Exogenous Variables

The following exogenous variables are defined on the tender level as they are derived from aggregate (market) data. We proxy the

*uncertainty* in the market by using a forecast of the variance of changes in the swap rates. To do this, we employ an exponential smoothing model where we let an algorithm choose the smoothing parameter such that the overall discrepancy between the one-step-ahead forecast and the realization is minimized.<sup>11</sup> The

*swap spread* is the EONIA swap rate for the respective operation minus the minimum bid rate. Thereby we measure a bank's outside option to get funds from the market but also the ability of banks to place low bids. Further, the swap rate is also an indicator of interest rate expectations during the life of the contract. The

*forward spread* is the spread between the forward rate for the specific operation for the next date when the operation will be carried out and the minimum bid rate. For instance, the forward spread for the MRO in the new framework is the one week forward rate (from one week in the future to two weeks) minus the minimum bid rate. This gives an indication about the expected price of a specific operation for the next date when this operation is available. The

*benchmark* is a proxy for the expected MRO auction size and measured by the benchmark allotment announced by the ECB on the announcement day of the operation. As prior to the change in the operational framework no benchmark was announced, we use the published forecast of autonomous factors. For the LTROs the allotment volume was pre-announced and changed only infrequently. We include this variable as Vålímäki (2006) shows that a higher expected allotment volume increases banks' uncertainty about their own allotment and hence increases their bid rate.

## 3.2 Descriptive Statistics

This section provides a descriptive analysis of bidding behavior along two different dimensions. First, we will slice the sample by the distance of MROs to the LTROs. We distinguish between three types of MROs: operations immediately before the LTRO ("before"), operations immediately after the LTRO ("after"), and

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<sup>11</sup>As a robustness check, also estimated a GARCH(1,1) model without a qualitative change of the results.

“other” MROs. Second, we will look at the same set of variables capturing bidding in the MRO but conditioning on LTRO participation of that MP. The purpose of this approach is to identify key differences in bidding behavior and set the scene for a more detailed econometric analysis.

When reporting averages we first average for a given tender and then over time (over tenders). This is to control for the varying participation over time. Further, whenever applicable or meaningful, we provide statistics for the whole sample and by bank size (small, medium, and large). To measure bank size, we would ideally use a metric directly related to a bank’s balance sheet which is, however, not available for most medium and small banks. Hence, we follow the literature and use banks’ reserve requirements to group them. As required reserves are a function of banks’ short term liabilities, this number serves as a proxy for the size of the balance sheet. In appendix A.1 we provide a more detailed methodological description of the grouping strategy. Note that due to the notational convention, a lower discount corresponds to a higher bid rate.

Table 1 shows differences in bidding for the three different operation types. Among all operation types, the discount is largest for the MRO before the LTRO. For the MRO immediately after the LTRO, the discount drops significantly for all groups, and becomes even negative for small banks. For operations being neither immediately before nor after the LTRO (“other”), the discount is between the two other types. The difference between the before and after-LTRO operations is largest for small banks (1.9 basis points) and smallest for large banks (1.2 basis points). On the other hand, participation is rather evenly distributed across operation types with the typical size-gradient. Award ratios are highest in MROs after the LTRO. This is consistent with the lowest discount: more aggressive bidding leads to high award ratios. The relative bid quantity does not display any strikingly different pattern between operation types.

Table 1: Summary Statistics Endogenous Variables: Before/After/Other MROs

	Before			After			Other		
Variable	Small	Medium	Large	Small	Medium	Large	Small	Medium	Large
Discount	1.20	1.64	1.73	-0.65	0.04	0.57	0.56	1.08	1.29
Participation	0.17	0.33	0.45	0.15	0.31	0.45	0.17	0.32	0.46
Award Ratio	0.92	0.88	0.86	0.95	0.91	0.86	0.94	0.89	0.85
Relative Bid Quantity	0.01%	0.09%	1.18%	0.01%	0.09%	1.16%	0.01%	0.09%	1.16%

*Notes:* Discount is computed as the weighted average where the weights are recomputed for the different groups. Award ratio is computed by dividing allotment and bid volume. Discount in basis points.

Table 2 displays bidding behavior of banks in MROs conditional on LTRO participation within the MP. Numbers from panel (A) demonstrate that banks bidding also in LTROs have a larger discount, participate more often, and have a lower award ratio. The latter reflects the less aggressive bidding, which seems to be compensated by higher bid quantities. Relative bid quantities are higher for LTRO bidders. In contrast to “participation” which puts the number of participations in relation to the number of MROs in that MP, the statistic “ $p(\text{Participation})$ ” measures the probability for a bank to participate at least in one MRO of the MP. The latter number is, by construction, higher. Therefore, the more interesting question is whether a bank, conditional on bidding at least in one MRO, is participating on average more often if it also decides to bid in the LTRO. To compute this, we first divide the share of banks participating at least once (“ $p(\text{Participation})$ ”) in the MROs if they bid in the LTRO by the same number if they did not bid in the LTRO. The results (denoted as  $\text{LTRO}_y/\text{LTRO}_n$ ) are shown in panel (B). The first line shows that the probability to participate (“ $p(\text{Participation})$ ”) in an MRO increases by a factor of 2.4 if a bank also bid in the LTRO. Then, we repeat the same calculation for the participation frequency in MROs (panel B, line 2). The number of MROs in which a bank participated increases on average by a factor of 2.6 if a bank bid also in an LTRO. Hence, LTRO participation is correlated with an increased bid frequency in the MROs. This holds across all groups. An additional compact way to display the difference in MRO bidding

Table 2: Endogenous Variables: Conditional Bidding Behavior

Panel (A): Bidding in MROs

Group	Not Bid in LTRO				Bid in LTRO			
	All	Small	Medium	Large	All	Small	Medium	Large
Discount	0.85	0.41	0.90	1.17	0.99	0.33	1.03	1.23
p(Participation)	0.31	0.22	0.35	0.45	0.73	0.56	0.73	0.87
Participation	0.24	0.15	0.27	0.37	0.60	0.40	0.59	0.78
Award Ratio	0.86	0.91	0.86	0.82	0.81	0.90	0.80	0.78
Relative Bid Quantity	0.33%	0.01%	0.08%	1.01%	0.60%	0.01%	0.11%	1.42%

Panel (B): Ratios p(Participation) &amp; Participation

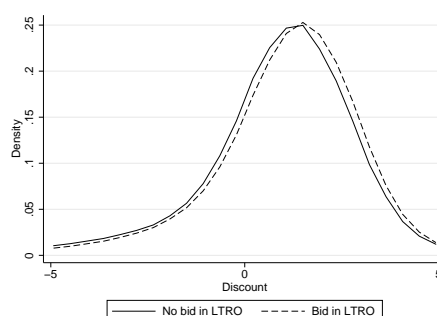
$LTRO_y/LTRO_n$	All	Small	Medium	Large
p(Participation)	2.4	2.6	2.1	1.9
Participation	2.6	2.8	2.2	2.1

*Notes:* Discount is computed as the unweighted average. Award ratio is computed by dividing allotment and bid volume. Discount in basis points. In panel (B), p(Participation) is probability to bid in an MRO if bid in the LTRO divided by the probability to bid in the MRO if not bid in the LTRO. Numbers are computed as  $\frac{x|LTRO_y}{x|LTRO_n}$  with “x” being either p(Participation) or Participation.

behavior by LTRO participation is to compare the (conditional) distribution of discounts. The distribution for LTRO bidders clearly shifts to the right (higher discount) and the difference in the distributions is confirmed by a formal Kolmogorov-Smirnov test (figure 1).

Finally, we put the importance of MROs and LTROs into perspective by showing LTRO financing as a share of total central bank financing by bank size (figure 2). Large banks obtain about 20%-30% of their financing in the LTROs while this number is considerable higher for small and medium sized banks; around 40%-60%.

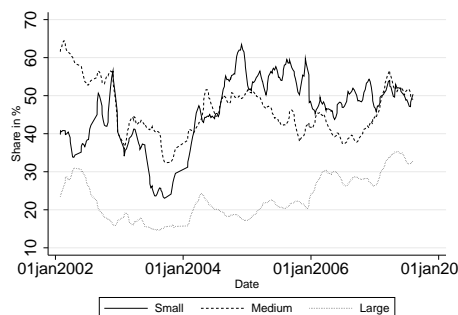
Figure 1: Conditional Discount Distribution



*Notes:* Kernel density estimate using a standard Gaussian kernel (bandwidth 0.5bp).

The take-away from this section is that banks have the lowest discount in MROs before the LTROs and are most aggressive after LTROs. Accordingly, they realize the smallest allotments in the MROs before the LTRO. When looking at bidding conditional on LTRO participation (irrespective of the timing), banks also bidding in LTROs bid at higher discounts, participate more frequently, and bid for higher (relative) volumes but are less successful. This suggests that banks also planning to obtain funds from the LTRO bid at lower rates but compensate this by higher volumes. Analyzing the data by size, we find that small banks are more aggressive bidders compared to large counterparties. On average, they bid at about 0.8 basis points higher than large banks.

Figure 2: Share of LTRO Volume in Total Eurosystem Financing



Notes: Volumes computed on any allotment day of an operation (including the allotment of that day).

Consequently, they achieve higher award ratios. On the other hand, small banks participate in less frequently compared to the group of large banks. In general, similar conclusions hold for LTROs: small banks bid at higher rates, realize higher allotments and bid less frequently than large banks. Further, in LTROs discounts are smaller, participation is less frequent, and the dispersion of bid volumes is more even (results available upon request).

## 4 Theoretical Motivation

Papers using ECB auction data (see section 2.1) have examined the effect of exogenous factors on bidding behavior but have so far neglected the role of the sequencing of operations. Also, due to the complex problem and the specificities of central bank liquidity auctions, the availability of theoretical models suitable to be tested using ECB auction data in the context of strategic bidding, is limited. Contrary to this, empirical and theoretical research has shown that bidders regard a sequence of auctions as one joint problem. Below, we briefly summarize the existing literature and outline some testable hypothesis derived from it.

