

Liquidity, Information, and the Overnight Rate¹

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Abstract

We model the interbank market for overnight credit with heterogeneous banks. An unsophisticated bank just trades to compensate its liquidity imbalance, while a sophisticated bank will exploit its private information about the liquidity situation in the market. It is shown that with positive probability, the liquidity effect is reversed, i.e., that a liquidity drainage from the banking system may generate an overall decrease in the market rate. This possibility is created by adverse incentives for a sophisticated bank to manipulate the market rate in the presence of asymmetric information. We also show that while strategic behavior increases the volatility of short-term interest rates, it lowers the expected quadratic deviation from the target rate.

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Non-technical summary

This paper considers a model of the interbank market for overnight loans. There are two types of credit institutions, unsophisticated and sophisticated banks. An unsophisticated bank is assumed to trade away its current account imbalance, while a sophisticated bank acts strategically in the money market. As a robust phenomenon, we obtain that a liquidity drainage from the banking system may generate a decrease in the market rate. The effect is driven by the inclination of strategic banks to delay the balancing of their reserve accounts. It is shown that this effect can be supportive to the objective of steering interest rates to a specific target. Specifically, we prove that the expected quadratic deviation from the target rate is lower in the presence of asymmetric information. In contrast, the publication of aggregate liquidity information would typically be detrimental to the objectives of monetary policy implementation. The theoretical analysis is complemented by anecdotal experimental and empirical evidence, which turns out to be consistent with the theoretical predictions.

1. Introduction

Cash market parlance as well as empirical evidence suggest the existence of a negative correlation between the daily rate for overnight credit in the interbank market on the one side and the aggregate outstanding liquidity in the banking system on the other. This effect, known as the liquidity effect (Hamilton, [13]), will be recognized as a version of the conventional theme that relatively scarcer commodities tend to be traded at relatively higher prices.

In this paper, we point out the possibility of a liquidity effect bearing a reversed sign. For this, we will consider an interbank market with heterogeneous information and asymmetric observability of liquidity positions. It is shown that an aggregate liquidity drainage from the banking system may generate an overall decrease in the market rate. As it turns out, this possibility is created by adverse incentives for some banks in the market. Specifically, there is an incentive to actively manipulate the market rate in order to exploit the value inherent to private information about liquidity flows. As a consequence of strategic behavior, the impounding of information into the market rate is delayed: the market is informationally inefficient (Grossman and Stiglitz [11]).

One corollary of our analysis is that the volatility of the overnight rate increases due to strategic behavior on the part of the sophisticated credit institution.⁴ This result comes about because in some occasions, the liquidity effect is overthrown by the manipulative trading of privately informed counterparties. This adds a noise component to the price process, thereby raising its volatility measure.⁵ On

⁴For an empirical study of the volatility of interest rates in the euro money market, we refer the reader to Cassola and Morana ([7]).

⁵Bartolini, Bertola and Prati ([3]) prove that the ex-ante expected variance of the market rate is monotonously increasing after the last central bank operation in a reserve maintenance period. They also obtain an explicit expression for the volatility.

the other hand, the strategic behavior of sophisticated banks lowers the expected quadratic deviation from the neutral-conditions rate, which is supportive to the objectives of monetary policy implementation.

Earlier contributions have pointed out the possibility of market manipulation (see, e.g., Allen and Gale, [2], Vila, [23], among others). Kumar and Seppi [16] describe a profitable trading strategy that combines position-taking in the futures market with manipulation of the spot price. A somewhat different approach, that has been originated by Hart [12] and extended by Jarrow [15], assumes an exogenous price process that is a function of the manipulator's asset position. This type of model allows the derivation of possibility and impossibility results. Closest to the current paper is the line of research that was originated by work of Kyle [17]. What is new in our approach is that it takes account of the peculiar information structure in the money market arising from the fact that banks can usually observe only liquidity flows that run through their own balance sheet.

The existing theoretical literature on the interbank market can be broadly divided into two categories. One class of models is based on the Bryant/Diamond/Dybvig tradition, focussing on issues such as the insurance motive of interbank trading, the public good property of holding liquid assets, and the problem of systemic risk. Early contributions in this vein are Bhattacharya and Gale [5], and Bhattacharya and Fulghieri [4]. See De Bandt and Hartmann [8] for a survey of this literature. The second class of models solves the individual reserve management problem under an averaging condition, and combines individual demand and supply to an equilibrium. The first paper in this class is Ho and Saunders [14], who significantly extend Poole's [20] seminal analysis on reserve management. To our knowledge, the only existing paper (other than this one) that discusses reserve

management in the presence of asymmetric information is Campbell [6], who studies the announcement effect of macro data on the Federal funds rate in the US.⁶

The rest of the paper is structured as follows. Section 2 deals with the case of a single sophisticated bank. Section 3 discusses volatility and variance of the market rate. In Section 4, we extend our analysis to the case of an arbitrary number of sophisticated banks. Section 5 reports on an experiment that is closely related to the model. The appendix contains technical derivations.

2. A single sophisticated bank

The model follows the Kyle ([17]) tradition, yet with a number of modifications that reflect the institutional specifics of liquidity management.⁷ As will become apparent, the main difference to the established framework is the information structure. The interpretation also differs slightly from the traditional framework. In particular, the traditional noise traders in the microstructure tradition have here the interpretation of behaviorally unsophisticated banks. We will start with the case of a single sophisticated bank. In fact, while this example allows an obvious interpretation with finitely many unsophisticated banks, we will, for the sake of simplicity, also assume only one unsophisticated bank.

The example has the following set-up. Three counterparties participate in the trading protocol of the money market, bank A, bank B, and a market maker. The time structure is as follows. On day 0, the market rate is r_0 . In the morning

⁶See also the discussion of Campbell's paper by Spindt ([21]).

⁷The choice of the Kyle framework is made mainly for analytical convenience. There should be no major difficulty replicating our results in a Campbell type set-up, which in particular would eliminate the necessity of having a market maker.

of day 1, the liquidity managers of bank A and B are individually informed about their idiosyncratic liquidity positions, and choose an order volume. The market maker observes the aggregate order volume, sets a price for day 1, and clears the market to break even. Finally, on day 2, the liquidity situation becomes public information.

Ex ante, there is a liquidity flow between each individual bank and the non-bank sector caused by market factors (banknotes in circulation, government deposits etc). In addition, there is a flow between bank A and B caused by customer transfers. We denote the flow from bank A to the non-bank sector by z_A , the flow from bank B to the non-bank sector by z_B , and the flow from bank A to bank B by y_{AB} , where flows can be negative. It is assumed that the components of the shock, i.e., z_A , z_B , and y_{AB} are normally and independently distributed, with expected values

$$E[z_A] = E[z_B] = 0, E[y_{AB}] = \bar{y},$$

and respective variances σ_A^2 , σ_B^2 , and σ_y^2 .

Aggregate autonomous factors are given by

$$z = z_A + z_B,$$

where, following a widely used convention, a positive sign indicates a liquidity drainage from the banking system, and a negative sign a liquidity inflow.

We assume that under symmetric and complete information about aggregate liquidity conditions z , market participants expect the overnight rate to be $r(z)$, where $r'(z) > 0$.⁸ To keep the model tractable, we will use the first-order approx-

⁸E.g., in the context of the Eurosystem, the liquidity situation at any given point of time after the last open market operation in a given reserve maintenance period will be indicative about the relative likelihood of reaching the top or bottom of the interest rate corridor. Invoking the martingale hypothesis then generates the suggested behavior.

imation

$$r(z) = r_0 + \rho z, \tag{1}$$

where $\rho > 0$ is an exogeneous parameter measuring the liquidity effect.

The realization of the liquidity shock at time 1 is observed by the individual banks as a change to the balance on their respective reserve accounts. Thus, bank A observes a liquidity outflow of

$$\tilde{z}_A = z_A + y_{AB},$$

while bank B observes

$$\tilde{z}_B = z_B - y_{AB}.$$

We consider a heterogeneous banking system. Specifically, bank A is assumed to possess a sophisticated liquidity management, and to choose an order volume x_A so as to minimize net funding costs. In contrast, bank B is unsophisticated, and just trades away any temporary imbalance on the reserve account. Thus, $x_B = z_B - y_{AB}$.⁹ This kind of heterogeneous behavior is suggested by descriptive studies of the money market. E.g., Nyborg et al. [18] find that larger banks in the euro area tend to act more strategically in the Eurosystem's main refinancing operations. Moreover, the descriptive literature of money markets provides anecdotal evidence for heterogeneous degrees of sophistication of market participants.

Still, the behavior of the non-sophisticated bank deserves discussion. A potential defense is that banks have position targets, which enter the individual bank's objective function (cf. Campbell, 1987). A natural target position for a bank

⁹In an alternative interpretation, bank B represents an aggregate of several unsophisticated banks, and the liquidity variables z_B and y_{AB} represent the respective aggregate net liquidity flows.

could be defined in terms of having a balanced reserve account. The relative weight that the objective of staying close to the target obtains in the bank's objective function reflects then the willingness to trade in the money market for speculative reasons. Our model replaces the continuum of possible relative weights by two extreme cases: the sophisticated bank gives zero weight to the position target, while the unsophisticated bank gives full weight to the position target, thereby ignoring the profit term.

Aggregate liquidity demand is then $x = x_A + x_B$. The market maker observes x , and determines the zero-profit market rate

$$\tilde{r}(x) = E[r_0 + \rho z | x].$$

Proposition 1. An equilibrium in the interbank market for overnight credit is constituted by the strategies

$$\begin{aligned} x_A(\tilde{z}_A) &= \beta(\tilde{z}_A - \bar{y}) \\ \tilde{r}(x) &= r_0 + \lambda(x + \bar{y}), \end{aligned}$$

where $\beta \in (0; 1)$, and

$$\lambda = \rho \frac{\beta\sigma_A^2 + \sigma_B^2}{\beta^2\sigma_A^2 + \sigma_B^2 + (1 - \beta)^2\sigma_y^2}. \quad (2)$$

Proof. See the appendix. ◻

It can be seen from Proposition 1 that the sophisticated bank never fully accommodates its liquidity demand, i.e., $\beta < 1$. Instead, it hides some of its excess liquidity or its liquidity deficit in order to misguide the market about the liquidity situation of the market. In addition, the sophisticated bank takes account of the

fact that its reserve balance is distorted by the expected flow to bank B. We will now derive conditions under which this strategic behavior of the sophisticated bank will cause a liquidity outflow of the banking system to induce a decrease in the market rate, reverting the liquidity effect.

