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Abstract

This paper examines whether there is a liquidity effect in the Japanese interbank market for overnight loans. If the reserve requirement is the only reason for banks to hold reserves, then the demand for reserves should be infinitely elastic at the overnight rate that is expected to prevail for the rest of the reserve maintenance period. If, however, reserves are also useful for facilitating transactions between banks, then the demand curve will be downward-sloping as a function of the overnight rate. We say that a liquidity effect exists if the demand curve is downward sloping, not horizontal, at the observed level of reserves. Estimating the slope of the demand curve for reserves must deal with the simultaneity problem because the central bank actively chooses the supply of reserves to guide the overnight rate to a range close to the target rate. This paper estimates the liquidity effect in the Japanese interbank market for overnight loans (the so-called Call market) . The estimation exploits the institutional features, particularly the fact that the rates observed in the morning are forward rates for funds deliverable at 1pm of the day. The results indicate that the large injection of reserves by the Bank of Japan after the Yamaichi debacle was not enough to eliminate the liquidity effect. The evidence found in this paper is consistent with the view that the Desk behaved optimally before and after the Yamaichi debacle.

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1 Introduction

Most economists believe that there is a negative short-run relationship between monetary aggregates and interest rates. This effect — called the liquidity effect — is surprisingly difficult to verify in data.[1] This paper examines whether a liquidity effect exists between bank reserves and the overnight rate in Japan using daily and intra-day data.

To define the term liquidity effect, suppose initially that the only reason banks hold reserves is to meet reserve requirements. Then, since the required reserve is the one-month total, not how the total is distributed between days within the maintenance period, daily reserves are perfect substitutes within the period. It then follows that the demand for reserves for any day other than the settlement day (the last day of the reserve maintenance period) is perfectly elastic at the expected overnight rate. Therefore, the actual overnight rate for the day should be equal to the expected overnight rate, and the daily overnight rate should follow a martingale. Any additional supply of reserves by a central bank, as long as it does not affect the expected rate, will not affect the overnight rate.

Since most payments between banks are settled by exchange of funds held in banks's reserve accounts at the central bank, banks would hold a certain amount of reserves even if there were no legal requirements. This transactions demand would be a decreasing function of the overnight rate. Put differently, the marginal benefit of holding additional reserves should decline as the reserve balance increases. The case considered in the previous paragraph can be interpreted as one where the actual reserve balance needed to meet reserve requirements is so large that the marginal benefit has declined to zero. If there is a liquidity effect in the sense that the marginal benefit is positive at the observed balance, then the overnight rate will not follow a martingale and an additional supply of reserves by the central bank will depress the overnight rate.

As will be shown in Section 5, the daily overnight rate in Japan (called the Call rate) does not follow a martingale. We can therefore conclude that there exists a liquidity effect in the Japanese interbank market for overnight loans. However, this finding is of limited importance, because interbank settlement is on a net basis with most payments occurring at 1pm, not the end of the day (5pm) when reserves are credited toward required reserves.[2] The rejection of the martingale hypothesis simply means that there is a liquidity effect for the 5pm balance; it has no implication

[1] For example, Leeper and Gordon (1992) uses monthly data on the Federal Funds rate and base money growth to examine the liquidity effect. For a recent study using Japanese data, see Miyao (1999).

[2] About 70% of all the payments are at 1pm (see, e.g., Miyanoya (2000)). This explains why the required reserve ratio (currently 1.3%) in Japan is so low compared to the 10% ratio in the U.S. where interbank settlements are on a real-time, gross basis.

for the liquidity effect for the 1pm reserve balance.