Important theoretical contributions on bidding behavior in sequential or regular auctions are Milgrom and Weber (2000), Weber (1983), Scoones (1994), or Wiggins (1994). In frictionless environments they mostly find that prices of (almost) identical goods in consecutive auctions should be identical. However, empirical evidence contradicts this and shows that prices tend to vary over a sequence of auctions. Also, the descriptive statistics in this paper reveal striking differences in bidding behavior along different dimensions. Theoretical explanations for such a systematic change of prices between auctions are for instance participation costs to stay in the auction (von der Fehr 1994) or depleted budgets as more expensive objects are auctioned first (Benoit and Krishna 2001). Ashenfelter (1989) surveys the literature and finds that declining prices of identical objects over the course of an auction can be attributed to quantity constraints and bidders' risk aversion while Ginsburgh (1998) shows that the majority of this price anomaly can be explained by non-strategic bidding and the behaviour of absentee bidders. This suggests that it is important to control for these effects by e.g. including a bank's size or country of origin.

Focussing on modeling strategic behavior over a sequence of auctions, Zeithammer (2006) shows that rational bidders reduce current bids if similar goods will be auctioned in upcoming auctions. An empirical test using data from e-Bay auctions confirms the hypothesis. Incorporating learning behavior on the sellers' and buyers' side, Zeithammer (2007) models bidding in sequential auctions and finds that rational bidders shade their bids more whenever they have larger buffers and expect similar objects to be on sale in the near future. Hence, one should control for the expected quantity at stake, past success, the expected number of competitors, or the (ex-

pected) time to the next auction. In the present context, this corresponds to the expected size for the allotment (benchmark), past award ratio(s), and the distance to the next operation or the position relative to the LTRO. The latter is important because banks can exploit the asymmetry along the time dimension: the MRO is allotted on Tuesday while the allotment of the LTRO is on Wednesday. Consequently, as once per MP banks have the opportunity to bid first in a MRO and then in a LTRO within a short period of time – usually within one or two days – offers opportunities to bid strategically and distribute the fulfillment of liquidity needs between two operations. This is a plausible working hypothesis as the liquidity position of banks can adjust rather quickly. While banks certainly develop baseline strategies for central bank liquidity auctions (see e.g. the size gradient in figure 2), this adjustment margin is more flexible than the overall funding strategy.<sup>12</sup> To be more precise, banks might view bidding in the MRO as a “test run” and then adjust their strategy in the LTRO (or the MRO following the LTRO) depending on the outcome of that operation. This is possible as long term money (LTROs) is a better substitute for short term funding (MROs) than vice versa. Hence, a low allotment in the MRO can be compensated in the LTRO one or two days later which makes opportunistic bids in the MRO before the LTRO less costly in expected terms. Especially banks with an active money market desk might have the incentives and capacity to exploit this. In addition, Ewerhart, Cassola, and Valla (2010) develop a model explaining bidding in liquidity auctions with progressively more expensive collateral, and show that banks have an incentive to split bids between several auctions closely following each other. This is because with increasing costs of collateral (illiquid collateral has no opportunity costs), banks’ marginal valuation of liquidity is decreasing with quantity (“declining valuation” argument). Putting the arguments of this section together, the first testable hypothesis is that in operations before the LTRO banks should bid, relative to MROs of type “other”, at lower rates. Moreover, LTROs participants should bid, compared to non-participants, at even lower rates.

Ewerhart, Cassola, and Valla (2010) show that in the case of a liquidity neutral allotment (i.e. fixed total allotment), bid levels should increase if the number of bidders with positive net demand decreases. While net demand cannot be observed directly (no individual data on the fulfillment of reserve requirements available), participation in the MRO after the LTRO is lower than in MROs of type “before” and “other” (table 1). Further, a high net demand of those banks is likely to induce more aggressive bidding by them. In fact, the award imbalance for LTRO is by far higher than for the MROs. Among MROs, the highest award imbalance is registered for the MRO before the LTRO. This suggests that the number of banks with relatively large liquidity needs in the operation after the LTRO might be high. In other words, the two operations within a short period of time (MRO and LTRO) introduce a higher potential for a shortfall of funds for banks. Hence, we conjecture that banks should bid, relative to “other” MROs, at higher rates. This is our second testable hypothesis.

## 5 Empirical Analysis

The first part of this section contains an econometric analysis using simple dummies to control for the distance of MRO and LTRO. Then, we develop a new approach to capture banks’ bidding strategies and use it for a more detailed econometric analysis in section 5.1. Lastly, we will extend the analysis by looking at individual bank bidding behavior over time (section 5.2).

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<sup>12</sup>This flexibility is also evidenced by, e.g. a varying reserve fulfillment pattern or underbidding in the old operational framework (showing that banks were willing to gamble for better “deal” in the future). On the other hand, banks’ long term financing strategy (i.e. maturity structure of assets and liabilities) is a function of deeper underlying factors and is unlikely to exhibit large changes during a single MP. For instance, Diamond (1991), Eisenschmidt and Holthausen (2013) show that the market is endogenously segmented with highly rated banks either borrowing long or short and weaker banks borrowing in the middle of the maturity spectrum.

## 5.1 Econometric Analysis

This section contains the core of the analysis where we examine how variations in the *discount* can be rationalized also conditioning on other potentially relevant factors. The choice of the control variables below follows the literature. To include simultaneously country and size dummies, the literature has usually employed random effect models. Based on a Hausman test, however, the random effects model is rejected. Hence, unless indicated otherwise (denoted “RE”) we will use fixed effects panel regressions with robust standard errors clustered at the bank level as the baseline estimation method.<sup>13</sup> However, for selected specifications, we also replicate the usual findings of the literature by using a random effects model and include then country and size fixed effects for selected specifications. To retain potential size-dependent differences in bidding we will estimate the models for the full dataset and separately by size. More robustness checks (alternative specifications, replication of results with random effects, etc.) are provided in appendix A.3.

The estimated equations will be of the form

$$discount_{i,t} = \beta_0 + \beta_1 X_{i,t}^{bank} + \beta_2 X_t^{agg} + \beta_3 S_{i,t} + b_i + u_{i,t} \quad (1)$$

where  $discount_{i,t}$  is the discount of bank  $i$  in operation  $t$ . The vector  $X_{i,t}^{bank}$  collects bank specific variables: the change in a bank’s award ratio (“ $\Delta$  Awrat. LT” and “MT”) over the last two operations, the outstanding volume from the LTROs, and size and country dummies when using a random effect specification. The former control for past success and liquidity buffers while the latter capture bank and country specific factors. The vector  $X_t^{agg}$  contains all tender level variables (hence the missing  $i$ -index): a dummy for the new operational framework (“New Framew.”), dummies for the last MROs in the MP and year, uncertainty, swap spread, forward spread, and award imbalance. All variables and the reasoning for using them are as defined in section 3.  $S_{i,t}$  contains a series of dummies capturing the bank specific bidding strategy which will be defined below. Finally,  $b_i$  captures the bank fixed effect and  $u_{i,t}$  is a white noise error term uncorrelated with explanatory variables.

### 5.1.1 Regression Results: Basic Regressions and using Dummies

The first two models in table 3 replicate the regressions from the literature with established regressors but add a dummy for MROs before and after the LTRO. The base category is then an MRO from the category “other”. The first model is estimated using random effects while the second uses fixed effects (labeled as RE or FE). The p-value of a Hausman-test is smaller than 0.01 rejecting the random effects specification. However, this can be also inferred by a visual inspection of the coefficients.

We first comment on the first two models (RE vs. FE) for the full sample and find that results are broadly in line with previous research, e.g. Bindseil, Nyborg, and Streubulaev (2009), Eisenschmidt, Hirsch, and Linzert (2009), Linzert, Nautz, and Bindseil (2004), Scalia, Ordine, and Bruno (2005). When using the RE model, we find that medium sized and large banks bid at higher discounts. If banks had an increasing allotment over the last two LTROs ( $\Delta$  Awrat. LT), they bid less aggressively in the MRO. This is because banks have a higher funding buffer originating from the last operation and can afford to bid at lower rates. While the effect of an increasing award ratio in the MROs ( $\Delta$  Awrat. MR) on discounts is mostly negative, it is not significant. The dummy for the last MRO of the year (Last MR Year) is negative. More aggressive bidding at the end of the year is a known seasonal phenomenon (liquidity hoarding). Bidding in the last MRO of the MP seems to be less aggressive. Higher uncertainty and higher expected future refinancing costs (forward spread) increase banks’ aggressiveness. This is in line with theoretical research, e.g. Nyborg and Streubulaev (2004), examining the

<sup>13</sup>Conclusions are very similar if using the random effect approach. Results are available upon request. Further, we do not use a sample selection correction approach as tests for validity indicate that the approach might be itself not valid; see appendix A.2 for more explanations.