A shock (z_A, z_B, y_{AB}) to the banking system will be referred to as **liquidity-absorbing** if $z_A + z_B > 0$. (Recall our earlier sign convention for autonomous factors). It should be clear that the interbank flow y_{AB} does not appear in this definition because it does not affect aggregate liquidity conditions. From Proposition 1, we know that a shock induces a decline in the equilibrium rate if the aggregate order volume is below average, i.e., if

$$x_A(\tilde{z}_A) + x_B(\tilde{z}_B) < -\bar{y}.$$

This latter condition is equivalent, again by Proposition 1, to

$$\beta(\tilde{z}_A - \bar{y}) + \tilde{z}_B < -\bar{y},$$

or

$$\beta z_A + z_B - (1 - \beta)(y_{AB} - \bar{y}) < 0.$$

We have shown in Proposition 1 that $\beta \in (0, 1)$. Thus, for a liquidity-absorbing shock (z_A, z_B, y_{AB}) to induce the market rate to fall, it suffices to simultaneously satisfy the following conditions:

$$\begin{aligned} z_A &> 0 \\ -z_A &< z_B < -\beta z_A \\ y_{AB} &\geq \bar{y} \end{aligned}$$

As these conditions describe a set of strictly positive measure in the three-dimensional euclidean space of liquidity shocks, we have shown a special case of the central result of our paper:

Proposition 2. For all parameter values of the model, there is a positive probability that a liquidity shock will cause both a liquidity drainage and a decreasing market rate.

Proof. See text above. ◻

Proposition 2 says that the path that the market rate takes in response to a newly established liquidity situation need not be monotonous: It may happen that the initial development of the market rate goes into the direction opposite to the one predicted by the liquidity effect.¹⁰ As we now want to show, this adds to the expected uncertainty of short-term interest rates.

3. Volatility and variance

As the benchmark case, we consider a scenario where both banks act non-strategically, i.e., the banks trade in the market with the sole intention of re-balancing their reserve accounts. In this case, total order volume turns out to be

$$\begin{aligned} x &= x_A(\tilde{z}_A) + x_B(\tilde{z}_B) \\ &= z_A + y_{AB} + z_B - y_{AB} \\ &= z, \end{aligned}$$

i.e., equal to the liquidity imbalance caused to the overall banking system. The market maker therefore obtains complete information about the aggregate liquidity situation of the banking system vis-à-vis the non-bank sector, and sets the price on day 1 equal to the full-information rate $r(z)$. Thus, in the benchmark

¹⁰Of course, a completely analogous derivation shows the robust possibility of a liquidity-providing shock to cause the market rate to increase.

setting with unsophisticated behavior by both banks, we obtain a change in the market rate between day 0 and day 1 equaling $r(z) - r_0$, and no change between day 1 and day 2 (see Figure 1). The volatility of the sequence of market rates (i.e., the ex-ante expected average standard deviation of the price increment between two consecutive trading days) in the absence of strategic behavior is therefore given by

$$v^u = \frac{1}{2}STD(r(z) - r_0).$$

We compare this benchmark volatility with the volatility in the original set-up with one sophisticated and one unsophisticated bank. Here, the price on day 1 is $\tilde{r}(x)$, where $x = x_A(\tilde{z}_A) + x_B(\tilde{z}_B)$, and the price on day 2 is $r(z)$. Thus, the volatility in a market with strategic behavior is given by

$$v^s = \frac{1}{2}\{STD(\tilde{r}(x) - r_0) + STD(r(z) - \tilde{r}(x))\}.$$

It turns out that strategic money trading increases the volatility of the price process.

Proposition 3. For all parameter values of the model, $v^s > v^u$.

Proof. See the Appendix. ¶

The idea of the proof is to show that with sophisticated trading, the day-to-day changes of the market rate are uncorrelated. Intuitively, if these changes were correlated, strategic market participants could exploit this correlation. More precisely, if there was a correlation between two consecutive market prices in equilibrium, then not all information that is common knowledge between market participants would be reflected in the market rate. In the linear model that we consider, this would give the potential for arbitrage.

We will now turn to the question of how the procrastinated trading of some banks will affect monetary policy implementation. The interpretation will be that the central bank has installed neutral liquidity conditions on day 0 (e.g., by making the benchmark allotment in the last tender of the maintenance period), and that the market rate r_0 on that day corresponds to the target rate. With this interpretation in mind, we will now define the expected quadratic average from the target rate on day 1. Day 2 can be neglected in the discussion of interest rate targeting because the full-information rate prevails by assumption. In the benchmark case of two unsophisticated banks, the rate on day 1 will be the full-information rate, i.e., $r(z)$, so that the expected quadratic deviation from the target rate is given by

$$V^u = E[(r(z) - r_0)^2].$$

In contrast, with one sophisticated bank, the partial-information rate $\tilde{r}(x)$ will prevail on day 1, so that the quadratic deviation amounts to

$$V^s = E[(\tilde{r}(x) - r_0)^2].$$

Using the previous results, we can show that strategic behavior lowers the expected deviation from the interest rate target.

Proposition 4. For all parameter values of the model, $V^s < V^u$.

Proof. See the appendix. ¶

Thus, and in mild contrast to the above finding on the volatility, it turns out that the average quadratic deviation from the interest rate r_0 is smaller in the presence of sophisticated behavior. If r_0 is interpreted as the central bank's target rate then this finding says that the informational inefficiency may in fact be supportive

to the objectives of monetary policy implementation. This leads us to the conclusion that the provision of public information about aggregate liquidity conditions after the last refinancing operation may in fact be detrimental to monetary policy implementation. This finding may explain why the ECB releases this information only immediately before an individual refinancing operation.

4. Extension to N sophisticated and M unsophisticated banks

Consider now the general case of $N \geq 0$ sophisticated banks $i = 1, \dots, N$ and of $M \geq 1$ unsophisticated banks $i = N + 1, \dots, N + M$. See Figure 2 for illustration. We will use the convention that unless indicated otherwise, the parameter i runs over all $N + M$ banks. Denote the liquidity flows from bank i to the non-bank sector by z_i , and the liquidity flow from bank i to bank j by y_{ij} , where $y_{ij} = -y_{ji}$. The expected value of the liquidity outflow from an individual firm to the non-bank sector is assumed to be $E[z_i] = 0$ for simplicity. For the expected interbank flow from bank i to bank j , we will write

$$E[y_{ij}] = \bar{y}_{ij}.$$

For reasons of tractability, we will turn out to be useful to impose certain symmetry restrictions on the variances of the involved liquidity flows.¹¹ Specifically, the variances of the flows from individual banks to the non-bank sector are assumed to be identical within the groups of sophisticated and unsophisticated banks, respectively, i.e.,

$$VAR(z_i) = \begin{cases} \sigma_s^2 & \text{for } i = 1, \dots, N \\ \sigma_u^2 & \text{for } i = N + 1, \dots, N + M. \end{cases}$$

¹¹Dropping these restrictions leads to a generic system of N quadratic equations in N variables, which typically does not allow an explicit solution.

Similarly, the variances of the flows between two individual banks are assumed to be the same if either both banks are sophisticated, or both banks are unsophisticated or one bank is, and the other is not. Thus, we assume

$$VAR(y_{ij}) = \begin{cases} \sigma_{ss}^2 & \text{for } i, j \in \{1, \dots, N\} \\ \sigma_{uu}^2 & \text{for } i, j \in \{N+1, \dots, N+M\} \\ \sigma_{su}^2 & \text{otherwise} \end{cases} .$$

As before, bank i observes the balance of its reserve account, i.e.,

$$\tilde{z}_i = z_i + \sum_{j \neq i} y_{ij},$$

(Recall our earlier convention that says here that the sum runs over all banks $j = 1, \dots, N+M$, leaving i out). For ease of notation, we will write

$$y_i = \sum_{j \neq i} y_{ij}$$

for the total liquidity flow from bank i to other banks in the system. Clearly, the expected liquidity imbalance for bank i is

$$E[\tilde{z}_i] = \sum_{j \neq i} \bar{y}_{ij} =: \bar{y}_i.$$

When aggregating over flows, we clearly have that the total flow of liquidity from the sophisticated to the non-sophisticated banks is given by

$$\bar{y} := \sum_{i=1}^N y_i = - \sum_{i=N+1}^{N+M} y_i.$$

This statistics will play a certain role in the subsequent analysis. The problem of a sophisticated bank $i = 1, \dots, N$ is to maximize expected profits from speculation

$$\pi_i(x_i) = E[(r(z) - \tilde{r}(x))x_i | \tilde{z}_i].$$

Individual order flow for bank i is denoted by $x_i(\tilde{z}_i)$. Aggregate order flow is then

$$x = \sum_{i=1}^N x_i(\tilde{z}_i) + \sum_{i=N+1}^{N+M} \tilde{z}_i.$$

With these specifications, the equilibrium analysis of the model generalizes in a straightforward way as follows.

Proposition 5. An equilibrium in the interbank market for overnight credit is constituted by the strategies

$$x_i(\tilde{z}_i) = \beta(\tilde{z}_i - \bar{y}_i) \quad (3)$$

for $i = 1, \dots, N$, and

$$\tilde{r}(x) = r_0 + \lambda(x + \bar{y}), \quad (4)$$

where $\beta \in (0; 1)$ and

$$\lambda = \rho \frac{N\beta\sigma_s^2 + M\sigma_u^2}{N\beta^2\sigma_s^2 + M\sigma_u^2 + (1 - \beta)^2 NM\sigma_{su}^2}. \quad (5)$$

Proof. See the appendix. ◻

We continue with the discussion of volatility and variance in the case of finitely many sophisticated banks. Generalizing our earlier definition, we will say that a shock $(\{z_i\}_{i=1, \dots, N+M}, \{y_{ij}\}_{i>j})$ to the banking system is **liquidity-absorbing** if

$$z = \sum_{i=1}^{N+M} z_i > 0.$$

According to Proposition 5, the market rate will fall in consequence of a liquidity shock if and only if the aggregate order flow is smaller than its expected value. Formally, this conditions is true if $x < -\bar{y}$. As total order flow is the sum of sophisticated and unsophisticated demand, this is tantamount to

$$\beta \sum_{i=1}^N (\tilde{z}_i - \bar{z}_i) + \sum_{i=N+1}^{N+M} \tilde{z}_i < -\bar{y}.$$

Using the definition of \tilde{z}_i and rearranging gives

$$\beta z_s + z_u + (1 - \beta)(y - \bar{y}) < 0,$$

where

$$\begin{aligned} z_s &= \sum_{i=1}^N z_i, \\ z_u &= \sum_{i=N+1}^{N+M} z_i \end{aligned}$$

are the flows of liquidity to the non-bank sector aggregated about sophisticated and unsophisticated banks, respectively. The adverse effect is driven now by the fact that the sophisticated banks delay a part of their refinancing needs, i.e., from $\beta \in (0, 1)$. For a liquidity-absorbing shock ($\{z_i\}_{i=1, \dots, N+M}, \{y_{ij}\}_{i>j}$) to induce the market rate to fall, it suffices to simultaneously satisfy the following conditions:

$$\begin{aligned} z_s &> 0 \\ -z_s &< z_u < -\beta z_s \\ y &\leq \bar{y}. \end{aligned}$$

These conditions specify a non-empty subset in the euclidean space of liquidity shocks, so we have generalized Proposition 2 to an arbitrary number of sophisticated banks. In fact, Propositions 3 and 4 extends likewise in a straightforward manner to the generalized set-up (note that the definitions of volatility and variance of the market rate are well-defined also in the extended model). We summarize our findings as follows.