Section 6 of the paper develops a model of reserve management, explicitly taking account of the fact that there are multiple settlement points. It will be shown that the demand for 1pm reserves is downward-sloping for the overnight rates above the rate expected to prevail at 5pm and is infinitely elastic at the expected rate. Therefore, to see whether a liquidity effect exists at 1pm, we need to estimate the slope of the demand curve for the 1pm reserve balance. The estimation must take into account the simultaneity problem due to the fact that the the central bank actively supplies reserves through open market operations to influence the overnight rate. A recent study of the liquidity effect in the U.S. Federal Funds market by Hamilton (1997) addresses this problem by using unexpected changes in the Treasury balance as an instrument. We can certainly apply the same idea to the Japanese interbank market, but the slope estimate is extremely unreliable due to weak correlation between the instrument and the balance at 1pm. In this paper, we overcome the simultaneity problem differently, by exploiting the fact that the morning overnight rates are really a forward rate for funds deliverable at 1pm.

Figure 1 plots the uncollateralized overnight rate averaged over the day with volume used as weights since 1996. There are several spikes occurring at the ends of September and March, and dips occurring at settlement days (15th of each month). Excluding those seasonalities, it appears that there is not much variation in the daily overnight rate. In particular, since March 1999, the rate is a constant at 3 basis points. But this masks the intra-day variation. Figure 2 plots the rates observed at 9am and 3:30pm. The figure makes clear that there is substantial variation, particularly after November 1997 when three prominent financial institutions — Hokkaido Takushoku Bank, Sanyo Securities, and most notably Yamaichi Securities — ceased to opearte.

The estimation of the liquidity effect will be carried out in Section 7. As a preparation, the preceding sections will do the following. Section 2 will quickly review the pertinent institutional features of the Japanese interbank market. Section 3 will test the rationality of forecasts of two components of changes in reserves, which are published by the Bank of Japan (BOJ). These forecasts will be used in the estimation of the liquidity effect. Section 4 will examine the policy reaction function of the BOJ's open market Desk. The findings of this section will be used in an essential way in the estimation. That the overnight rate does not follow a martingale is shown in Section 5. Section 6 then develops a model of reserve management with multiple points of settlement. The implied demand curve for reserves will be estimated in Section 7. Section 8 collects the conclusions of the paper.

2 The Japanese Interbank Market

This section is a brief review of pertinent aspects of the Japanese interbank market. Most symbols to be used in this paper are introduced here.[3]

2.1 The Required Reserve System and Market Operations by the Bank of Japan

All depository institutions (to be called banks in this paper), as in many other countries, are subject to reserve requirements on their customers' deposits. Unlike the U.S. system, banks hold required reserves only as deposits at the BOJ; vault cash is not counted as reserves. Another difference from the U.S. is that the reserve maintenance period is a month and lags behind the accounting period by two weeks. Let REQ be the cumulative sum of required reserves. If R_t is the reserve balance at the end of day t of the current reserve maintenance period and if $CUMBAL_t$ is its cumulative sum, then by definition,

$$CUMBAL_t \equiv c_1 R_1 + c_2 R_2 + \cdots + c_t R_t \tag{2.1}$$

Here, c_t is the factor that converts a weekday into calendar days. For example, if the t-th working day of the reserve maintenance period is not followed by a holiday or a weekend, we have $c_t = 1$; if it is a Friday and if the following Monday is not a holiday, then $c_t = 3$. If the settlement day is the T-th day of the period, the reserve requirement can be written as

$$CUMBAL_T \geq REQ. \tag{2.2}$$

For an individual bank, a change in its reserves consists of four factors: (i) transfers of funds with other banks holding deposits at the BOJ, (ii) transfers of funds with institutions having deposits at the BOJ that are not subject to the reserve requirement (e.g., the government), (iii) cash deposited to the BOJ, and (iv) financial transactions other than (iii) with the BOJ (e.g., a sale of government securities to the BOJ). For banks as a whole, since the net amount of (i) is zero, a change in R_t is the sum of (ii), (iii), and (iv). In BOJ publications, item (ii) is called the *fiscal factor*, (iii) is called the *cash factor*, and (iv) is open market operations. For example, if a corporation pays an income tax to the government by having its bank transfer the amount to the account held by the government at the BOJ, then it is an debit item in the fiscal factor. The fiscal factor includes foreign exchange interventions by the government.

[3] For further details of the materials of this section, particularly those relating to the change in the definition of the BOJ publications effective March 16, 2000, see Miyanoya (2000).