Table 3: MRO Bid Rate Regressions: Standard Variables and Before/After-Dummies

	All (RE)	All	All	Small	Medium	Large
New Framew.	1.615 (31.7)***	1.615 (31.6)***	1.614 (31.6)***	1.755 (14.0)***	1.617 (22.2)***	1.524 (18.5)***
Medium	0.486 (5.0)***					
Large	0.614 (4.9)***					
$\Delta$ Awrat. MR	-0.007 (0.4)	-0.010 (0.6)	-0.010 (0.6)	0.007 (0.2)	-0.026 (1.0)	-0.028 (0.8)
$\Delta$ Awrat. LT	0.047 (2.7)***	0.047 (2.7)***	0.050 (2.9)***	0.070 (1.7)*	0.095 (4.0)***	-0.012 (0.4)
Last MR MP	0.013 (1.1)	0.014 (1.3)	0.014 (1.2)	0.094 (3.6)***	0.020 (1.2)	-0.037 (2.1)**
Last MR Year	-7.882 (47.5)***	-7.869 (47.3)***	-7.869 (47.3)***	-9.213 (32.8)***	-7.691 (30.5)***	-7.018 (23.2)***
Uncertainty	-0.310 (44.1)***	-0.310 (44.0)***	-0.310 (44.1)***	-0.331 (24.7)***	-0.330 (31.5)***	-0.273 (22.4)***
Swap Spr.	0.142 (51.3)***	0.142 (51.4)***	0.142 (51.3)***	0.158 (24.8)***	0.141 (34.7)***	0.130 (31.3)***
Forw. Spr.	-0.083 (51.1)***	-0.083 (51.2)***	-0.083 (51.2)***	-0.099 (30.0)***	-0.084 (36.9)***	-0.069 (26.1)***
Award Imb.	0.877 (6.8)***	0.855 (6.6)***	0.854 (6.6)***	1.989 (7.3)***	1.057 (5.2)***	-0.168 (0.9)
Benchmark	-0.005 (18.1)***	-0.005 (17.9)***	-0.005 (17.9)***	-0.004 (7.0)***	-0.005 (11.4)***	-0.005 (12.0)***
Outst. LTRO	-4.E-05 (1.5)	-4.E-05 (1.6)	-4.E-05 (1.6)	-6.E-03 (2.0)*	-6.E-05 (0.4)	-4.E-05 (1.5)
After	-0.364 (18.7)***	-0.362 (18.7)***	-0.362 (18.7)***	-0.405 (9.0)***	-0.407 (15.0)***	-0.258 (7.8)***
Before	0.535 (42.2)***	0.536 (42.2)***				
Before   LTRO <sub>n</sub>			0.513 (32.5)***	0.681 (20.9)***	0.509 (23.4)***	0.372 (13.6)***
Before   LTRO <sub>y</sub>			0.590 (23.4)***	0.829 (13.7)***	0.621 (16.0)***	0.476 (13.3)***
Constant	0.824 (4.7)***	1.216 (23.5)***	1.216 (23.6)***	0.355 (3.0)***	1.244 (16.0)***	1.754 (21.2)***
<i>N</i>	86,760	86,760	86,760	20,284	38,893	27,583
<i>R</i> <sup>2</sup>	0.30	0.31	0.31	0.36	0.31	0.27
<i>F</i>			6.21	4.53	6.10	4.55

Notes: Stars denote levels of significance: \*  $p < 0.1$ ; \*\*  $p < 0.05$ ; \*\*\*  $p < 0.01$ . First model estimated using random effects(RE); other models fixed effects. Robust standard errors clustered on the MFI level. RE regressions include country dummies. Base category is a small bank with a bid in a operation of type "other", or a bank which did not bid in the LTRO. The variable "Before | LTRO<sub>y</sub>" indicates that the bank participated in the LTRO of that MP. F-values for test on equality of coefficients of "Before | LTRO<sub>y</sub>" and "Before | LTRO<sub>n</sub>". *R*<sup>2</sup> reported as "within" for FE and "overall" for RE.

“winner’s curse” or “losers nightmare” hypothesis with the negative sign speaking in favor of the latter. As a higher swap spread indicates more room for low bids, the coefficient on this variable should be (and is) positive. Award imbalance is the lagged value of the standard deviation of individual award ratios. A higher dispersion of past awards might indicate a larger dispersion of liquidity needs. If some banks fear being short-squeezed in the secondary market they will bid more aggressively and the sign of this variable should be negative. We cannot confirm this hypothesis. However, this coefficient is negative (i.e. banks bid more aggressively) if the model is estimated only on the old sample (see table 16 in appendix A.3). One explanation is that in the new framework banks do not have a buffer stemming from the last MRO which limits the scope for sophisticated bidding. In the old framework, a high allotment (expected or unexpected) in the past week provided incentives to bid at relatively low rates this week due to the presence of a buffer. As an optimal response, banks with liquidity needs had to bid at higher rates to secure funds in that auction. Given the absence of this adverse incentive, a higher past award imbalance might not induce more competition any more. As in the new framework banks’ liquidity position is reset to zero every week, bidding behavior will come closer to true liquidity needs without the necessity for more aggressive “precautionary bidding”. In line with this potential change in behaviour, award imbalance for MROs (LTROs) dropped from 0.25 (0.30) to 0.19 (0.26) in the new framework.<sup>14</sup> The coefficient on the expected allotment size as measured by the published benchmark (or level of autonomous factors) is negative. This confirms the hypothesis that higher total liquidity needs induce banks to bid at higher rates (Välimäki 2006). The intuition is that as aggregate tender volumes increase, banks’ uncertainty around their own (yet unknown) liquidity needs increases; hence more aggressive bidding increases the probability of a higher allotment. More outstanding liquidity from the past LTRO decreases the discount but has a quantitatively small effect.

The dummies on the MRO before (after) the LTRO are positive (negative). This is what we would expect from the descriptive statistics in table 1 but now these results are obtained after partialling out a number of factors. Hence, we can confirm that differences in bidding behavior are not exclusively explained by exogenous factors but seem to be due to banks’ strategic behavior. In the last four models in table 3 we estimate only fixed effects models, separately by size, but extend the analysis from above by looking more specifically at bidding in the MRO before the LTRO conditional on LTRO participation. We do so by breaking up the dummy for a bid in the Pre-LTRO operation into two dummies. The variable “Before | LTRO<sub>y</sub>” (LTRO<sub>n</sub>) captures the bid of a bank before the LTRO having participated (not participated) in the LTRO. This approach replicates the descriptive statistics of table 2 but controls for a number of other factors.

The usual control variables are practically unchanged and hence we skip a discussion. The only notable difference is that the effect of a higher dispersion of past awards induces small and medium sized banks to bid at lower rates while large banks become more aggressive. A potential explanation is that small banks bid usually at higher rates and obtain always a high allotment. Large banks, however, are likely to have a more active money market desk adjusting the bidding strategy more frequently and more aggressively to external factors. Both dummies for the MRO before the LTRO operations are – as expected from the previous models – positive. Therefore, a more rigorous and meaningful test is to compare the size of the two dummies, i.e. whether the discount in the MRO before the LTRO is larger if a bank also participated in the following LTRO. We can confirm this for all samples. Further, we can reject equality of the two coefficients at conventional levels (see F-values at the bottom of the table) for all models.

As a robustness check we also run regressions with a set of dummies capturing how many weeks (or days) an MRO is before an LTRO (see table 15 in appendix A.3). We find that banks are bidding least aggressively in the MRO one week before the LTRO and the discount is lower in the MROs being farther away from the

<sup>14</sup>Using a panel-probit model, one can show that the effect of lagged award imbalance on participation is significantly lower in the new framework. Results available upon request.

LTRO. This should not come as a surprise as the MRO one week before the LTRO is likely to be the Pre-LTRO operation.

We conclude with the finding that controlling for various other variables banks bid less (more) aggressively in the MRO before (after) the LTRO. Further, banks bid less aggressively in the MRO before the LTRO if they also participate in the following LTRO. These results are in line with the hypotheses developed earlier. Obviously, bidding in the LTRO after a low bid rate in the MRO is endogenous: bidding at opportunistic rates in the MRO will leave the bank with a relatively low allotment forcing it to also come to the LTRO. However, note that we are interested precisely in this endogenous component as it reflects the bank's decision before knowing the outcome of the next MRO or LTRO. The notion of banks bidding less aggressively if they plan to bid in the LTRO is not compatible with the argument that a bank was hit by a bad (liquidity) shock and was hence forced to bid in the next LTRO. In such a case, banks in the MRO would bid more aggressively – the opposite of what is found.

### 5.1.2 Characterization of Bidding Strategies

We characterize bidding strategies for a bank by a vector of the form  $S_{t,i} = \{b_{\mathbb{1}}, a_{\mathbb{1}}, o_{\mathbb{1}}, L_{\mathbb{1}}\}_{t,i}$  where  $b$  indicates an MRO before the LTRO,  $a$  denotes a MRO after the LTRO,  $o$  stands for an other MRO, and  $L$  stands for an LTRO. Obviously, this categorization is aligned with the approach taken in the descriptive statistics provided earlier. The indicator function  $\mathbb{1}$  takes on the value of  $y$  if a bank bid in that operation and  $n$  otherwise. For instance,  $\{b_y, a_y, o_n, L_n\}_{t,i}$  states that in MP  $t$ , bank  $i$  bid only in the MRO before and after the LTRO but not in the other MROs or in the LTRO. Using this concept, one can fully characterize all bidding strategies with 15 vectors. In the econometric setup, each of these vectors will be represented by a dummy. The distribution of these strategies is rather uneven with about 60% of the banks in the sample not being active in any operation of a given MP. Another 27% participate only in MROs and 4% bid only in LTROs. The share of banks bidding in both operation types – the “overlap” we use for identifying joint bidding behavior – is about 10%. Among the strategies, the most popular strategy is to bid in all MRO types but not the LTRO (16%), followed by participation in all MRO types and the LTRO (7%), and bidding only in “other” MROs and not the LTRO (3%). The other strategies seem to be less popular (see table 14 in appendix A.3 for an full list).

These vectors are only indicators for a given strategy but cannot capture the bidding behavior *within* this strategy. In the example from above we know in which operation a bank bid but do not know how a bank bid in those operations. To capture the behavior within a given a strategy, each variable  $S_{t,i}$  is further split up to capture bids in individual MROs;  $S_{t,i}b_y$  and  $S_{t,i}a_y$  in the example from above. This gives 24 dummies which fully characterize bidding and can be used in an econometric exercise to extract bidding behavior in a specific operation but *conditioning* on the strategy of the bidder. In other words, we do not just use a dummy to denote, e.g. an MRO before the LTRO, as done it table 3 but also indicate which strategy a bank had when it bid in that operation .