Proposition 6. With finitely many strategic banks, there is a positive probability that a liquidity drainage causes the market rate to fall. On average, the volatility of the market rate is larger, while the quadratic deviation from the neutral rate r_0 is smaller in the presence of sophisticated liquidity management.

Proof. See the appendix. ¶

5. An experiment

During the summer term 2003, a student of the University of Bonn, Katrin Mayer, conducted an explorative experiment on money market trading within the operational framework of the Eurosystem.¹² The objective for this project was to obtain a better understanding of the trading behavior after the last central bank operation in a given reserve maintenance period, in particular, concerning the dissemination of information into the market, the development of the dispersion of prices. The experiment thereby has an immediate bearing on the recently released changes to the operational framework of the Eurosystem.

The challenge with this kind of experiment is the availability of a critical number of subjects that understand the operational framework sufficiently well. We recruited a number of students that had been active participants of a course on monetary policy implementation. As a consequence, the number of sessions is very low, and we cannot hope to get statistically significant results. However, we found the outcome of our only two sessions very instructive, and we consider it as anecdotal evidence that is consistent with the predictions of the theoretical model. Moreover, to our knowledge, an experiment of this kind has not been performed so far.¹³

The experimental money market consisted of six banks, two of which were large, and four of which were small. Large banks differed from small banks by having a

¹²Ms Mayer's diploma thesis (in German) should be consulted for further details.

¹³The only related contribution is the PhD thesis of Häselbarth (1970, in German), who performed a very sophisticated experiment within the operational framework of the Bundesbank.

larger minimum reserve requirement (twice the amount of a small bank), by the initial reserve account balance, and by a larger volatility of liquidity shocks.

The trading week consisted of five trading periods (Monday to Friday). At the beginning of the trading period, each bank learned its own reserve account balance, but not those of the other institutes. Banks could then freely bargain about overnight credits, where amounts had to be multiples of 0.1 bn euro, and interest rates had to have at most two decimal points bilateral agreements involved an immediate transfer of the principal against a trading ticket; trading tickets have been checked and stamped by the market organizer each trading period lasted 10 minutes.

The shocks that affected the individual banks have been prepared using the table shown in Figure 3. E.g., in the first session, aggregate liquidity was initially rich, but was taken out of the system in a continuous way. Each day 0.3 bn euros were taken out. In contrast, in the second session, aggregate liquidity was scarce initially, and injected continuously over time into the system. In fact, a closer look to the figures will reveal that the shocks in the second session just had the opposite sign, when compared to the first session. To make this intransparent to the subjects, we permuted the roles of the participants (keeping the size of the banks for a given subject constant, however).

Figure 4 shows a ticket that documents a credit contract between two banks. The ticket specifies lender and borrower, the amount of the credit, and the interest rate to be paid. The market organizer stamped the tickets to make them “official,” and noted the time within the trading day at which the contract has been stamped.

Between the end of a trading period and the beginning of the subsequent trading period, the market organizer documented the individual reserve account balances.

The market organizer then arranged the repayment of the respective principals. Finally, reserve account holdings were affected by liquidity shocks using the prepared table of shocks.

Figure 5 depicts the development of aggregate liquidity in the system, and compares it to the average market rate. It can be seen that the experimental market did not aggregate the information in an efficient manner. In contrast, in both sessions, the market rate reflects only on the last day the actual liquidity conditions. Note that this evidence, while anecdotal, is in line with the prediction of our simple model. In particular, the informational inefficiency that is present in the experimental money market is consistent with the hypothesis of strategic position taking by sophisticated liquidity managers.

Market participants learned aggregate liquidity conditions only at a very slow rate. Figure 6 shows the bilaterally contracted interest rates over the trading week, ignoring the time during which no trade was possible (i.e., between the trading periods). Also here, it becomes clear that the trend created in the market rate underrepresented the underlying development in aggregate autonomous factors. In both sessions, the subjects seem to have realized what was going on only on the last day.

Figure 7 depicts the development of the trading volume. Interestingly, we have a hump-shaped development in both sessions. Our interpretation (which is consistent with statements made by the participants after the experiment) is that subjects first wanted to wait and see on the first day where the market would be heading. This reluctance then broke up on the second and third day, and subjects essentially tried to balance their reserve accounts. Approximately half of the group tried to individually speculate by building up a red or black position

during this period. The idea of taking a position was apparently well-understood. Trading volume on days 4 and 5 was low, reflecting the fine-tuning of individuals.

One interesting phenomenon in the empirics of the euro money market is the J-shape of the price dispersion (see Gaspar et al., 2003). Figure 8 shows the development of price dispersion in the experimental money market. We found it interesting that the pattern that has been documented for data from the euro money market reappears in this simple experimental market.

A brief case study To allow the reader to see the abstractions that we have made in the formal analysis and in the experiment, we conclude this section with a description of the maintenance period 24 March - 23 April 2003. The considered maintenance period was a period without interest rate changes. Short-term expectations, as measured in the term structure of interest rates, were neutral, and the central bank's liquidity management had targeted average daily excess reserves equal to EUR 0.6 billion, which corresponds to the normal value of excess reserves in the euro area. The overnight rate remained calm except at the end of period. The spread between market rate and the main policy rate, the minimum bid rate, was essentially normal (about 5 basis points). The market rate deviated from its smooth path on the last two days of the maintenance period. As can be seen on Figures 9 and 10, the overnight rate moved upwards above the middle of corridor except towards the last few hours of the period when it spikes downwards. Figure 11 shows that the period ended with plenty liquidity, resulting in a large net recourse to the deposit facility (EUR 4.0 billion).

6. Conclusion

We have modified the Kyle ([17]) framework to capture some institutional as-

pects of the interbank market for overnight liquidity. Main assumptions included heterogeneous levels of sophistication in banks' liquidity management, as well as asymmetric information distribution resulting from a decentralized realization of an autonomous factor shock. It was shown that under these conditions, the liquidity effect may be overthrown in the sense that a liquidity drainage from the banking system may induce the market rate to decrease.

The prediction of the model is that sophisticated banks procrastinate their balancing of liquidity needs, and that information in fact is impounded into prices only with a certain delay. We have anecdotal evidence that this may be true also in experimental money markets. This strategic behavior may help to explain the specific pattern of money market data at the end of the maintenance period, especially the J-formed price dispersion.

We have also performed an indicative experiment capturing some elements of trading in the euro money market after the last central bank operation in a given reserve maintenance period. The experimental analysis delivered three main findings: the market rate did not immediately reflect aggregate liquidity conditions. Moreover, the trading volume has been hump-shaped over the time after the last operation. Finally, the dispersion of prices first decreased slightly, and then increased dramatically on the last day.

Appendix

Proof of Proposition 1. The proof has three steps. We first check the optimality of bank A's strategy, given the linear pricing rule and the unsophisticated behavior of bank B. Profits for bank A, conditional on observing the realized

liquidity imbalance \tilde{z}_A , are given by

$$\begin{aligned} E[(r(z) - \tilde{r}(x))x_A|\tilde{z}_A] &= E[\{\rho z - \lambda(x + \bar{y})\}x_A|\tilde{z}_A] \\ &= \{\rho E[z|\tilde{z}_A] - \lambda(x_A + E[x_B|\tilde{z}_A] + \bar{y})\}x_A, \end{aligned}$$

where, by the projection theorem for normally distributed random variables,

$$\begin{aligned} E[z|\tilde{z}_A] &= \frac{\sigma_A^2}{\sigma_A^2 + \sigma_y^2}(\tilde{z}_A - \bar{y}) \\ E[x_B|\tilde{z}_A] &= -\bar{y} - \frac{\sigma_y^2}{\sigma_A^2 + \sigma_y^2}(\tilde{z}_A - \bar{y}). \end{aligned}$$

The corresponding first-order condition is

$$x_A(\tilde{z}_A) = \frac{\rho E[z|\tilde{z}_A]}{2\lambda} - \frac{1}{2}(E[x_B|\tilde{z}_A] + \bar{y}).$$

Using the explicit expressions for the conditional expectations gives

$$x_A(\tilde{z}_A) = \beta(\tilde{z}_A - \bar{y}),$$

where

$$\beta = \frac{\rho}{2\lambda} \frac{\sigma_A^2}{\sigma_A^2 + \sigma_y^2} + \frac{1}{2} \frac{\sigma_y^2}{\sigma_A^2 + \sigma_y^2}. \quad (6)$$

We continue by checking the zero-profit or no-arbitrage condition for the market maker, assuming a linear strategy for bank A, and liquidity-balancing for bank B. Under these conditions,

$$E[r(z)|x] = r_0 + \rho E[z|x],$$

where, by another application of the projection theorem,

$$\begin{aligned} E[z|x] &= \frac{COV(z, \beta z_A + z_B - (1 - \beta)y_{AB})}{VAR(\beta z_A + z_B - (1 - \beta)y_{AB})}(x + \bar{y}) \\ &= \frac{\beta\sigma_A^2 + \sigma_B^2}{\beta^2\sigma_A^2 + \sigma_B^2 + (1 - \beta)^2\sigma_y^2}(x + \bar{y}). \end{aligned}$$

We show now that $\beta \in (0; 1)$. Note first that $\lambda > 0$ by the second-order condition for the sophisticated bank's problem. From (6) then it follows that $\beta > 0$. It therefore remains to be shown that $\beta < 1$. Plugging (2) into (6) and rearranging yields the quadratic equation

$$\beta^2 + \beta(2\zeta + \xi) - (\zeta + \xi) = 0, \quad (7)$$

where $\zeta = \sigma_B^2/\sigma_A^2$ and $\xi = \sigma_y^2/(\sigma_A^2 + \sigma_y^2)$. This equation possesses a unique positive root, given by

$$\beta(\zeta, \xi) = -(\zeta + \frac{\xi}{2}) + \sqrt{(\zeta + \frac{\xi}{2})^2 + \zeta + \xi}.$$