Let $CASH$, $FISCAL$ be the cash and fiscal factors, respectively. If the amount of open market operations is $OPER$, the identity describing the change in (aggregate) reserves can be written as[4]

$$CASH_t + FISCAL_t + OPER_t = R_t - R_{t-1}, \tag{2.3}$$

The Bank of Japan releases its forecast of $CASH_t$ and $FISCAL_t$ (denoted $ECASH_t$ and $EFISCAL_t$) at 5:30pm on the working day before day t and actual values of $CASH_t$ and $FISCAL_t$ at the same time on day t.[5]

As in the U.S., open market operations can be divided into two kinds: outright purchases or sales of government securities and repurchase agreements (RPs). Unlike the Fedwire, which is the wholesale payment system operated by the Fed, the Japanese system of interbank settlement (called the BOJ net), is on a net basis, with netting at several points during the day (1pm, 3pm, and 5pm). Therefore, three time points characterize an RP operation: (1) the day the RP operation is notified to the dealers and an auction is held, (2) the delivery time and day (to be referred to in this paper (and also in BOJ publications) as the *start*), and (3) the time and day of maturity (the *end*). An outright transaction has no *end*. Those operations whose *start* is on the date of notification are called *same-day operations*. All other operations will be called *pre-arranged operations*. Most same-day operations are notified at 9:20am and its *start* is 3pm. Additional same-day operations, if any, are usually notified between 9:30am and 11am and have a *start* of 3pm. Those notified at about 12:10pm have a *start* of 5pm.[6] Therefore, the market operation factor in the identity (2.3)

[4] Effective March 16, 2000, in BOJ publications, deposits held by financial institutions that are not subject to reserve requirements (such as the brokers in the interbank market), are included in R_t, so that its changes are no longer included in $FISCAL_t$ (Miyanoya (2000)). Before the advent of zero interest rates, deposits at the BOJ held by those financial institutions were small. Anyway, our analysis is about the period before March 1999, and R_t in our analysis and also in the BOJ publications is deposits at the BOJ held by banks (i.e., financial institutions subject to reserve requirements).

[5] Actually, the figures for day t released on the day are preliminary estimates, but they are essentially a rounded values of the actual figures to be released on day $t+1$. They are so close that the BOJ stopped releasing actual figures effective March 16, 2000.

[6] Same-day operations for delivery at 5pm are used to drain reserves so that $CUMBAL_t$ equals REQ on the settlement day. However, since November 1997, the time of the Yamaichi debacle, those operations are also used on a daily basis to drain reserves that were previously supplied for the 1pm settlement time. For more details (in Japanese) of BOJ operations, see Miyanoya (2000, Section 3.6).

above can be divided into four components:

$$\begin{aligned} OPER_t = OPER_{0t} &\quad \text{(pre-arranged operations whose } \textit{start} \text{ or } \textit{end} \text{ is on date } t\text{)} \\ + OPER_{1t} &\quad \text{(same-day operations notified at 9:20am, with a } \textit{start} \text{ of 3pm)} \\ + OPER_{2t} &\quad \text{(additional same-day operations with a } \textit{start} \text{ of 3pm)} \\ + OPER_{3t} &\quad \text{(additional same-day operations with a } \textit{start} \text{ of 5pm).} \end{aligned} \tag{2.4}$$

It will become relevant for later discussion that same-day operations cannot affect the reserve balance at 1pm, because their *start* (delivery time) is either 3pm or 5pm.