This characterization allows to form naïve unobserved counterfactuals. Assume that we observe two strategies  $\{b_y, a_y, o_n, L_n\}_{t,i}$  and  $\{b_y, a_y, o_n, L_y\}_{t,i}$  where the latter includes also bidding in the LTRO. A comparison of the two coefficients measures difference in bidding behavior in the MROs as a function of LTRO participation *conditioning* on bidding in an operation before the LTRO. In addition to only including a dummy, here we are able to look into the “black box” of the operation prior to the LTRO. Note that the LTRO-effect is not only identified by exploiting differences within banks over time (as we do not observe sufficient many changes for individual banks over time) but by exploiting also the differences between banks within one MP. Although this approach is far from perfect, it provides us with a tool to construct otherwise unobserved counterfactuals by comparing “statistical twins”.

### 5.1.3 Regression Results: Capturing Bidding Strategies

After the previous section's simple approach we include now the variables capturing the bidding strategies defined above into our estimations. The results in table 4 are organized as follows: the upper part of the table contains the standard explanatory variables used in the previous regressions. The lower part of the table shows coefficients for the strategy dummies. For instance, "a/o" in the column "MRO" indicates that a bank bid in an MRO after the LTRO and in "other" operations. A "y" in the column "LTRO" indicates that a bank bid in the LTRO of that MP. Lastly, the column "Pos." indicates what kind of position the respective bid had in the classification of MROs where we continue to follow the established convention (e.g. a "o" for "other" MROs). Using the example from above, "a/o y o" denotes a bid from a bank with the strategy "a/o" and LTRO participation in an "other" MRO. The variables are grouped such that the first three blocks (four lines each) contain bids of banks which bid in two operations, the middle block contains banks which bid in all MRO types, and the last block shows results for banks which participated in only one operation type. Unless otherwise stated, relative comparisons are made with reference to the base category (the constant) which is a small bank bidding in all types of operations and is hence shown in the line "b/a/o, cons."

Turning to the results we note that for the standard variables the previously established results still hold and skip a detailed discussion. The focus will be on variables capturing bid strategies where we highlight two key findings related to our hypotheses. First, for any given strategy, banks bid prior to the LTRO (Pos. "b") with the highest discount. This does not depend on LTRO participation but is valid in general. The hypothesis that LTRO bidders bid at even lower rates is confirmed for 12 out of 16 possible cases (i.e. the discount on the MRO before the LTRO is higher if a bank also bid in the following LTRO). The cases which are not in line with expectations are for strategies of a bank which bid before and after the LTRO ("b/a"). Table 5 shows a compact overview about the hypothesis whether banks bid less aggressively in the MRO if they also bid in the LTRO. The entries in the first 4 lines are p-values from testing the hypothesis  $H_0 : \beta_b(S_{i,L_y}) = \beta_b(S_{i,L_n})$  separately by strategy type  $i$ . For three out of four cases with the wrong sign ("b/a"), the coefficients are not significantly different. For the other 12 cases, we find that the difference is significant for 7 pairs.

To complement the individual tests, we conduct two alternative tests for joint significance. The entries in the line "Joint 1" test the hypothesis  $\beta_b(S_{i,L_y}) = \beta_b(S_{i,L_n})$  jointly for all four strategies.<sup>15</sup> This tests whether banks' bidding behavior systematically differs in the operations before the LTRO by participation in the LTRO. However, a rejection might imply that banks also bid more – rather than less – aggressively. Also, it might imply that they bid more aggressively for some strategies and less aggressively for others. The rejection of this hypothesis (at the 5% level, 6% for the sample with small banks) suggests that banks systematically bid differently by LTRO participation. Lastly, we test  $H_0 : \sum_i \Delta_i \geq 0$  with  $\Delta_i = \beta_b(S_{i,L_y}) - \beta_b(S_{i,L_n})$ , i.e. whether the sum of the individual differences in coefficients is non-negative. Thus, the test is whether banks bid *on average* less aggressively if they bid in the LTRO. The p-values (line "Joint 2") are all above conventional rejection thresholds showing that the sum is non-negative.<sup>16</sup>

Second, banks bid in general more aggressively in operations after the LTRO. The most aggressive bidding behavior can be attributed to banks bidding only in the MRO after the LTRO ("a") and banks which also bid in the MRO before the LTRO ("b/a"). In these two cases, banks bid on average about 1.2 basis points higher compared to only 0.3 basis points for the other two strategies. Among the two "aggressive" strategies, banks which also bid in the LTRO (column "y") bid, compared to non-participants, at substantially higher rates (1.3

<sup>15</sup>We do this as joint testing of sequential on-sided hypothesis for more than 2 pairs is not easily interpretable.

<sup>16</sup>When interpreting this result one has to bear in mind that just summing up the coefficients might be misleading. The reason is that the sum of all differences does not take the uncertainty around the individual coefficients into account. For instance, when doing this for the sample utilizing data from the sample of large banks only, the sum is negative. This is in principle in contradiction to our main hypothesis but the p-value for the hypothesis that this is larger than zero is 0.37.

basis points). For banks with strategy “a/o” and “b/a/o” this difference is negligible (0.1 basis points). These results support the hypothesis that banks are more aggressive in the post-LTRO operation if they missed their target allotment in the earlier MRO and LTRO. Detailed results (analogous to table 5) can be found in table 12 in the appendix.

Lastly, we observe that banks bidding in all operations (“b/a/o”) have a less “volatile” bid strategy. While the two hypotheses are also confirmed for this group, they do not bid (compared to bidders participating in one or two operation types) at very low rates before the LTRO and neither do they bid at high rates in the operation after the LTRO. This could be explained by their role as liquidity distributors (or wholesalers). Hence, their valuation represents the view of a larger number of entities (“the market”) with more evenly distributed liquidity needs (Milgrom and Weber 2000).

Controlling for the full array of combinations/strategies has the potential of providing the most detailed information. The downside of the approach is, however, that the small number of observations per strategy (dummy) makes estimates less precise. To alleviate this problem, we compressed complete strategies into broader categories but retain the idea of comparing bidding in an MRO before the LTRO conditional on LTRO participation. We operationalized this by keeping the split/conditional dummies for the MROs before the LTRO but condensing bids from all other operations into one dummy (table 6). For instance, in the upper block *b/o* | *b/a* captures a bid in a MRO before the LTRO from banks which bid in two MRO types of that MP; i.e. in addition to the MRO before the LTRO they also bid in an operation type “other” or “after”. The other bids for these two strategy types are captured by “Bid in 2 op. types”. In other words, we compress the *b/o* and *b/a* blocks into one. Similarly, the dummy “Bid in 3 op. types” compresses all non pre-LTRO operations for banks bidding in all three operation types into one but retains two dummies to control for conditional bidding prior to the LTRO.

The results are cleaner compared to the regression using the full battery of dummies. The “sign” is correct for 11 out of 12 cases; it is wrong only for large banks bidding in the MRO before the LTRO. Out of the 11 cases, for 10 coefficients the differences are significant (on the 10% level). A compact overview over the p-values is given in table 7. Thus, these results reinforce the conclusion from the more detailed analysis.

To conclude, we find confirmation for the hypotheses that banks bid differently in operations before and after an LTRO. In general, banks bid in the MRO before the LTRO at lower rates as compared to “other” MROs. Moreover, MRO participants which also bid in the following LTRO bid at even lower rates, compared to peers not bidding in the LTRO. The overall support for this hypothesis is stronger in the shorter regressions with a more parsimonious strategy formulation; a likely reason being that the full battery of dummies captures relatively more noise (due to the small number of observations per cell). In combination with the fact that LTRO participants bid in general more frequently and for higher amounts. These findings support the conjecture that banks view obtaining liquidity from the two operations as (asymmetric) substitutes and bid lower before the LTRO as they split their demand between two operations. The higher discount in the MRO before the LTRO can be explained by both, bidders which participated in more operation types and ones which only bid in the MRO before the LTRO.

As regards the second hypothesis, we find that banks generally bid more aggressively in the MRO after the LTRO. Even more striking, counterparties which participated also in the LTRO preceding the MRO bid at substantially higher rates. These findings reflect that “short” banks, with potentially large net liquidity needs after the LTRO, must bid more aggressively; i.e. they went out empty handed from preceding auctions. In addition, the ones which happen to have liquidity needs in that particular operation will have to adjust their bids up in order to secure their allotment (Cassola, Hortaçsu, and Kastl 2013), pushing the average discount down.

This finding could be also interpreted as a violation of the martingale hypothesis. Empirical evidence