If $\beta \geq 1$, then the left-hand side of (7) is strictly positive, so we must have $\beta < 1$. \blacktriangleleft

Proof of Proposition 3. We start from the obvious triangle decomposition

$$r(z) - r_0 = (r(z) - \tilde{r}(x)) + (\tilde{r}(x) - r_0).$$

Hence,

$$\begin{aligned} VAR(r(z) - r_0) &= VAR(r(z) - \tilde{r}(x)) + VAR(\tilde{r}(x) - r_0) \\ &\quad + 2COV(r(z) - \tilde{r}(x), \tilde{r}(x) - r_0). \end{aligned}$$

We will focus for the moment on the covariance term. Using

$$\begin{aligned} r(z) - r_0 &= \rho(z_A + z_B) \\ \tilde{r}(x) - r_0 &= \lambda(\beta z_A + z_B - (1 - \beta)(y_{AB} - \bar{y})), \end{aligned} \quad (8)$$

and using the independence of z_A , z_B , and y_{AB} , we obtain

$$\begin{aligned} &COV(r(z) - \tilde{r}(x), \tilde{r}(x) - r_0) \\ &= \lambda COV(\rho(z_A + z_B) - \lambda(\beta z_A + z_B - (1 - \beta)(y_{AB} - \bar{y})), \\ &\quad \beta z_A + z_B - (1 - \beta)(y_{AB} - \bar{y})) \\ &= \lambda\{\beta(\rho - \beta\lambda)\sigma_A^2 + (\rho - \lambda)\sigma_B^2 - \lambda(1 - \beta)^2\sigma_y^2\} \\ &= 0, \end{aligned}$$

where we used (2) in the last equation. This yields

$$VAR(r(z) - r_0) = VAR(r(z) - \tilde{r}(x)) + VAR(\tilde{r}(x) - r_0).$$

Thus,

$$\begin{aligned} 4(v^s)^2 &= VAR(\tilde{r}(x) - r_0) + VAR(r(z) - \tilde{r}(x)) \\ &\quad + 2STD(\tilde{r}(x) - r_0)STD(r(z) - \tilde{r}(x)) \\ &> VAR(\tilde{r}(x) - r_0) + VAR(r(z) - \tilde{r}(x)) \\ &= VAR(r(z) - r_0) \\ &= 4(v^u)^2, \end{aligned}$$

proving the assertion. \blacktriangleleft

Proof of Proposition 4. By definition,

$$\begin{aligned} V^u &= E[(r(z) - r_0)^2] \\ &= \rho^2 E[(z_A + z_B)^2] \\ &= \rho^2(\sigma_A^2 + \sigma_B^2). \end{aligned}$$

On the other hand, by (8) and (2), we get

$$\begin{aligned} V^s &= E[(\tilde{r}(x) - r_0)^2] \\ &= \lambda^2 E[\{\beta z_A + z_B - (1 - \beta)(y_{AB} - \bar{y})\}^2] \\ &= \lambda^2 \{\beta^2 \sigma_A^2 + \sigma_B^2 + (1 - \beta)^2 \sigma_y^2\} \\ &= \rho^2 \frac{(\beta \sigma_A^2 + \sigma_B^2)^2}{\beta^2 \sigma_A^2 + \sigma_B^2 + (1 - \beta)^2 \sigma_y^2} \\ &= \frac{\beta \sigma_A^2 + \sigma_B^2}{\sigma_A^2 + \sigma_B^2} \frac{\beta \sigma_A^2 + \sigma_B^2}{\beta^2 \sigma_A^2 + \sigma_B^2 + (1 - \beta)^2 \sigma_y^2} V^u. \end{aligned}$$

The assertion then follows from $\beta < 1$. \blacktriangleleft

Proof of Proposition 5. The proof follows the lines of the proof of Proposition 1. The details are as follows. Assuming that the market maker's price-setting behavior (4) is common knowledge, expected profits for bank i , for $i = 1, \dots, N$, are given by

$$\begin{aligned}\pi_i(x_i) &= E[(r(z) - \tilde{r}(x))x_i|\tilde{z}_i] \\ &= E[(\rho z - \lambda(x + \bar{y}))x_i|\tilde{z}_i] \\ &= \{\rho E[z|\tilde{z}_i] - \lambda(x_i + E[x_{-i}|\tilde{z}_i] + \bar{y})\}x_i,\end{aligned}$$

where

$$x_{-i} = \sum_{j \neq i} x_j.$$

The corresponding first-order condition is

$$x_i(\tilde{z}_i) = \frac{\rho}{2\lambda} E[z|\tilde{z}_i] - \frac{1}{2} E[x_{-i}|\tilde{z}_i] - \frac{\bar{y}}{2}, \quad (9)$$

for $i = 1, \dots, N$. We will now calculate the two expected values in (9). For $i = 1, \dots, N$, we have by the projection theorem that

$$\begin{aligned}E[z|\tilde{z}_i] &= \frac{COV(z, \tilde{z}_i)}{VAR(\tilde{z}_i)}(\tilde{z}_i - E[\tilde{z}_i]) \\ &= \frac{\sigma_i^2}{\sigma_i^2 + \sum_{j \neq i} \sigma_{ij}^2}(\tilde{z}_i - \bar{y}_i).\end{aligned}$$

The second expected value is given by

$$E[x_{-i}|\tilde{z}_i] = E[x_{-i}] + \frac{COV(x_{-i}, \tilde{z}_i)}{VAR(\tilde{z}_i)}(\tilde{z}_i - \bar{y}_i),$$

where

$$E[x_{-i}] = \sum_{j=N+1}^{N+M} \bar{y}_j = -\bar{y},$$

and the covariance and variance terms are given by

$$COV(x_{-i}, \tilde{z}_i) = \sum_{\substack{j=1 \\ j \neq i}}^N COV(x_j, \tilde{z}_i) + \sum_{j=N+1}^{N+M} COV(x_j, \tilde{z}_i)$$

$$\begin{aligned}
&= \sum_{\substack{j=1 \\ j \neq i}}^N COV(\beta_j(z_j + \sum_{k \neq j} y_{jk}), z_i + \sum_{l \neq i} y_{il}) + \\
&\quad + \sum_{j=N+1}^{N+M} COV(z_j + \sum_{k \neq j} y_{jk}, z_i + \sum_{l \neq i} y_{il}) \\
&= \sum_{\substack{j=1 \\ j \neq i}}^N \beta_j COV(y_{ji}, y_{ij}) + \sum_{j=N+1}^{N+M} COV(y_{ji}, y_{ij}) \\
&= - \sum_{\substack{j=1 \\ j \neq i}}^N \beta_j \sigma_{ij}^2 - \sum_{j=N+1}^{N+M} \sigma_{ij}^2,
\end{aligned}$$

and by

$$VAR(\tilde{z}_i) = \sigma_i^2 + \sum_{j \neq i} \sigma_{ij}^2.$$

Thus, from (9), we get (3), where the vector $(\beta_1, \dots, \beta_N)$ is the solution of the system of equations

$$2\beta_i = \frac{1}{\sigma_i^2 + \sum_{j \neq i} \sigma_{ij}^2} \left\{ \frac{\rho}{\lambda} \sigma_i^2 + \sum_{\substack{j=1 \\ j \neq i}}^N \beta_j \sigma_{ij}^2 + \sum_{j=N+1}^{N+M} \sigma_{ij}^2 \right\}, \quad (10)$$

for $i = 1, \dots, N$. In the symmetric set-up, to which we refined ourselves earlier above, this leads to

$$2\beta = \frac{\sigma_s^2(\rho/\lambda) + (N-1)\beta\sigma_{ss}^2 + M\sigma_{su}^2}{\sigma_s^2 + (N-1)\sigma_{ss}^2 + M\sigma_{su}^2}. \quad (11)$$

Next, we check the zero-profit condition for the market maker. We find that

$$\begin{aligned}
E[r(z)|x] &= r_0 + \rho E[z|x] \\
&= r_0 + \rho \frac{COV(z, x)}{VAR(x)} (x - E[x]),
\end{aligned} \quad (12)$$

where

$$\begin{aligned}
COV(z, x) &= COV\left(\sum_{i=1}^{N+M} z_i, \sum_{j=1}^N x_j(\tilde{z}_j)\right) + COV\left(\sum_{i=1}^{N+M} z_i, \sum_{j=N+1}^{N+M} \tilde{z}_j\right) \\
&= COV\left(\sum_{i=1}^{N+M} z_i, \sum_{j=1}^N \beta_j z_j\right) + COV\left(\sum_{i=1}^{N+M} z_i, \sum_{j=N+1}^{N+M} z_j\right) \\
&= \sum_{i=1}^N \beta_i \sigma_i^2 + \sum_{i=N+1}^{N+M} \sigma_i^2,
\end{aligned}$$

and

$$\begin{aligned}
VAR(x) &= VAR\left(\sum_{i=1}^N x_i(\tilde{z}_i) + \sum_{i=N+1}^{N+M} \tilde{z}_i\right) \\
&= VAR\left(\sum_{i=1}^N \beta_i(z_i + \sum_{j \neq i} y_{ij}) + \sum_{i=N+1}^{N+M} (z_i + \sum_{j \neq i} y_{ij})\right) \\
&= \sum_{i=1}^N \beta_i^2 \sigma_i^2 + \sum_{i=N+1}^{N+M} \sigma_i^2 + VAR\left(\sum_{i=1}^N \beta_i \sum_{j \neq i} y_{ij} + \sum_{i=N+1}^{N+M} \sum_{j \neq i} y_{ij}\right) \\
&= \sum_{i=1}^{N+M} \beta_i^2 \sigma_i^2 + \sum_{i>j} (\beta_i - \beta_j)^2 \sigma_{ij}^2,
\end{aligned}$$

where we let $\beta_i := 1$ for $i = N + 1, \dots, N + M$. Moreover, we have

$$\begin{aligned}
E[x] &= E\left[\sum_{i=1}^N \beta_i(z_i + \sum_{j \neq i} (y_{ij} - \bar{y}_{ij})) + \sum_{i=N+1}^{N+M} (z_i + \sum_{j \neq i} y_{ij})\right] \\
&= \sum_{i=N+1}^{N+M} \sum_{j \neq i} \bar{y}_{ij} = -\bar{y}.
\end{aligned}$$

Using this information, (12) implies (4), where

$$\lambda = \rho \frac{\sum_{i=1}^{N+M} \beta_i \sigma_i^2}{\sum_{i=1}^{N+M} \beta_i^2 \sigma_i^2 + \sum_{i>j} (\beta_i - \beta_j)^2 \sigma_{ij}^2}.$$