2.2 A Market Pressure Indicator

There is an indicator of reserve abundance, published by the BOJ and closely watched by the market. For lack of better term, we will call this indicator the *reserve surplus*.[7] To define this indicator, let m_t be defined by

$$\begin{aligned} m_t &= \text{calendar days (including today) left in the current maintenance period} \\ &= c_t + c_{t+1} + \cdots + c_T. \end{aligned} \tag{2.5}$$

Here, c_t is the factor that converts working days to calendar days. Therefore, the number of calendar days *excluding* today is m_{t+1} and the average reserve balance to be maintained in the rest of the maintenance period is $(REQ - CUMBAL_t)/m_{t+1}$ per calendar day. The *ex-post reserve surplus* is defined as the difference between the reserve balance at the end of the day and this average required balance:[8]

$$\text{ex-post reserve surplus for day } t = R_t - \frac{REQ - (CUMBAL_{t-1} + c_t R_t)}{m_{t+1}}. \tag{2.6}$$

If R_t cannot be observed until the day's end, one can calculate its ex-ante value using the forecast of each factor in the identity (2.3). At the time most same-day operations are notified (at 9:20am), given $ECASH_t$ and $FISCAL_t$, the implied value of R_t can be calculated as

$$R_{nt} \equiv R_{t-1} + ECASH_t + EFISCAL_t + \sum_{i=0}^{n} OPER_{it} \qquad (n = 1, 2, 3). \tag{2.7}$$

Likewise, $CUMBAL_t$ can be calculated by multiplying R_{nt} by c_t adding $CUMBAL_{t-1}$ to it. A forecast of reserve surplus that results from the forecasts of R_t and $CUMBAL_t$ thus obtained is

[7]This indicator makes sense only if the overnight rate is positive. For this reason, the BOJ stopped publishing it after March 15, 2000.

[8]This cannot be defined for the settlement day (the last day of the maintenance period) because $m_{t+1} = 0$. The BOJ calculates the reserve surplus for the settlement day using the different formula (2.12) below.

the *ex-ante reserve surplus*:

$$Z_{nt} \equiv \text{ex-ante reserve surplus for date } t \text{ at point } n = R_{nt} - \frac{REQ - (CUMBAL_{t-1} + c_t R_{nt})}{m_{t+1}}. \tag{2.8}$$

As noted above, after the Yamaichi debacle, the BOJ routinely conducted additional same-day operations after 9:20am. Therefore, Z_{1t}, which is the ex-ante reserve surplus as of 9:20am, is not necessarily a good estimate of the ex-post reserve surplus for the post-Yamaichi period.

For later use, we will rewrite this definition in two ways utilizing the identities

$$m_t = m_{t+1} + c_t, \;\; CUMBAL_t = CUMBAL_{t-1} + c_t R_t. \tag{2.9}$$

A routine algebra shows that Z_{nt} can be rewritten as

$$\begin{aligned} Z_{nt} &= \frac{m_t}{m_{t+1}} R_{nt} - \frac{1}{m_{t+1}} \Big(REQ - CUMBAL_{t-1} \Big) \\ &= \frac{m_t}{m_{t+1}} \left(R_{t-1} + ECASH_t + EFISCAL_t + \sum_{i=0}^{n} OPER_{it} \right) - \frac{1}{m_{t+1}} \Big(REQ - CUMBAL_{t-1} \Big), \end{aligned} \tag{2.10}$$

and also as

$$\begin{aligned} Z_{nt} = \frac{m_{t-1}}{m_{t+1}} & \Big(R_{t-2} + CASH_{t-1} + FISCAL_{t-1} + OPER_{t-1} \Big) \\ & + \frac{m_t}{m_{t+1}} \left(ECASH_t + EFISCAL_t + \sum_{i=0}^{n} OPER_{it} \right) \\ & - \frac{1}{m_{t+1}} \Big(REQ - CUMBAL_{t-2} \Big). \end{aligned} \tag{2.11}$$

In definition (2.8) of the reserve surplus, today's reserve balance is compared to the required average balance for the remaining period excluding today. It may appear that a more natural definition is to compare today's balance with the required balance for the remaining period including today. The definition of Z_t, for example, would be modified as

$$\text{modified reserve surplus} = R_t - \frac{REQ - CUMBAL_{t-1}}{m_t}. \tag{2.12}$$

However, as will be shown in Section 6, the original definition provides a more appropriate measure of the slackness of the market for reserves.