Table 4: MRO Bid Rate Regressions: Complete Strategies

	All	Small	Medium	Large		
New Framew.	1.653 (32.3)***	1.795 (14.3)***	1.665 (22.9)***	1.544 (18.6)***		
$\Delta$ Awrat. MR	0.000 (0.0)	0.016 (0.5)	-0.004 (0.2)	-0.024 (0.7)		
$\Delta$ Awrat. LT	0.051 (2.9)***	0.077 (1.9)*	0.093 (3.9)***	-0.011 (0.4)		
Last MR MP	0.024 (2.1)**	0.107 (4.2)***	0.035 (2.1)**	-0.038 (2.1)**		
Last MR Year	-7.836 (47.3)***	-9.153 (32.9)***	-7.650 (30.6)***	-7.015 (23.1)***		
Uncertainty	-0.307 (44.3)***	-0.328 (25.0)***	-0.324 (31.4)***	-0.274 (22.8)***		
Swap Spr.	0.143 (53.3)***	0.161 (26.4)***	0.143 (36.5)***	0.130 (31.8)***		
Forw. Spr.	-0.084 (51.9)***	-0.100 (31.5)***	-0.086 (37.6)***	-0.069 (26.4)***		
Award Imb.	0.861 (6.8)***	1.922 (7.5)***	1.081 (5.4)***	-0.105 (0.6)		
Benchmark	-0.005 (18.5)***	-0.004 (7.3)***	-0.005 (12.0)***	-0.005 (12.0)***		
Outst. LTRO	-5.E-05 (1.8)*	-6.E-03 (2.1)**	-3.E-05 (0.2)	-4.E-05 (1.7)*		
Strategy						
MRO	LTRO	Pos.				
b/o		b	0.559***	0.757***	0.500***	0.250**
b/o	y	b	0.823***	1.141***	0.752***	0.598***
b/o		o	0.191***	0.108	0.219***	0.156*
b/o	y	o	0.295***	0.215*	0.296***	0.380*
a/o		o	0.080	-0.072	0.113	0.170*
a/o	y	o	0.221***	0.396***	0.241**	0.110
a/o		a	-0.159**	-0.358**	0.011	-0.062
a/o	y	a	-0.327**	-0.891**	-0.309*	-0.074
b/a		b	0.591***	0.969***	0.619***	-0.177
b/a	y	b	0.049	0.227	-0.009	0.078
b/a		a	-0.542**	-1.183***	-0.662*	0.581
b/a	y	a	-1.798***	-2.730**	-2.037***	-0.628
b/a/o		b	0.515***	0.610***	0.533***	0.372***
b/a/o	y	b	0.596***	0.757***	0.637***	0.488***
b/a/o		a	-0.340***	-0.425***	-0.354***	-0.296***
b/a/o	y	a	-0.274***	-0.208**	-0.348***	-0.267***
b/a/o		o	-0.075*	-0.148*	-0.071	-0.083
b/a/o, cons.	y	o	1.187***	0.386***	1.199***	1.743***
o		o	0.397***	0.274***	0.400***	0.491***
o	y	o	0.387***	0.407**	0.395**	0.271
b		b	0.613***	0.638***	0.517***	0.708***
b	y	b	0.869***	1.214***	1.039***	-0.282
a		a	-0.699***	-0.239	-1.247***	-0.243
a	y	a	-2.060***	-2.654***	-2.222***	-0.688
$R^2$			0.31	0.36	0.32	0.27
N			86,760	20,284	38,893	27,583

Notes: Stars denote levels of significance: \*  $p < 0.1$ ; \*\*  $p < 0.05$ ; \*\*\*  $p < 0.01$ . t-values for strategy dummies available upon request. Fixed effect models with robust standard errors clustered on the MFI level. Base category is the bid of a small bank in an "other" MRO with the strategy to bid in all operations (b/a/o, cons.). Bid codes as *b* (before the LTRO), *a* (after the LTRO), *o* (other), and *y* (bid in LTRO).

Table 5: Joint Hypothesis Tests for Models in Table 4

Strategy	All	Small	Medium	Large
b/o	0.01	0.02	0.10	0.08
b/a	0.31	0.43	0.43	0.43
b/a/o	0.04	0.12	0.12	0.11
b	0.16	0.14	0.01	0.01
Joint 1	0.01	0.06	0.03	0.01
Joint 2	0.82	0.77	0.84	0.37

Notes: First four lines contain p-values for individual test for parameter equality. Joint 1 and 2 as described in text.

Table 6: MRO Bid Rate Regressions: Complete Strategies, cont'd

	All	Small	Medium	Large		
New Framew.	1.635 (31.8)***	1.797 (14.2)***	1.642 (22.3)***	1.531 (18.7)***		
Δ Awrat. MR	0.015 (0.9)	0.034 (1.1)	0.008 (0.3)	-0.018 (0.5)		
Δ Awrat. LT	0.057 (3.2)***	0.081 (2.0)**	0.106 (4.4)***	-0.010 (0.3)		
Last MR MP	0.077 (7.4)***	0.163 (6.9)***	0.091 (5.8)***	0.004 (0.3)		
Last MR Year	-8.110 (48.2)***	-9.518 (33.7)***	-7.960 (31.4)***	-7.156 (23.3)***		
Uncertainty	-0.306 (44.4)***	-0.327 (25.0)***	-0.325 (31.6)***	-0.271 (22.9)***		
Swap Spr.	0.146 (55.3)***	0.163 (27.2)***	0.146 (37.7)***	0.132 (33.6)***		
Forw. Spr.	-0.087 (55.3)***	-0.104 (34.1)***	-0.090 (40.9)***	-0.072 (27.7)***		
Award Imb.	0.972 (7.4)***	2.160 (7.6)***	1.183 (5.7)***	-0.073 (0.4)		
Benchmark	-0.005 (17.1)***	-0.004 (6.6)***	-0.005 (10.8)***	-0.005 (11.7)***		
Outst. LTRO	-5.E-05 (1.9)*	-7.E-03 (2.3)**	-1.E-04 (0.7)	-5.E-05 (1.8)*		
Strategy						
MRO	LTRO	Pos.				
b/o   b/a	b	b	0.556***	0.812***	0.491***	0.181*
b/o   b/a	y	b	0.705***	1.079***	0.633***	0.476**
Bid in 2 op. types			0.054	-0.042	0.074	0.119*
b/a/o	b	b	0.502***	0.630***	0.497***	0.359***
b/a/o	y	b	0.611***	0.773***	0.652***	0.501***
Bid in 3 op. types			-0.183***	-0.214***	-0.214***	-0.179***
b/a/o, cons.	y	o	1.140***	0.278**	1.166***	1.727***
b	b	b	0.616***	0.670***	0.521***	0.690***
b	y	b	0.924***	1.284***	1.100***	-0.240
Bid in 1 op. type			0.167***	0.199**	0.070	0.287***
R <sup>2</sup>			0.10	0.07	0.43	0.41
N			86,760	20,284	38,893	27,583

Notes: Stars denote levels of significance: \* p<0.1; \*\* <0.05; \*\*\* p<0.01. t-values for strategy dummies available upon request. Fixed effect models with robust standard errors clustered on the MFI level. Base category is the bid of a small bank in an "other" MRO with the strategy to bid in all operations (b/a/o, cons.). Bid codes as *b* (before the LTRO), *a* (after the LTRO), *o* (other), and *y* (bid in LTRO).

Table 7: Joint Hypothesis Tests for Models in Table 6

Strategy	All	Small	Medium	Large
b/o   b/s	0.03	0.09	0.15	0.06
b/a/o	0.00	0.08	0.00	0.02
b	0.09	0.10	0.01	0.02
Joint 1	0.00	0.04	0.00	0.00
Joint 2	1.00	0.99	1.00	0.17

Notes: First three lines contain p-values for individual test for parameter equality. Joint 1 and 2 as described in text.

suggests that this is indeed the case for the euro area and also the US (Hamilton (1997), Bindseil and Seitz (2001) Ejerskov, Mossand, and Stracca (2003) Quiros and Mendizabal (2006)). Potential explanations are limits to credit lines, transaction costs, information problems among banks, reluctance to borrow from central bank overnight facilities, existence of the “liquidity effect”, or risk aversion.

## 5.2 Bidding Dynamics of Repeated Bidders

In addition to the econometric analysis focussing on the *level* of the discount in specific operation types, in this section we apply a novel approach to study the *evolution* of the bank specific discount over time. By looking at a series of MROs, we capture exclusively the dynamic bidding behavior of counterparties participating in a number of MROs before the LTRO. Hence, we exclude “static” bidders participating in only one operation. To this end, we discretize in each MRO the distribution of discount into five categories (quintiles). A high discount (i.e. less aggressive bidding) is represented by a high “rank” in the distribution. Moving up, i.e. to a higher rank, in the distribution between two MROs corresponds to a higher discount and less aggressive bidding over time. To also capture opting out from an operation, we add this event to the most aggressive category.<sup>17</sup>

Using this concept, we compute, separately by LTRO participation, the transition matrix between any two adjacent MROs whereby the states correspond to the tender specific quintile of the distribution; see above.<sup>18</sup> Such a Markov matrix measures probabilities, conditional on LTRO participation and previous rank, of moving within the distribution of discount between two MROs. This tells us whether banks tend to become, on average, more or less aggressive over a sequence of operations. Such a sequence is defined as a series of MROs between two LTROs. For instance, in the sequence ... LTRO<sub>t-1</sub>, MRO<sub>t</sub>, MRO<sub>t+1</sub>, MRO<sub>t+2</sub>, LTRO<sub>t+3</sub>, MRO<sub>t+4</sub> ... we classify MRO<sub>t</sub> to LTRO<sub>t+3</sub> as a “bid sequence” and MRO<sub>t+4</sub> would then start a new sequence. We adopt this approach to have a sufficiently long sequence of MROs. However, we also repeat the exercise using only the MROs *before* the LTRO from one MP. While this procedure reduces the number of observations by about 60%, it ensures that we look only at MROs from one MP. Then, in most cases we observe only 2 MROs per MP; essentially capturing how banks adjust their bids between the two MROs before the LTRO.

Using these transition matrices, we compute the sum of probabilities to move up or to move down in the distribution *conditional* on the rank in the previous operation. This summarizes what the probability for a bank is to become more or less aggressive. As the last step, in table 8 we report the difference between these sums separately for LTRO participants and non-participants. For instance, in panel (A) of table 8 the number 3.7 (column “All”, row “1: most aggressive”) is computed as the sum of probabilities to move up to rank 2, 3, 4,

<sup>17</sup>The reasoning for classifying “dropping out” in the most aggressive category is that not bidding is probably due to the fact that a bank does not want to obtain liquidity at the “expected highest price” in the auction. A bank could always bid at very high rates (thereby being at the lower end of the distribution, i.e. in quintile 1) and obtain liquidity. But as it decides not to do so, we put it into the category with the lowest discount.

<sup>18</sup>The transition probability  $p(x_{t+1}|x_t)$ , where  $x$  corresponds to a quintile, is computed between *any two* adjacent MROs reflecting averages. For instance, this could be between the quintiles in MRO<sub>t</sub> and MRO<sub>t+1</sub>, or, between quintiles in MRO<sub>t+2</sub> and MRO<sub>t+3</sub>. Conditioning on a longer history, say  $p(x_{t+1}|x_t, x_{t-1})$  would certainly add value but would make a compact overview and interpretation more difficult.



or 5 (given that the bank was at rank 1 in the previous operation) for banks which did participate in the LTRO minus the same number for a bank which did not bid in the LTRO.