The symmetric set-up implies (5). Combining (11) and (5) yields the quadratic equation

$$\beta^2 + A\beta - B = 0,$$

for constants A and B satisfying $A \geq B \geq 0$. Thus, as in the proof of Proposition 1, there is a unique positive root $\beta < 1$. \blacksquare

Proof of Proposition 6. The first assertion is proved in the text before the Proposition. For the second assertion, recall from the proof of Proposition 2 that it suffices to show that

$$COV(r(z) - \tilde{r}(x), \tilde{r}(x) - r_0) = 0.$$

From (1) and (4), we obtain

$$\begin{aligned}
& COV(r(z) - \tilde{r}(x), \tilde{r}(x) - r_0) \\
&= COV(\rho z - \lambda(x + \bar{y}), \lambda(x + \bar{y})) \\
&= COV(\rho \sum_{i=1}^{N+M} z_i - \lambda \sum_{i=1}^{N+M} \beta_i(z_i + y_i), \lambda \sum_{i=1}^{N+M} \beta_i(z_i + y_i)) \\
&= \lambda COV(\sum_{i=1}^{N+M} \{z_i(\rho - \lambda\beta_i) - \lambda\beta_i y_i\}, \sum_{i=1}^{N+M} \beta_i(z_i + y_i)) \\
&= \lambda \{ \sum_{i=1}^{N+M} (\rho - \lambda\beta_i)\beta_i\sigma_i^2 - \lambda \sum_{i>j} (\beta_i - \beta_j)^2 \sigma_{ij}^2 \} \\
&= \lambda \{ N(\rho - \beta\lambda)\beta\sigma_s^2 + M(\rho - \lambda)\sigma_u^2 - NM(1 - \beta)^2 \sigma_{su}^2 \} \\
&= 0,
\end{aligned}$$

where we used (5) in the last equation. This proves the assertion concerning the volatility. As for the quadratic deviation from the neutral rate r_0 , we have

$$\begin{aligned}
V^s &= E[(\tilde{r}(x) - r_0)^2] \\
&= \lambda^2 E[\{ \sum_{i=1}^N \beta(z_i + y_i - \bar{y}_i) + \sum_{i=N+1}^{N+M} (z_i + y_i) + \bar{y} \}^2] \\
&= \lambda^2 E[\{ \beta z_s + z_u - (1 - \beta)(y - \bar{y}) \}^2] \\
&= \lambda^2 \{ N\beta^2\sigma_s^2 + M\sigma_u^2 - (1 - \beta)^2 NM\sigma_{su}^2 \} \\
&= \rho^2 \frac{(N\beta\sigma_s^2 + M\sigma_u^2)^2}{N\beta^2\sigma_s^2 + M\sigma_u^2 + (1 - \beta)^2 NM\sigma_{su}^2} \\
&= \frac{N\beta\sigma_s^2 + M\sigma_u^2}{N\sigma_s^2 + M\sigma_u^2} \frac{N\beta\sigma_s^2 + M\sigma_u^2}{N\beta^2\sigma_s^2 + M\sigma_u^2 + (1 - \beta)^2 NM\sigma_{su}^2} V^u \\
&> V^u,
\end{aligned}$$

where we have used

$$\begin{aligned}
V^u &= E[(r(z)^2 - r_0)^2] \\
&= \rho^2 (N\sigma_s^2 + M\sigma_u^2)
\end{aligned}$$

and $\beta \in (0, 1)$. This proves the assertion concerning the variance, and thereby the Proposition. \blackspadesuit

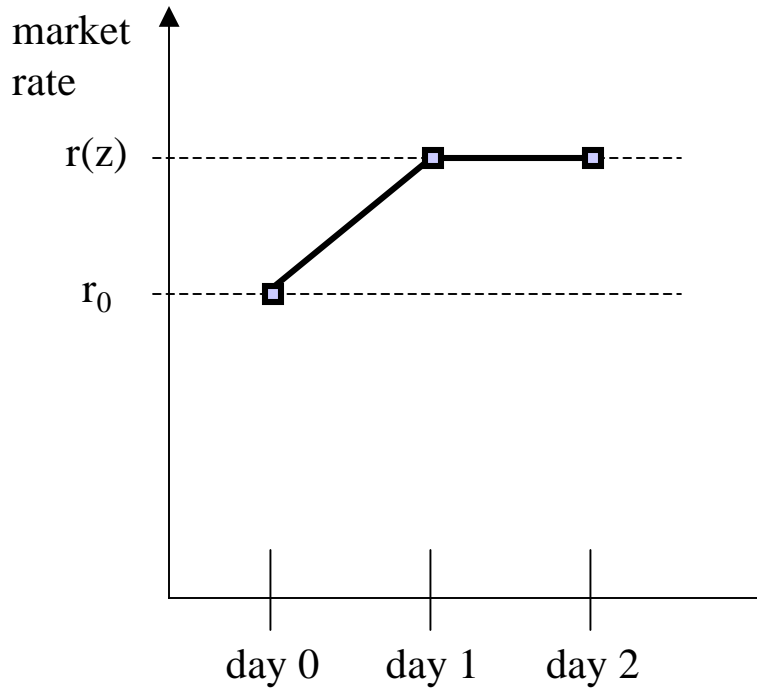
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Non-strategic
behavior of bank A



Strategic
behavior of bank A

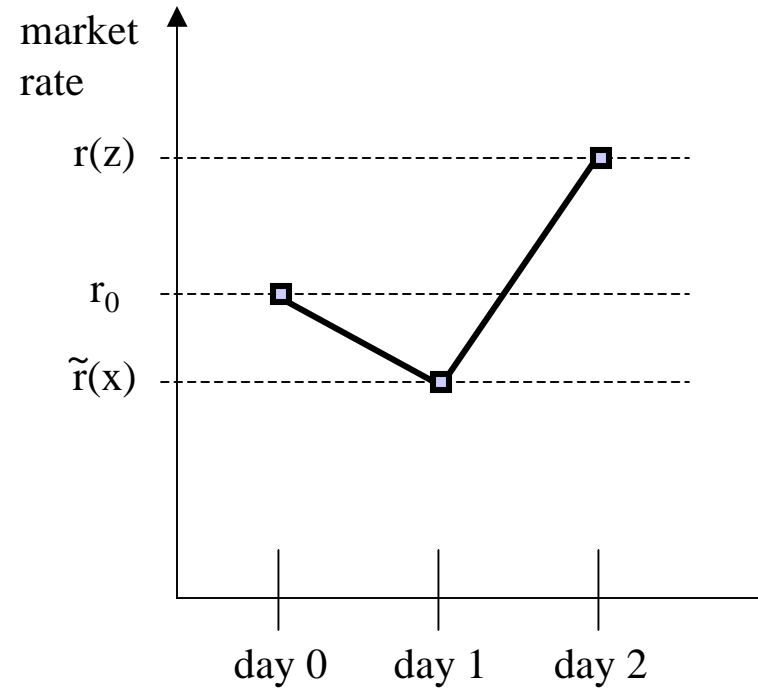


Figure 1. Volatility of the market rate; example: liquidity drainage.

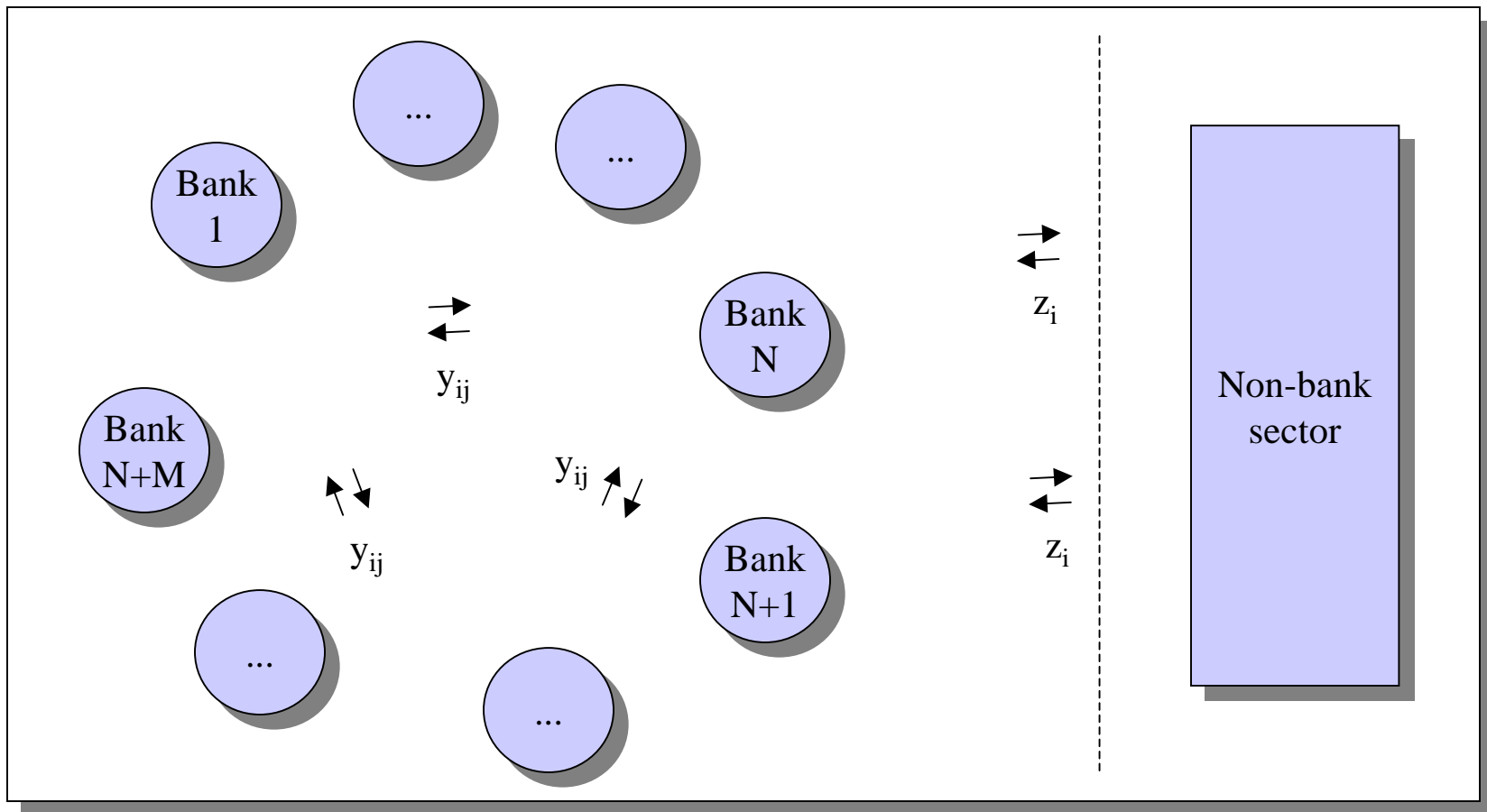


Figure 2. The generalized model.