3 Are Forecasts Rational?

In the empirical analysis of Section 7, we will equate the forecasts of the cash and fiscal factors published by the BOJ with those of the market's. In this section, we test whether the BOJ forecasts are rational

The forecasts for day t are released at about 5:30pm of day $t-1$, along with the actual values for day $t-1$. Therefore, the forecast errors should be serially uncorrelated if expectations are rational. The forecast errors for the cash and fiscal factors can be calculated as

$$UCASH_t \equiv CASH_t - ECASH_t, \quad UFISCAL_t \equiv FISCAL_t - EFISCAL_t. \tag{3.1}$$

Figure 3 plots those forecast errors from 1996 to February 12, 1999, where the policy board of the BOJ issued the directive calling for zero interest rates. The figure indicates that the forecast errors are less than 100 billion yen (about 1 billion dollars). The largest forecast error is for the fiscal factor for October 23, 1998, when the LTCB (the Long-Term Credit Bank) was nationalized. On that day, a BOJ uncollateralized loan of 3 trillion yen (about 30 billion dollars) was made to the Depository Insurance Agency, which promptly transferred the amount to the LTCB's account at the BOJ. The amount of the BOJ loan was more or less anticipated; morning editions of newspapers on that day speculated that the amount would be about 2 to 3 trillion yen. Therefore, in the test of rationality, we set the forecast error for the fiscal factor for that day at zero. (This modification of the data, however, didn't change the rest results substantially.)

The test results are in Table 1. The first-order serial correlation coefficient for $UCASH$ is 0.23, which is very statistically significant, and -0.098 for $UCASH_t$, whose t value of 2.7 is also significant. The Ljung-Box Q statistic with 12 lags, too, indicates significant serial correlation. Thus we can easily reject the hypothesis that the forecasts of the cash and fiscal factors are rational.

4 The Reaction Function of the Trading Desk

Figure 4 plots the ex-ante reserve surplus at two time points (given by (2.8) for $n = 1, 3$) from January 4, 1996 to February 12, 1999. For the period before the Yamaichi debacle in November 1997, it hardly changes between the two time points within the day because there were very few same-day additional operations. In the post-Yamaichi period, there is a substantial difference because same-day additional operations are used to drain large amount of funds that were made available through pre-arranged operations to build up a reserve balance at 1pm. This feature can be seen more clearly in Figure 5, where the average net inflows to reserves due to the BOJ market operations at three settlement times are shown.

In BOJ publications (see e.g., Miyanoya (2000)), the ex-ante reserve surplus is viewed as the monetary policy instrument. This section estimates the policy reaction function for the reserve surplus. The nature of market operations characterized by the estimated reaction function will become relevant when we estimate the liquidity effect in Section 7.

4.1 Reserve Surplus at 9:20am

We utilize the following specification of the reaction function:

$$\begin{aligned} Z_{nt} = \psi_0 + \psi_1 Z_{n,t-1} \\ &+ \psi_2 \cdot \left(\frac{m_t}{m_{t+1}} ECASH_t \right) + \psi_3 \cdot \left(\frac{m_t}{m_{t+1}} EFISCAL_t \right) \\ &+ \psi_4 \cdot \left(\frac{m_{t-1}}{m_{t+1}} UCASH_{t-1} \right) + \psi_5 \cdot \left(\frac{m_{t-1}}{m_{t+1}} UFISCAL_{t-1} \right) \\ &+ \psi_6 \cdot (i_{1t} - BENCH_t) \\ &+ \psi_7 \cdot MARCH_t + \psi_8 \cdot MARCH_{t-1} + \psi_9 \cdot SEPT_t + \psi_{10} \cdot SEPT_{t-1}. \end{aligned} \tag{4.1}$$