Positive entries in panel (A) of table 8 mean that if a bank participates in the LTRO, it is more likely to move up in the distribution, i.e. become less aggressive, than to stay or move down (including dropping out) compared to its peer who did not bid in the LTRO. This indicates that banks bidding in the LTRO tend to become less aggressive in the next operation(s) approaching the LTRO. Introducing “dropping out” as a separate sixth state does not change the conclusion. In panel (B) we repeat the exercise for the case to move down in the distribution. The negative entries confirm that banks which bid only in the MROs were more likely to drop out at some point or to follow a more aggressive bidding pattern in the next operation(s). Note that the first quintile measures the difference in the probability to drop out. Hence, banks bidding in the next LTRO are less likely drop out. We confirm this conditional (on LTRO participation) opting in or out behavior in section A.3.2 of the appendix. Furthermore, the described patterns hold across size categories and results from the restricted sample as defined above are qualitatively similar (available upon request).

Table 8: Probabilities to Move in Transition Matrix

Quintile	Panel (A) - $\Delta$ in $p(\text{move up})$				Panel (B) - $\Delta$ in $p(\text{move down})$			
	All	Small	Medium	Large	All	Small	Medium	Large
1: most aggressive	3.7	0.5	2.9	5.1	-4.1	-5.3	-1.5	-4.5
2	7.1	1.8	5.7	8.3	-6.3	-3.3	-2.8	-7.2
3	7.0	1.9	6.4	5.3	-9.3	0.5	-5.6	-9.3
4	4.3	6.3	5.2	1.0	-10.7	-5.6	-10.1	-6.9
5: least aggressive	-	-	-	-	-9.0	-8.7	-7.8	-6.2

Notes: Numbers computed as  $p(\text{move up}|\text{rank} = x, \text{LTRO}_y) - p(\text{move up}|\text{rank} = x, \text{LTRO}_n)$  and  $p(\text{move down}|\text{rank} = x, \text{LTRO}_y) - p(\text{move down}|\text{rank} = x, \text{LTRO}_n)$ . Probabilities to move up or down do not include the probability to stay in the same quintile. For panel (A) and quintile 5 we do not report numbers as banks cannot move further up in the distribution. Underlying transition matrices available upon request.

## 6 Conclusion

In this paper we used individual bidding data from the Eurosystem’s tender operations to examine banks’ behavior in the context of joint bidding in MROs and LTROs. More specifically, we are interested whether banks bid at lower rates in MROs before the LTRO and at higher rates after the LTRO, compared to “other” operations. We motivate this question by the theoretical literature suggesting that banks behave strategically in a sequence of auctions. In order to measure this, we develop an innovative way to include a bank’s bidding strategy in an otherwise standard econometric framework.

We find that in general, banks bid in the MRO before the LTRO at lower rates as compared to “other” MROs. Moreover, MRO participants which also bid in the following LTRO bid at even lower rates, compared to peers not bidding in the LTRO. The positive evidence in favour of this hypothesis is stronger in simpler regressions; a likely reason being that more sophisticated econometric models capture more noise. These findings support the conjecture that banks view obtaining liquidity from the two operations as (asymmetric) substitutes and bid lower before the LTRO as they split their demand between two operations. The discount in the MRO before the LTRO can be explained by both, bidders which participated in more operation types and ones which only bid in the MRO before the LTRO. Moreover, banks bidding in the next LTRO, tend to lower their bids in MROs closer to the LTRO. Here, we refer to the analysis exploiting only the behavior of banks participating over time more than once in the MRO before the LTRO.

For bidding after the LTRO, we find that banks generally bid more aggressively in the MRO after the LTRO. Even more striking, counterparties which participated also in the LTRO preceding the MRO bid at substantially higher rates. These findings reflect that “short” banks, with potentially large net liquidity needs after the LTRO, must bid more aggressively. In addition, counterparties which happen to have liquidity needs in that particular operation are forced to adjust their bids up in order to obtain sufficient amounts of liquidity (Cassola, Hortaçsu, and Kastl 2013). Lastly, we observe that banks bidding in all operations (“b/a/o”) have a less “volatile” bid strategy. This is because more regular bidders’ valuation, acting as liquidity distributors, is likely to represent a larger number of entities (“the market”) with more evenly distributed liquidity needs (Milgrom and Weber 2000) free from purely individual biases or adverse realization of shocks. These findings hold for the whole sample and for banks of different size.

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## A Appendix

### A.1 Imputation of Minimum Reserves

We follow the literature and use the minimum reserve requirements (MRR) to group banks into different size categories.<sup>19</sup> Before July 2012 data on MRR were only collected by national central banks and are not available for the entire time span for all banks. To fill these gaps, the following imputation procedure was developed. First, we compute the average bidding amount per maintenance period  $t$  for bank  $i$  and denote this by  $\bar{b}_{i,t}$ . Denoting the MRR for bank  $i$  in period  $t$  by  $mrr_{i,t}$  we estimate country by country models of the form

$$mrr_{i,t} = a_1 \bar{b}_{i,t}^{a_2 + \mathbb{1}_{a_3}}, \quad (2)$$

where  $\mathbb{1}$  is an indicator function (dummy) taking on the value of 1 for the crisis period starting in August 2007. Including more variables did not significantly improve the in-sample forecast performance. Second, we use the estimated parameters to impute the missing minimum reserve requirements. Third, we re-scale the individual MRR (observed and imputed) by the euro area *aggregate* MRR. Forth, we use these numbers to compute the average re-scaled individual MMR, i.e.  $\bar{mrr}_i = \frac{1}{T} \sum_{t=1}^T mrr_{i,t}$  for all banks. This procedure ensures that we have one proxy per bank and this number is not distorted by the time when a bank enters the dataset as we use the “real” MRR for classification purposes. Finally, we group banks into three groups: “small” if they are in the first two quintiles, “large” if they are in the upper quintile and “medium” for the rest. The unbalanced grouping is done to have sufficiently many observations per group. For instance, small banks bid less frequently and we include more of them.

Tables 9 and 10 provide an evaluation of the exercise. We overestimate the share of small banks and underestimate the share of medium sized banks. Note that the shares do not correspond to quintiles as the number of observations is not evenly distributed across banks: we apply the grouping rule per bank and not per observation so that banks cannot switch between groups. In table 10 we summarize some moments of the observed and imputed data. We can replicate small values for the reserve requirement but fail to produce larger outcomes. The out of sample prediction with a mean of 196 mln is also close to the observed mean of 192 mln. However, the model has some difficulties to match the distribution for small and medium sized banks.

Table 9: Distribution of Banks

Group	Observed	Imputed
Small	42.8%	45.3%
Medium	39.9%	38.6%
Large	17.2%	16.1%

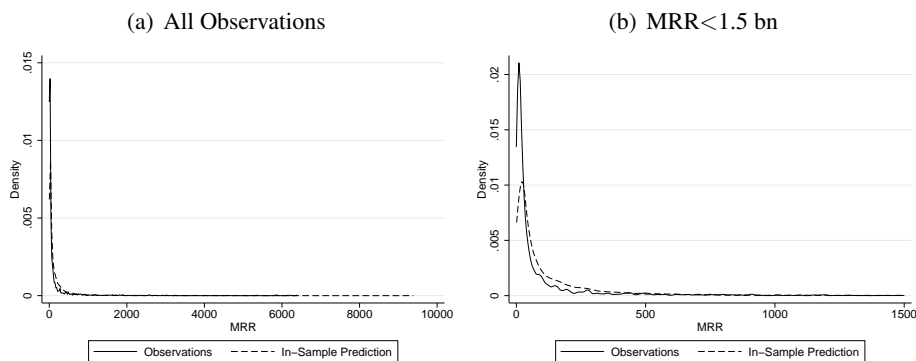
Table 10: Moments of MRR: data vs. imputation

Variable	N	Mean	Std. Dev.	Min	Max
In Sample	10523	201	503	1	9387
Data	10523	192	639	0	6382
In+Out Sample	53175	176	458	0	8141

*Notes:* Volume in EUR millions. We exclude underbid operations after the grouping exercise which leads to a slight deviation from the above mentioned relative group sizes.

<sup>19</sup>Alternatively one can also use the bidding volume to group banks, see e.g. Bindseil, Nyborg, and Streubulaev (2009).

Figure 3: Backfitting MRR Imputation



Notes: Histogram of observed and imputed MRR. The right graph is a replication of the left with a cut-off point for MRR at 1500 to enhance visibility of small values.

## A.2 Identification of Selection Bias

In this paper we do not follow previous research using the two-step selection approach by initially estimating a probit model and then including the Inverse Mill's Ratio (IMR) as an explanatory variable in the second stage. The reason is that identification without an exclusion restriction can be in practice very problematic, if not misleading (Puhani 2000). Technically, the IMR is a linear combination of the explanatory variables; i.e. a function of  $x\beta$  with  $\beta$  being the coefficient vector from the first stage selection equation. If there is little variation in  $x$ , then the relationship between explanatory variables and IMR is close to linear which then introduces a severe collinearity problem in the second stage. To show this, we plot the relationship between IMR and the predicted selection probability from the first stage probit model in figure 4 which clearly demonstrates that this relationship has very little curvature. A more stringent test is to run a regression with the IMR being the dependent variable and explained by the other variables. The results of this regression are in table 11. The first column ("Participation") is the first stage selection process and the second column ("Discout") is the second stage including IMR to control for the selection bias. The column "IMR" shows the results of the regression explaining IMR as a function of the selection/identification variables. The last column provides the standardized ( $\beta$ ) coefficients of the IMR-regression. The coefficients of all variables have expected (i.e. as predicted by theory) signs. However, two observations stand out. First, the  $R^2$  in the IMR-regression is 0.996 which means that the selection equation is perfectly explained by this set of covariates. Second, the two most important coefficients in explaining this are the size dummies. These arguments demonstrate that this approach is technically feasible but not valid as identification is based only on non-linearity which is violated. Hence, results from selection models applied to ECB auction data using this approach should be interpreted with care.