First session: tight liquidity conditions																
		AccBal	AccBal	Shock	AccBal	AccBal	Shock	AccBal	AccBal	Shock	AccBal	AccBal	Shock	AccBal	AccBal	TotSh
		Morning	Evening		Morning	Evening		Morning	Evening		Morning	Evening		Morning	Evening	
Bank	ResRq	Mo	Mo	Mo-Tu	Tu	Tu	Tu-We	We	We	We-Th	Th	Th	Th-Fr	Fr	Fr	Week
1	2.0	1.5	2.0	0.3	1.8	2.4	-0.4	1.4	1.3	0.4	1.8	2.0	-0.5	1.3	1.7	-0.2
2	2.0	1.7	1.9	-0.4	1.3	2.1	0.3	1.6	2.0	-0.5	1.1	1.7	0.4	1.5	1.8	-0.2
3	1.0	1.1	1.2	0.2	1.3	0.7	-0.2	1.1	1.0	0.1	1.2	0.9	-0.3	0.9	0.7	-0.2
4	1.0	1.2	1.0	-0.3	0.9	0.9	0.2	1.1	0.9	-0.2	0.9	0.8	0.1	1.0	1.1	-0.2
5	1.0	1.3	1.0	0.1	1.4	0.9	-0.3	1.1	1.3	0.2	1.3	0.9	-0.2	1.1	0.8	-0.2
6	1.0	1.4	1.0	-0.2	1.2	0.9	0.1	1.3	1.1	-0.3	1.0	1.0	0.2	1.2	0.9	-0.2
Total	8.0	8.2			7.9			7.6			7.3			7.0		
Delta				-0.3			-0.3			-0.3			-0.3			-1.2
Second session: loose liquidity conditions																
		AccBal	AccBal	Shock	AccBal	AccBal	Shock	AccBal	AccBal	Shock	AccBal	AccBal	Shock	AccBal	AccBal	TotSh
		Morning	Evening		Morning	Evening		Morning	Evening		Morning	Evening		Morning	Evening	
Bank	ResRq	Mo	Mo	Mo-Tu	Tu	Tu	Tu-We	We	We	We-Th	Th	Th	Th-Fr	Fr	Fr	Week
1	2.0	2.5	2.2	-0.3	2.2	2.2	0.4	2.6	2.2	-0.4	2.2	2.2	0.5	2.7	2.2	0.2
2	2.0	2.3	1.8	0.4	2.7	1.8	-0.3	2.4	1.9	0.5	2.9	2.3	-0.4	2.5	2.4	0.2
3	1.0	0.9	1.1	-0.2	0.7	1.0	0.2	0.9	1.0	-0.1	0.8	1.0	0.3	1.1	1.1	0.2
4	1.0	0.8	0.8	0.3	1.1	1.0	-0.2	0.9	1.0	0.2	1.1	1.1	-0.1	1.0	1.1	0.2
5	1.0	0.7	0.8	-0.1	0.6	1.2	0.3	0.9	1.2	-0.2	0.7	1.1	0.2	0.9	1.3	0.2
6	1.0	0.6	1.1	0.2	0.8	0.9	-0.1	0.7	1.1	0.3	1.0	1.0	-0.2	0.8	0.9	0.2
Total	8.0	7.8			8.1			8.4			8.7			9.0		
Delta				0.3			0.3			0.3			0.3			1.2

Figure 3. Liquidity shocks.

TICKET		
for an overnight credit		
Lender:	Bank 1	
Borrower:	Bank 2	
Amount:	0.1	bn €
Interest rate:	2.40	%
Stamp (Market Organizer):	03.01.	04:35

Figure 4. The figure shows a (translated) ticket that documents a credit contract between Bank 1 and Bank 2, where Bank 1 provides the credit and Bank 2 receives the credit. The amount is 0.1 bn € and the interest rate 2.40%. The stamp says that this is the third contract on the first day of the trading week, i.e., on Monday. In addition, the market organizer noted the time within the trading day at which the contract has been stamped. In this example, the agreement was documented 4 minutes and 35 seconds after the beginning of the trading period.