Here, m_t is remaining calendar days defined in Section 2, Z_{nt} is the ex-ante reserve surplus in question (Z_{1t} in this subsection), $ECASH_t$, $EFISCAL_t$, $UCASH_{t-1}$ and $UFISCAL_{t-1}$ are the forecasts and associated forecast errors for the cash and fiscal factors defined in the previous section, i_{1t} is the overnight rate as of 9am,[9] $BENCH_t$ is the target rate specified in the most recent directive (0.5% until September 10, 1998 and 0.25% until February 12, 1999), $MARCH_t$ is a dummy variable for the end of March, $SEPT_t$ is a dummy for the end of September. The reason lagged as well as current values of those dummies are included in the regression is simply that the lagged dependent variable (Z_{t-1}) is included in the regression. *ECASH*, *EFISCAL*, *UCASH*, and *UFISCAL* enter the regression with multipliers $\frac{m_t}{m_{t+1}}$ and $\frac{m_{t-1}}{m_{t+1}}$ because, as clear from (2.11), the cash and fiscal factors affect the reserve surplus with those multipliers. The reserve surplus, cash and fiscal factors are in 100 billion yen (about one billion dollars), and the rates are in basis points. The trading Desk can observe the values of all the regressors in (4.1) at 9:20am when it notifies the dealers.

In the estimation of the reaction function, reported in Table 2, we take into account the following.

1. The whole sample period of January 4, 1996 to February 12, 1999 is divided into two subperiods before and after the Yamaichi debacle of November 27, 1997 because, as clear from Figure 4, there is a change in policy regime.

[9] Real-time information on the overnight rate is available through commercial vendors. The data used here were compiled from real-time data by the BOJ. The compiled data have rates at seven points in time (9am, 10am, 11:30am, 12:30am, 1:30pm, 2:30pm, and 3:30pm). i_{1t} is the 9am rate.

2. The sample period includes over 30 reserve maintenance periods, which implies that the data is really an (unbalanced) panel. However, it is well known that pooled OLS is efficient when the error has no serial correlation.[10] The Breusch-Godfrey statistic for serial correlation (with 5 lags),[11] shown in the last column of the table, does indicate statistically significant serial correlation for either subsample, but we decided not to correct for serial correlation in calculating standard errors because the first-order serial correlation coefficient of the errors is between 0.06 and 0.13.

3. As mentioned in Section 2, the reserve surplus cannot be defined for settlement days. So settlement days are dropped from the sample. This necessitates us to drop the first days of maintenance periods because the regression has a lagged dependent variable.

4. It doesn't affect the results reported in Table 2(a) how we treat the large forecast error for the fiscal factor associated with the nationalization of the LTCB. The results reported in Table 2(a) are based on the data that leave the 3 trillion yen forecast error as is.

5. In the post-Yamaichi subsample, the reserve surplus exhibits large swings. The OLS estimates may be sensitive to those extreme values. To address this issue, we estimated the reaction function also by maximum likelihood for the following error specification. Let ζ_t be the error term of the reaction function. We assume that the distribution of ζ_t is given by[12]

$$\zeta_t = \sigma v_t, \quad \text{the density of } v_t \text{ is } \; f(v_t) = \frac{1-p}{\sqrt{2\pi}} \exp\left(-\frac{v_t^2}{2}\right) + \frac{p}{\sqrt{2\pi}\tau} \exp\left(-\frac{v_t^2}{2\tau^2}\right). \qquad (4.2)$$

That is, v_t is drawn from a mixture of normal distributions. With probability $1-p$ it is $N(0,1)$ and with probability p it is normal with variance τ^2. If $p > 0$ and τ^2 is far greater than 1, then this is useful for capturing both the frequent small values and occasional large values. The ML (maximum likelihood) estimate of the model for the post-Yamaichi period is in Appendix Table 1.[13]

[10] See, e.g., Hayashi (2000, Chapter 5).

[11] For the Breusch-Godfrey statistic, see, e.g, Hayashi (2000, Chapter 2).

[12] The model estimated by Hamilton (1997) is more general than this because he allows σ to be time-dependent.