Figure 4: IMR and Selection Probabilities

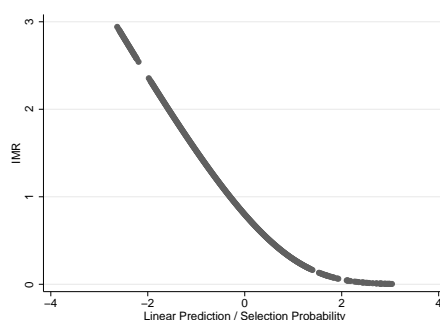


Table 11: Robustness Check of Selection Procedure

	Participation	Discount	IMR	$\beta$
IMR		1.473***		
New Framew.	0.099***	1.139***	-0.075***	-0.108
Medium	0.651***	1.277***	-0.489***	-0.703
Large	1.438***	2.334***	-1.037***	-1.224
$\Delta$ Awrat. LT	0.025***	0.089***	-0.018***	-0.014
$\Delta$ Awrat. MR	-0.086***	-0.112***	0.062***	0.052
Last MR MP	0.000	-0.202***	0.000***	0.000
Last MR Year	-0.014	-7.605***	0.010***	0.004
Uncertainty	0.003*	-0.295***	-0.002***	-0.010
Swap Spr.	0.002**	0.189***	-0.001***	-0.018
Forw. Spr.	0.000	-0.089***	0.000***	-0.007
Award Imb.	0.391***	-0.658***	-0.292***	-0.066
Benchmark	0.000***	-0.004***	0.000***	-0.100
Outst. LTRO	0.000***	0.000***	0.000***	-0.031
Before LTRO	0.018***	0.404***	-0.013***	-0.017
After LTRO	-0.024***	-0.713***	0.017***	0.021
Constant	-1.622***	-1.619**	1.982***	
$R^2$	0.093	0.304	0.996	
N	347170	98661	347170	

Notes: Stars denote levels of significance: \*  $p < 0.1$ ; \*\*  $p < 0.05$ ; \*\*\*  $p < 0.01$ . Results including standard errors / t-values available upon request. Random effect models with robust standard errors clustered on the MFI level. Regressions include country dummies. “Participation” denotes the participation/selection equation, “Discount” denotes the second stage regression including Inverse Mill’s Ratio (IMR), “IMR” is a regression with IMR as dependent variable, and “ $\beta$ ” are the standardized coefficient from the corresponding IMR-model. The explanatory variables are as defined in the main text. Participation estimated with a Probit model, IMR as OLS.

## A.3 Supplementary Material

### A.3.1 Difference in Bidding by LTRO participation

Panel (A) of table 12 shows the individual tests  $H_0 : \beta_a(S_{i,L_y}) = \beta_a(S_{i,L_n})$  by strategy  $i$  and the two joint tests (analogous to the test for the “b” operation in the main body of the paper). Panel (B) uses the output from table 4 and computes  $\beta_a(S_{i,L_n}) - \beta_a(S_{i,L_y})$ . If positive, LTRO participants bid at higher rates in the post LTRO MRO.

Table 12: Joint Hypothesis Tests for Models in Table 4

Panel (A): p-values				
Strategy	All	Small	Medium	Large
a/o	0.33	0.23	0.12	0.97
b/a	0.02	0.24	0.06	0.15
b/a/o	0.22	0.12	0.94	0.74
a	0.02	0.02	0.27	0.66
Joint 1	0.01	0.01	0.13	0.66
Joint 2	0.00	0.01	0.02	0.23

Panel (B): $\beta_a(S_{i,L_n}) - \beta_a(S_{i,L_y})$				
Strategy	All	Small	Medium	Large
a/o	0.168	0.533	0.32	0.012
b/a	1.256	1.547	1.375	1.209
b/a/o	-0.066	-0.217	-0.006	-0.029
a	1.361	2.415	0.975	0.445

Notes: First four lines of panel (A) contain p-values for individual test for parameter equality. Joint 1 and 2 as described in text. Numbers in panel (B) computed as  $\beta_a(S_{i,L_n}) - \beta_a(S_{i,L_y})$ .

### A.3.2 Bidding Dynamics over Time

To further examine the role of LTRO participation for participation in MROs, we compute also the probabilities of participation in an MRO conditional on participation in the previous MRO and conditional on bidding in the LTRO. The transition matrices are shown in table 13. The results confirm that if banks bid in the next LTRO, they bid more frequently in general (last line). Looking at conditional bidding probabilities reveals that banks which intend to bid in the LTRO at the end of the sequence return with a higher probability to an MRO if they did not bid in the previous tender ( $\text{Out}_{t-1} \rightarrow \text{Bid}_t$ ). Also, if they bid in the previous MRO, they are more likely to bid also in the next MRO if they will participate in the LTRO at the end of the sequence ( $\text{Bid}_{t-1} \rightarrow \text{Bid}_t$ ).

Table 13: Conditional Bidding Probabilities

	Not Bid in LTRO		Bid in LTRO	
	$\text{Out}_t$	$\text{Bid}_t$	$\text{Out}_t$	$\text{Bid}_t$
$\text{Out}_{t-1}$	95.3	4.7	83.1	16.9
$\text{Bid}_{t-1}$	15.5	84.6	9.9	90.1
$p(\text{Out}_t) \& p(\text{Bid}_t)$	76.8	23.3	37.8	62.2

Notes:  $\text{Out}_t$  ( $\text{Bid}_t$ ) indicates that a bank did (not) bid in an MRO in operation  $t$ .



### A.3.3 Distribution of Bidding Strategies

Table 14 shows the distribution of bidding patterns in MROs. The two columns add up to 100%.

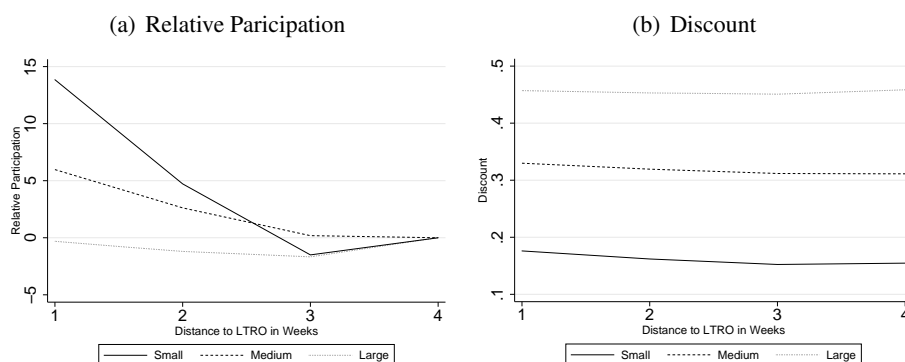
Table 14: Distribution of Bidding Strategies

MRO	No LTRO bid	LTRO bid
b	1.2%	0.3%
b/a	0.4%	0.2%
b/o	3.0%	0.8%
b/a/o	16.4%	7.1%
a	0.7%	0.3%
a/o	1.9%	0.6%
o	3.1%	0.7%
no bid	59.8%	3.6%

### A.3.4 Robustness Checks

As an alternative to the main text, we measure here the distance to an LTRO in days instead of using the before/after/other classification. Practically, distance is defined as follows: 1=0-8 days; 2=9-16 days; 3=17-23 days; 4=more than 23 days before the LTRO. Panel (A) of figure 5 shows the difference in participation where we define 4 weeks prior to the LTRO be the baseline (hence relative participation is 0). Participation is monotonically increasing towards the LTRO (1 week is close) with small banks bidding about 15% more often one week before the LTRO. When interpreting the results one has to keep in mind that a distance of 4 is an MRO after the LTRO while 1 corresponds to an MRO before the LTRO. There is a sizable difference between 1 and 4 and weeks with 2 and 3 weeks being clearly in the middle. As regards the discount, the closer the next LTRO is (1 is close), the higher is the discount. While operations being two or three weeks away seem to be roughly similar, operations one 4 weeks before the LTRO are clearly more contested and command a much lower discount. The operation being less than one week away has the highest discount.

Figure 5: Participation and Discount by Distance to LTRO



Notes: "Distance" is defined as follows: 1=0-8 days; 2=9-16 days; 3=17-23 days; 4=more than 23 days before the LTRO.

Further, we convert the distance measures just introduced into dummies and add them as control variables to the otherwise standard regression. The idea behind the procedure is identical to the one in table 3; except that the new variables are 3 dummies capturing the distance to the LTRO. The baseline is then an operation 4 weeks before the LTRO (essentially a post-LTRO MRO). The first model employs a random effect estimation

technique while the second is the fixed effect estimator applied to the full sample. The other models are fixed effects models on different samples (by bank size). We again discuss only the distance variables. The most striking result is that the MRO one week before the LTRO has the highest discount. The other two dummies are relatively similar but significantly different from the baseline which corresponds to the MRO after the LTRO.