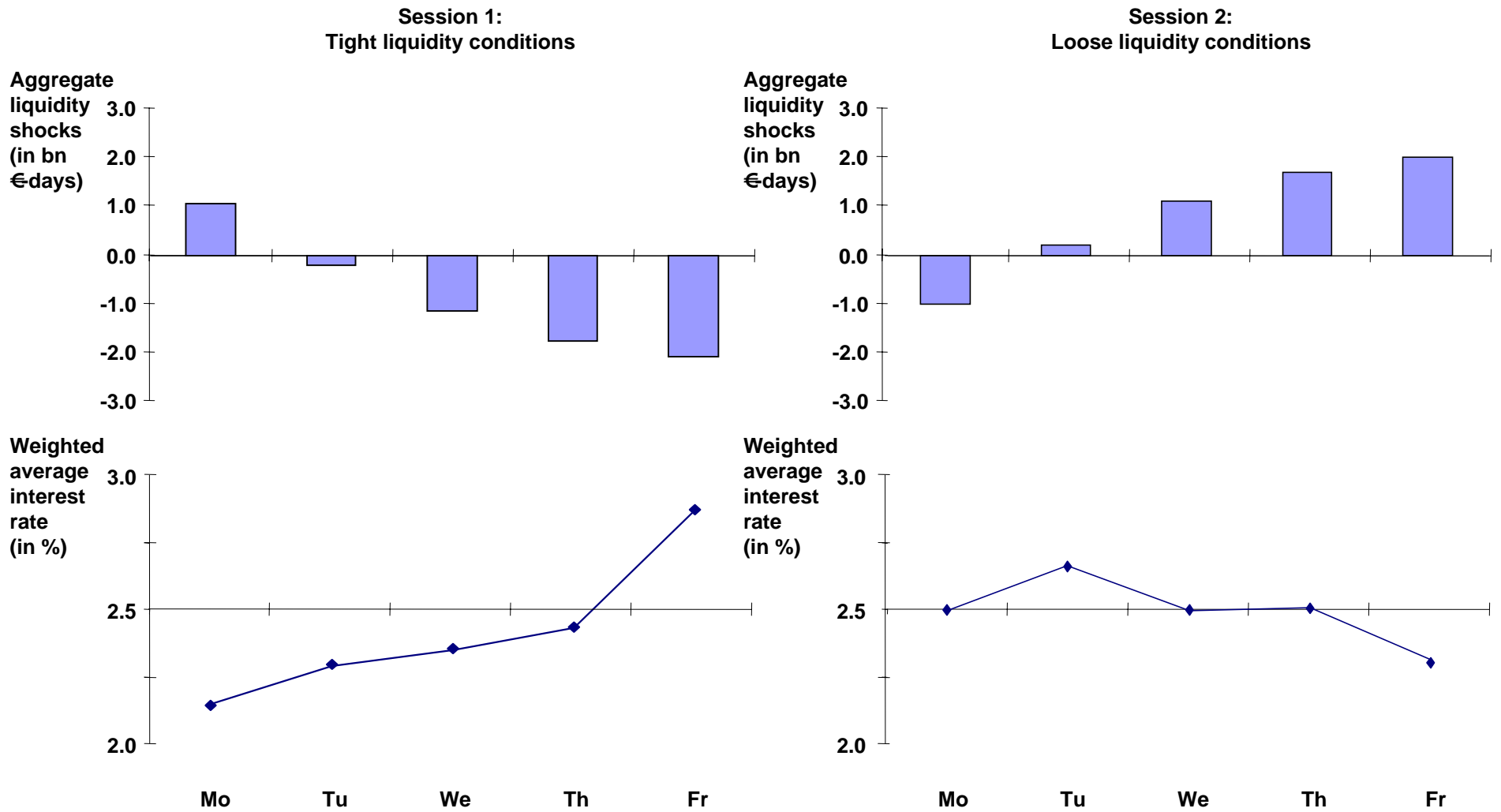


Figure 5. The market rate does not reflect aggregate liquidity conditions

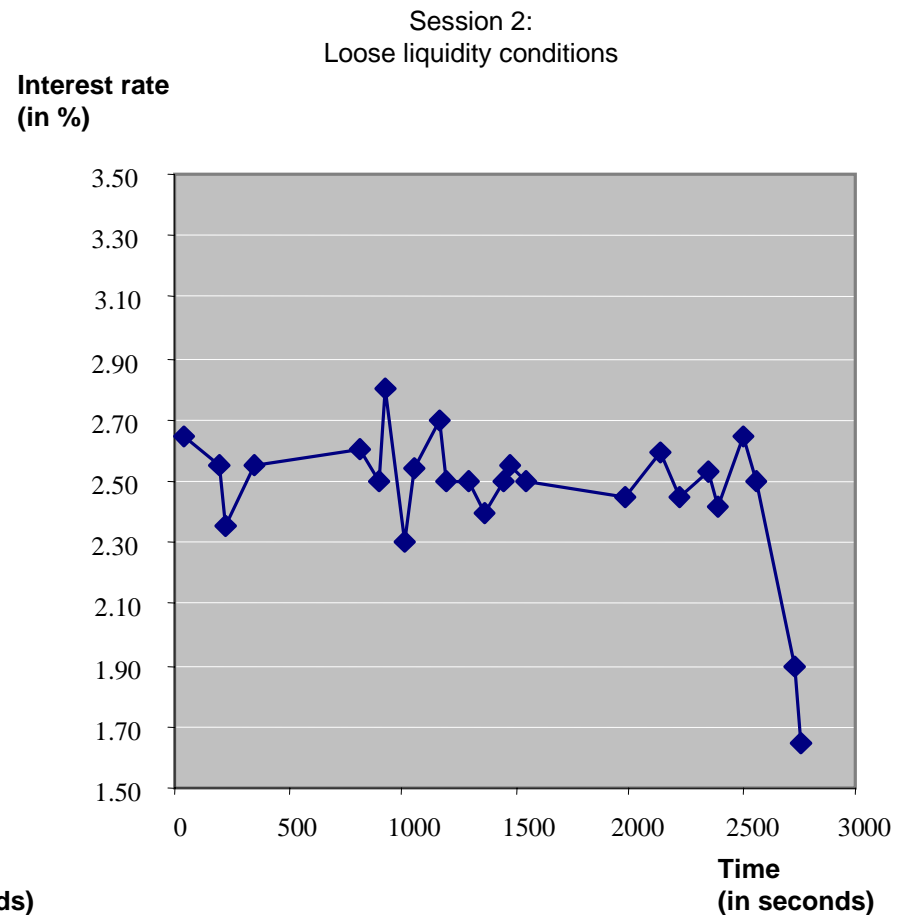
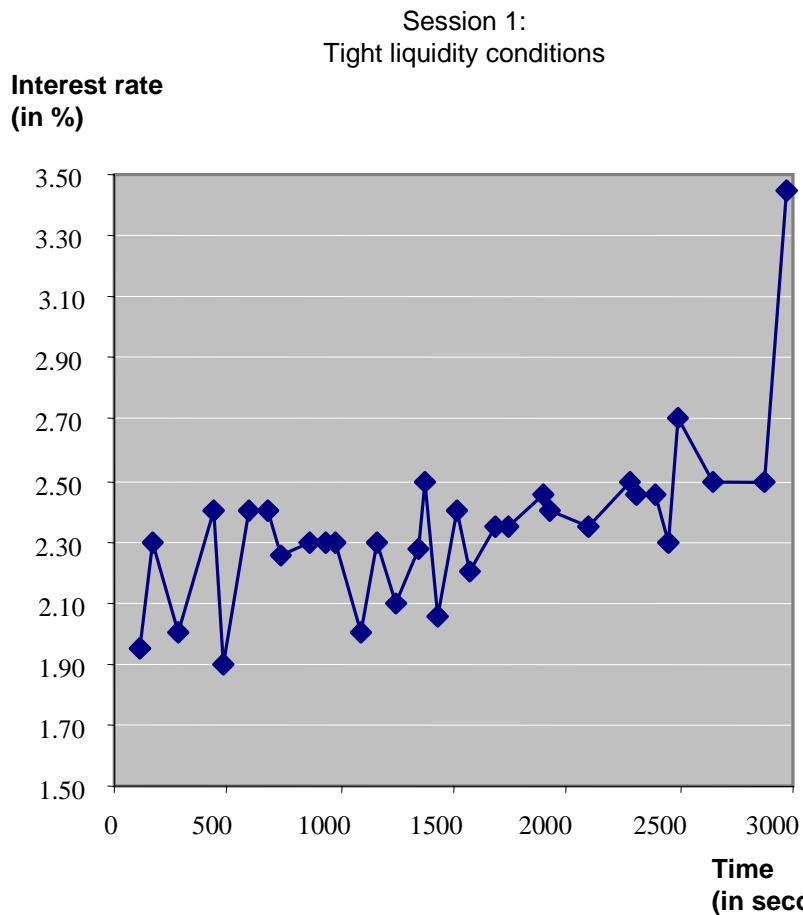
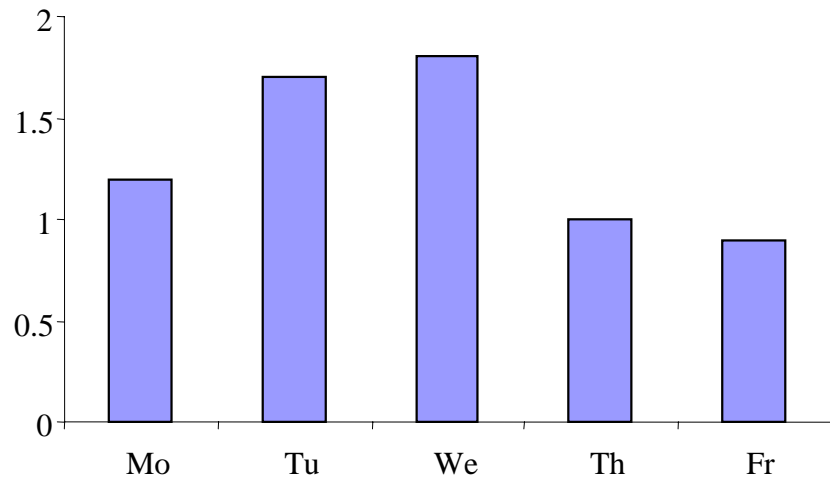


Figure 6. Slow learning of aggregate liquidity conditions before final surprise. The figure shows the development of bilaterally contracted trading rates over time.

Session 1:
Tight liquidity conditions

Session 2:
Loose liquidity conditions

Trading volume
(in bn €)



Trading volume
(in bn €)

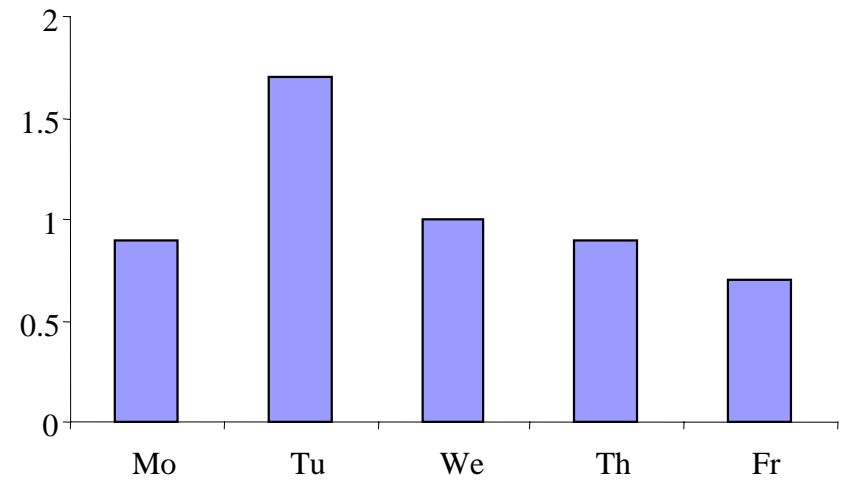
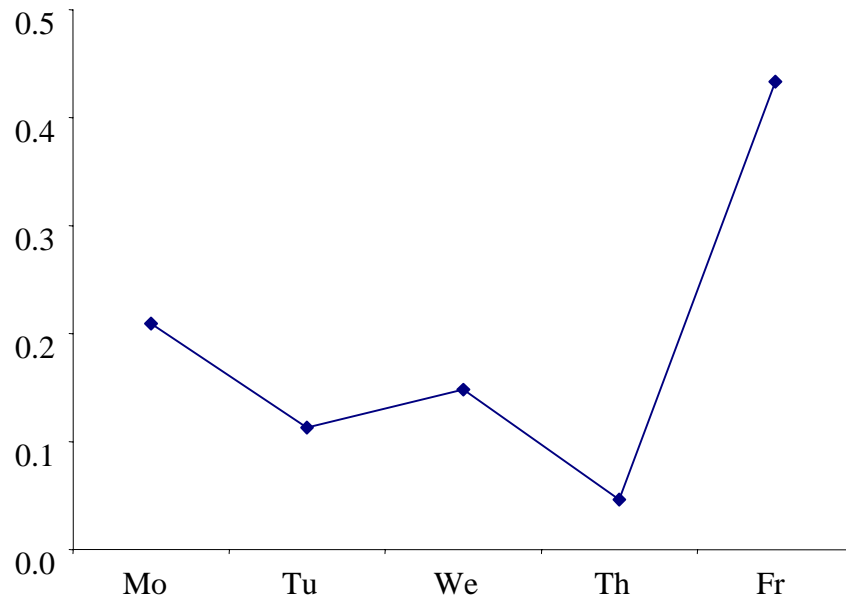


Figure 7. Hump-shaped trading volume.

Session 1:
Tight liquidity conditions

Weighted average
standard deviation
(in %)



Session 2:
Loose liquidity conditions

Weighted average
standard deviation
(in %)

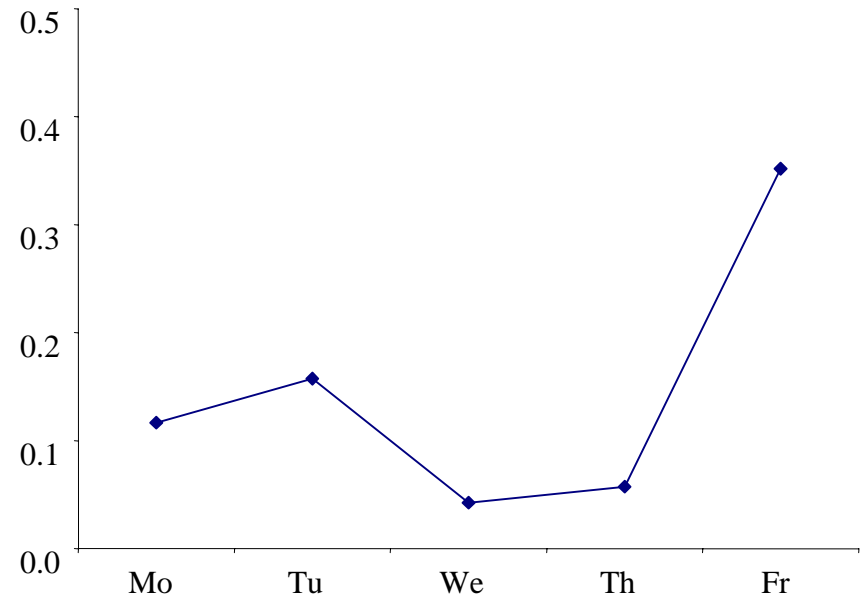


Figure 8. Price dispersion decreases during initial learning period and increases dramatically on the last day.