[13] For the pre-Yamaichi period, it was not possible to obtain convergence in an ML iterative procedure. As clear from Figure 4, there are no extreme values in the pre-Yamaichi period, making it possible to fit a mixture with different variances. To obtain ML estimates reported in the table and also in Table 3 on, we used as the initial values for the regression coefficients their OLS estimates. For τ and p, we used two different initial values, $((\tau = 1.2, p = 0.9), (\tau = 4, p = 0.1))$. For σ, the initial value is such that the standard deviation of ζ_t implied by (4.2) and the assumed initial values for τ and p is equal to the OLS standard error of the regression. Both starting points produced the same ML estimates.

Regression #1 and #3 in Table 2(a) reports the estimates by pooled OLS for two subsamples. Several features are noteworthy.

(i) In either subsample, $\frac{m_t}{m_{t+1}} ECASH_t$ and $\frac{m_t}{m_{t+1}} EFISCAL_t$ are not significantly different from zero. This implies that the Desk conducted open market operations to offset anticipated changes in the cash and fiscal factors. This can be accomplished by conducting same-day open market operations at 9:20am in amounts equal to the negative of the anticipated changes.

(ii) In the pre-Yamaichi period, same-day additional operations were very rare and the Desk allowed the day's reserve balance to be affected by unexpected changes in the cash and fiscal factors. If the Desk does not react to those unexpected changes the next day, it will affect the reserve surplus for the next day. That is, in (2.11), the expected components of $CASH_{t-1}$ and $FISCAL_{t-1}$ are offset by 9:20am same-day operations on date $t-1$. Z_{nt} would be affected if the Desk did not respond to the unexpected components of $CASH_{t-1}$ and $FISCAL_{t-1}$ by offseting same-day operations on date t. The insignificance of the coefficients of $\frac{m_{t-1}}{m_{t+1}} UCASH_{t-1}$ and $\frac{m_{t-1}}{m_{t+1}} UFISCAL_{t-1}$ in regression #1 indicates that the Desk in fact conducted offsetting operations the following day. In the corresponding regression (regression #3) for the post-Yamaichi period, the $UCASH_{t-1}$ coefficient is large but not significantly different from zero. We conclude that for either subsample, $UCASH_t$ and $UFISCAL_t$ are *temporary* liquidity shocks that last only a day.

(iii) The coefficient of the lagged dependent variable is about 1, which means that the Desk tried to smooth reserve surplus.

(iv) The coefficient of $i_{1t} - BENCH_t$ measures the Desk's reaction to the opening rate of the day. The estimate for the post-Yamaichi period implies that a one basis point increase in the overnight rate prompts the Desk to increase reserves by 33 billion yen (about 330 million dollars), which is about 7 times as large as the amount for the pre-Yamaichi period.

(v) As seen from regressions #2 and #4, unexpected cash and fiscal changes for the day, $\frac{m_t}{m_{t+1}} UCASH_t$ and $\frac{m_t}{m_{t+1}} UFISCAL_t$, are not significant. When arranging operations, the Desk does not observe the cash and fiscal factors of the day.

4.2 Reserve Surplus as of 12:10pm

We now turn to reserve surplus as of 12:10pm (Z_{3t} in (2.8)), which were so much different from Z_{1t} in the post-Yamaichi period. To see whether the Desk responds to the day's cash and fiscal factors, we include $\frac{m_t}{m_{t+1}} UCASH_t$ and $\frac{m_t}{m_{t+1}} UFISCAL_t$. We also include $(i_{2t} + i_{3t})/2 - BENCH_t$ (where i_{2t}, i_{3t} are the rate at 10am and 11:30am). Table 2(b) shows the estimate for the post-Yamaichi period. As in the reaction function for Z_{1t}, the coefficients of $\frac{m_t}{m_{t+1}} ECASH_t$ and $\frac{m_t}{m_{t+1}} EFISCAL_t$ are close to zero, as expected. Furthermore,

(vi) The day's unexpected fiscal factor ($\frac{m_t}{m_{t+1}} UFISCAL_t$) is not significant (this is more evident in Appendix Table 1). Transfers from the government account at the BOJ to the reserve accounts held by banks take place before noon (and sometimes 3pm), but those from banks to the government are at 3pm. So it is actually not feasible for the Desk to respond to the day's fiscal factor at 12:10pm.[14]

(vii) In contrast, the coefficient of the unexpected cash factor ($\frac{m_t}{m_{t+1}} UCASH_t$) is fairly close to -1. (This is more evident in Appendix Table 1.) Sincde vault cash is not creditable toward required reserves, banks deposit their vault cash as reserves after they close at 3pm. To meet withdrawals by their customers, banks withdraw cash from their reserve accounts at 9am. Therefore, the Desk is in a position to observe the amount of cash withdrawals by noon. The coefficient of -0.84 in the appendix table implies that the Desk was able to offset a substantial portion of the day's cash factor.