Table 15: MRO Bid Rate Regressions: Timing Variables

	All (RE)	All	Small	Medium	Large
New Framew.	1.954 (38.0)***	1.955 (37.9)***	2.171 (17.6)***	1.944 (26.0)***	1.832 (22.0)***
Medium	0.503 (5.2)***				
Large	0.636 (5.0)***				
$\Delta$ Awrat. MR	0.005 (0.3)	0.002 (0.1)	0.022 (0.7)	-0.005 (0.2)	-0.029 (0.9)
$\Delta$ Awrat. LT	0.041 (2.4)**	0.041 (2.4)**	0.057 (1.4)	0.079 (3.4)***	-0.016 (0.6)
Last MR MP	0.040 (3.0)***	0.041 (3.1)***	0.122 (3.9)***	0.039 (1.9)*	-0.001 (0.0)
Last MR Year	-7.649 (45.9)***	-7.638 (45.7)***	-8.983 (31.2)***	-7.358 (28.9)***	-6.905 (22.9)***
Uncertainty	-0.288 (41.5)***	-0.288 (41.3)***	-0.309 (22.9)***	-0.307 (29.4)***	-0.253 (21.5)***
Swap Spr.	0.145 (55.6)***	0.145 (55.6)***	0.163 (27.6)***	0.145 (37.8)***	0.131 (33.3)***
Forw. Spr.	-0.083 (53.4)***	-0.083 (53.4)***	-0.098 (32.3)***	-0.085 (39.2)***	-0.068 (26.4)***
Award Imb.	0.267 (2.2)**	0.246 (2.0)**	1.178 (4.5)***	0.423 (2.1)**	-0.634 (3.6)***
Benchmark	-0.007 (23.8)***	-0.007 (23.7)***	-0.007 (10.6)***	-0.006 (14.9)***	-0.007 (15.2)***
Outst. LTRO	-4.E-05 (1.4)	-4.E-05 (1.5)	-4.E-03 (1.7)*	-5.E-05 (0.4)	-4.E-05 (1.4)
Dist.: 1w	1.031 (27.4)***	1.027 (27.4)***	1.158 (13.1)***	1.183 (21.9)***	0.729 (12.6)***
Dist.: 2w	0.355 (8.2)***	0.350 (8.1)***	0.377 (3.5)***	0.514 (8.3)***	0.119 (1.8)*
Dist.: 3w	0.342 (8.5)***	0.338 (8.4)***	0.289 (2.9)***	0.489 (8.1)***	0.187 (3.1)***
Constant	0.416 (2.3)**	0.832 (11.1)***	0.015 (0.1)	0.710 (6.2)***	1.547 (13.4)***
$N$	86,760	86,760	20,284	38,893	27,583
$R^2$	0.31	0.32	0.36	0.32	0.28

Notes: Stars denote levels of significance: \*  $p < 0.1$ ; \*\*  $p < 0.05$ ; \*\*\*  $p < 0.01$ . First model estimated using random effects(RE); other models fixed effects. Robust standard errors clustered on the MFI level. RE regressions include country dummies. Base category is a small bank with a bid in a operation of type “other”, or a bank which did not bid in the LTRO. “Distance” is defined as follows: 1w=0-8 days; 2w=9-16 days; 3w=17-23 days; 4w=more than 23 days before the LTRO.  $R^2$  reported as “within” for FE and “overall” for RE.

As a next robustness check we divide the sample by operational framework. To this end, we replicate the models shown in tables 3 and 4 for the full sample (“All”) but separately by old and new framework. Further, we add another dimension by estimating the models with random and fixed effects. This gives in total four variants.

Table 16 shows the model with a dummy for the post-LTRO and the split pre-LTRO dummies. The conclusions drawn from the dummies lead to the conclusion derived already in the main text. Banks bid more (less) aggressive after (before) the LTRO relative to an operation of type “other”. Turning to the conditional “before”-dummies we confirm that banks which bid also in the coming LTRO (Before | LTRO<sub>y</sub>) bid lower compared to

the control group not participating in the LTRO. This holds for all specifications, regardless of time period and estimation technique.

Table 16: MRO Bid Rate Regressions: Simple Variables and Before/After-Dummies

	Old (RE)	Old (FE)	New (RE)	New (FE)
Medium	0.514 (3.5)***		0.518 (6.4)***	
Large	0.593 (3.0)***		0.722 (7.6)***	
$\Delta$ Awrat. MR	0.015 (0.5)	0.000 (0.0)	-0.023 (1.2)	-0.023 (1.2)
$\Delta$ Awrat. LT	0.138 (3.4)***	0.137 (3.4)***	-0.007 (0.3)	-0.006 (0.3)
Last MR MP	-0.309 (7.6)***	-0.297 (7.3)***	0.157 (16.3)***	0.159 (16.6)***
Last MR Year			-7.806 (46.0)***	-7.803 (45.8)***
Uncertainty	-0.186 (20.1)***	-0.187 (20.1)***	-0.382 (57.0)***	-0.381 (56.4)***
Swap Spr.	0.137 (9.8)***	0.140 (10.0)***	0.137 (65.0)***	0.137 (64.9)***
Forw. Spr.	-0.035 (5.4)***	-0.036 (5.6)***	-0.085 (55.4)***	-0.085 (55.4)***
Award Imb.	-0.214 (1.0)	-0.257 (1.2)	2.301 (26.4)***	2.292 (26.2)***
Benchmark	0.007 (12.5)***	0.007 (12.1)***	-0.006 (22.7)***	-0.006 (22.1)***
Outst. LTRO	8.E-05 (1.3)	8.E-05 (1.3)	-2.E-05 (0.8)	-2.E-05 (0.8)
After	-0.570 (13.5)***	-0.566 (13.4)***	-0.298 (25.6)***	-0.295 (25.3)***
Before   LTRO <sub>n</sub>	0.493 (11.2)***	0.486 (11.0)***	0.614 (48.4)***	0.617 (48.3)***
Before   LTRO <sub>y</sub>	0.650 (12.0)***	0.637 (11.7)***	0.647 (28.1)***	0.646 (27.9)***
Constant	-0.304 (1.1)	0.009 (0.1)	2.585 (15.3)***	3.077 (34.7)***
<i>N</i>	23,395	23,395	63,365	63,365
<i>R</i> <sup>2</sup>	0.10	0.09	0.42	0.43
<i>F</i>	7.31	6.67	1.28	1.00

Notes: Stars denote levels of significance: \*  $p < 0.1$ ; \*\*  $p < 0.05$ ; \*\*\*  $p < 0.01$ . Random effect (RE) and fixed effect (FE) models with robust standard errors clustered on the MFI level. RE regressions include country dummies. Base category is a small bank with a bid in a operation of type “other”, or a bank which did not bid in the LTRO. The variable “Before LTRO<sub>y</sub>” indicates that the bank participated in the LTRO of that MP. F-values for test “Before LTRO<sub>y</sub>” = “Before LTRO<sub>n</sub>”. *R*<sup>2</sup> reported as “within” for FE and “overall” for RE.

Lastly, in table 17 we re-estimate the model with the condensed strategies (corresponding to table 6 in the main text) for the four variants described above. Table 18 summarizes the results in terms of p-values in the usual way. The conclusions are unchanged from the main text.

Table 17: MRO Bid Rate Regressions: Complete Strategies, cont'd

	Old (RE)	Old (FE)	New (RE)	New (FE)		
Medium	0.527 (3.6)***		0.554 (6.9)***			
Large	0.635 (3.2)***		0.780 (8.2)***			
Δ Awrat. MR	0.049 (1.7)*	0.032 (1.1)	-0.015 (0.8)	-0.015 (0.8)		
Δ Awrat. LT	0.148 (3.6)***	0.147 (3.6)***	-0.002 (0.1)	-0.001 (0.0)		
Last MR MP	-0.171 (5.3)***	-0.160 (4.9)***	0.200 (20.4)***	0.202 (20.6)***		
Last MR Year			-8.028 (47.0)***	-8.020 (46.7)***		
Uncertainty	-0.184 (20.3)***	-0.185 (20.3)***	-0.374 (56.0)***	-0.373 (55.4)***		
Swap Spr.	0.119 (8.1)***	0.123 (8.3)***	0.142 (67.4)***	0.142 (67.3)***		
Forw. Spr.	-0.025 (3.6)***	-0.026 (3.9)***	-0.090 (58.5)***	-0.091 (58.4)***		
Award Imb.	-0.302 (1.4)	-0.347 (1.6)	2.432 (27.5)***	2.422 (27.3)***		
Benchmark	0.008 (13.0)***	0.007 (12.6)***	-0.006 (22.0)***	-0.006 (21.5)***		
Outst. LTRO	7.E-05 (1.1)	7.E-05 (1.1)	-3.E-05 (1.0)	-3.E-05 (1.0)		
Strategy						
MRO	LTRO	Pos.				
b/o   b/a		b	0.419***	0.408***	0.828***	0.821***
b/o   b/a	y	b	0.643***	0.630***	0.977***	0.963***
Bid in 2 op. types			-0.093	-0.097	0.081**	0.075*
b/a/o		b	0.605***	0.598***	0.581***	0.582***
b/a/o	y	b	0.756***	0.746***	0.660***	0.660***
Bid in 3 op. types			-0.221***	-0.221***	-0.145***	-0.144***
b/a/o, cons.	y	o	-0.429	-0.070	2.450***	3.000***
b		b	0.795***	0.732***	0.646***	0.650***
b	y	b	1.424***	1.324***	0.560***	0.469***
Bid in 1 op. type			-0.038	-0.050	0.137***	0.121**
$R^2$				0.09		0.43
N			23,395	23,395	63,365	63,365

Notes: Stars denote levels of significance: \* p<0.1; \*\* <0.05; \*\*\* p<0.01. t-values for strategy dummies available upon request. Random effect (RE) and fixed effect (FE) models with robust standard errors clustered on the MFI level. RE regressions include country dummies. Base category is the bid of a small bank in an “other” MRO with the strategy to bid in all operations (b/a/o, cons.). Bid codes as *b* (before the LTRO), *a* (after the LTRO), *o* (other), and *y* (bid in LTRO). R<sup>2</sup> reported as “within” for FE and “overall” for RE.

Table 18: Joint Hypothesis Tests for Models in Table 17

Strategy	Old (RE)	Old (FE)	New (RE)	New (FE)
b/o   b/s	0.14	0.15	0.15	0.17
b/a/o	0.02	0.02	0.03	0.03
b	0.01	0.03	0.67	0.37
Joint 1	0.01	0.01	0.08	0.07
Joint 2	1.00	1.00	0.73	0.57

Notes: First three lines contain p-values for individual test for parameter equality. Joint 1 and 2 as described in text.