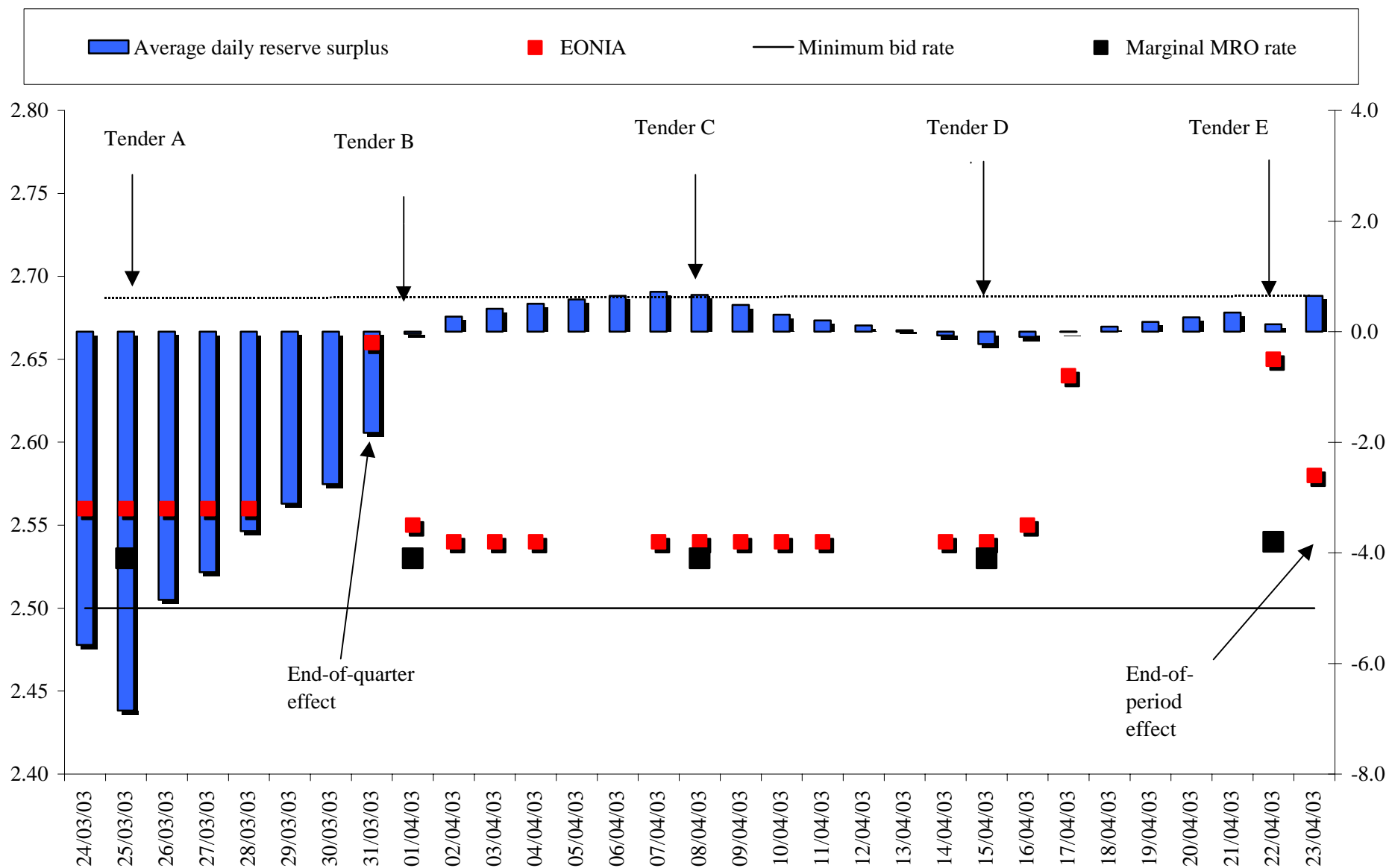


Figure 9. Liquidity conditions and interest rates during the maintenance period March 24 - April 23, 2003.

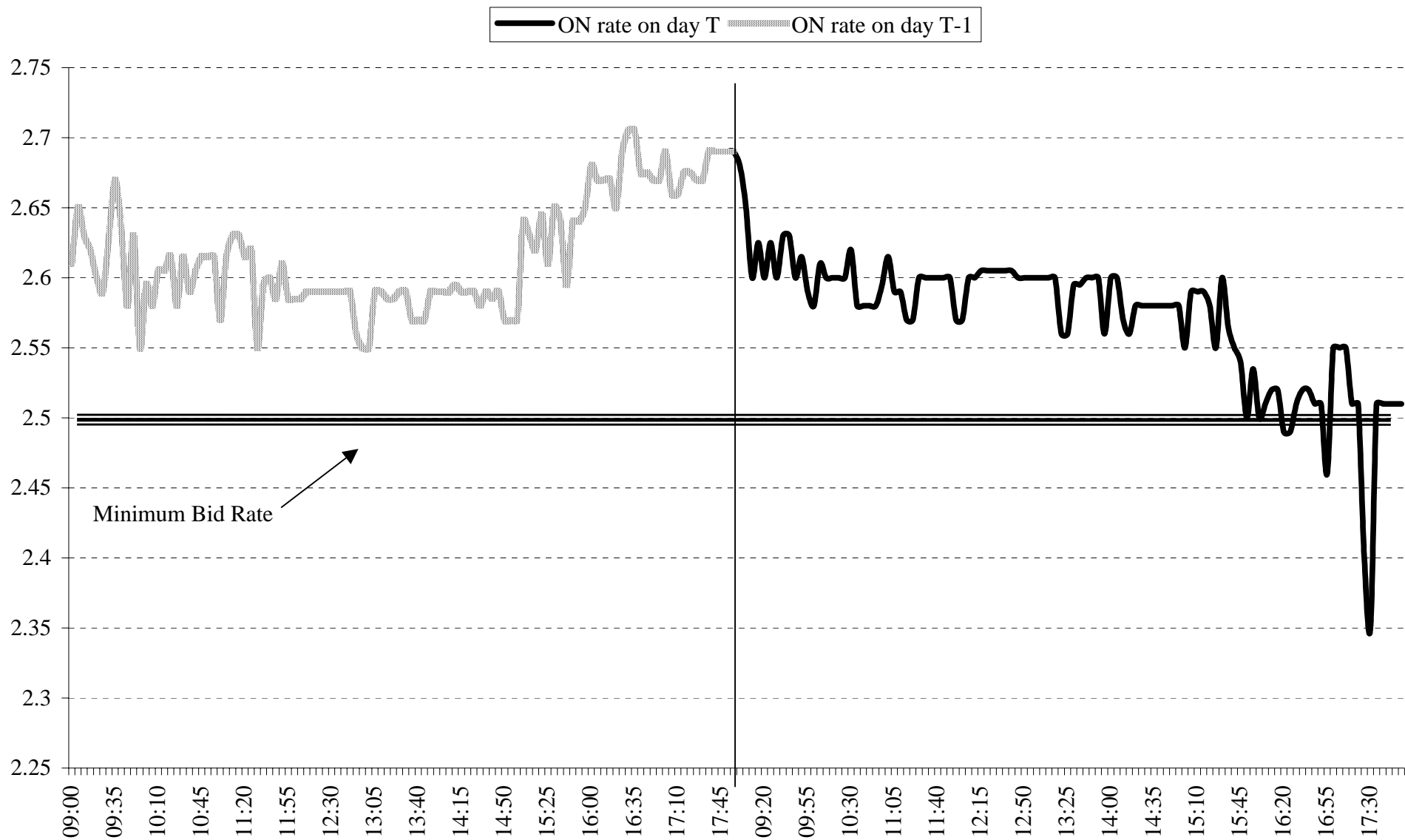


Figure 10. EONIA during the last two days of the maintenance period ending April 23, 2003.

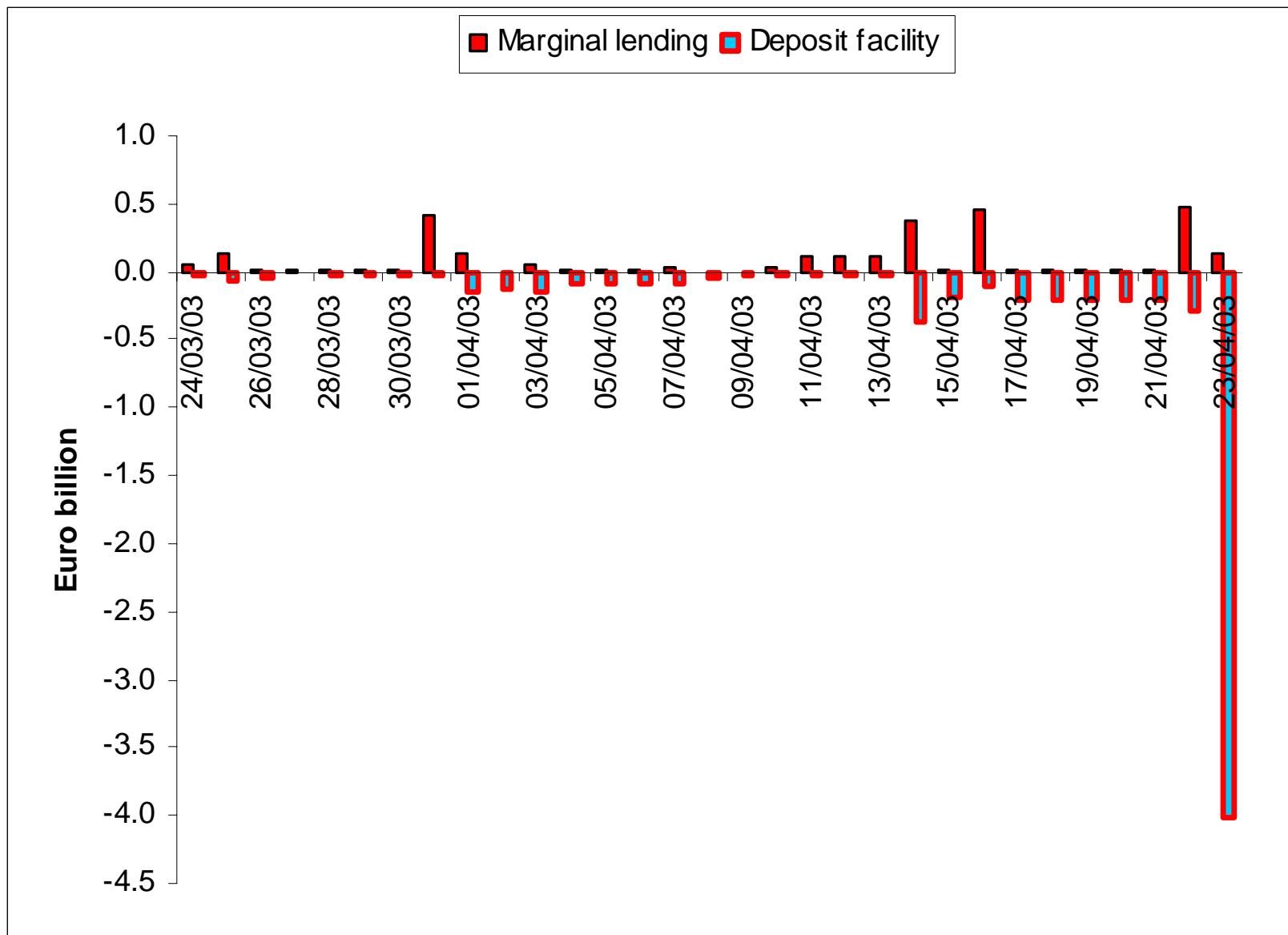


Figure 11. Daily recourse to the standing facilities in the maintenance period ending April 23, 2003.