(viii) The coefficient of $(i_{2t} + i_{3t})/2 - BENCH_t$ is positive, implying that same-day additional operations are affected by the developments to the overnight rate in the morning.

5 Is the Overnight Rate a Martingale?

We now examine whether the overnight rate follows a martingale. There are several econometric and substantive issues to be resolved in the test.

First, it is not appropriate to use the daily averages of intra-day rates. As will be shown in Section 6, the overnight rate should follow a martingale within each day if there is no liquidity effect. It is well known that an averaged process that results from aggregating to the sampling interval (e.g., a day) is not a martingale even if the underlying process is a martingale (this is the time-aggregation problem). To test the martingale hypothesis, therefore, points-in-time data need to be used.

[14] The large fiscal factor resulting from the nationalization of the LTCB was known in the morning. If $UFISCAL_t$ for that date is set to zero, the OLS estimate in regression #5 changes from -0.19 to -0.78. However, the estimate by ML hardly changes.

Second, there is a question of which settlement point of the day to look at. Our data set has the overnight rates at seven observation points in time (9am, 10:30am, 11:30am, 12:30pm, 1:30pm, 2:30pm, and 3:30pm). Those rates correspond to different delivery points in time. The morning rates (including the rate at 12:30pm) are for delivery at 1pm, the rates between 1pm and 3pm are for delivery at 3pm, and the rates after 3pm are for 5pm delivery. For those rates, the following holds.

(a) Because it is the balance at 5pm that will be credited toward reserves, the overnight rate at 3:30pm is the rate that should follow a martingale.

(b) As will be shown in Section 6 (see (6.20)), the difference between the rate at 12:30pm and the rate at 3:30pm can be interpreted as a liquidity premium attached to a reserve balance at 1pm. If there is no liquidity effect in the 1pm balance, then the difference should be unpredictable.

(c) The morning rates, i.e., the rates at 9am, 10am, 11:30am and 12:30pm, are actually *forward rates* for funds to be delivered at 1pm. Therefore, if expectations are rational, the morning rates should follow a martingale. In particular, the difference between the 12:30pm rate and 9am rate should be unpredictable.

In this section, we test not only the martingale hypothesis for the 3:30pm rate but also whether the change in the rate between 9am and 12:30pm is unpredictable. The issue of estimating the liquidity effect for the 1pm balance will be taken up in Section 7.

Let i_{7t} be the 3:30pm rate in date t of the current maintenance period. Under the martingale hypothesis, the daily change in the 3:30pm rate, $i_{7t} - i_{7,t-1}$, should be uncorrelated with any variable whose value is known at 3:30pm on date $t-1$. We include as the regressors a constant, the lagged change $(i_{7,t-1} - i_{7,t-2})$, and $Z_{3,t-1}$, the reserve surplus as of 12:10pm on date $t-1$.[15] We also include changes from $t-1$ to t of the seasonal dummy changes (for March and September). For example, if $MARCH_t$ is the end-of-March dummy, the regression equation includes $MARCH_t - MARCH_{t-1}$ and $MARCH_{t-1} - MARCH_{t-2}$.[16] There is no reason for the change from the last day

[15] The ex-post reserve surplus for day $t-1$ cannot be included because it is not known at 3:30pm of date $t-1$.

[16] The reason we include $MARCH_{t-1} - MARCH_{t-2}$ is simply that the regression includes the lagged dependent variable $(i_{7,t-1} - i_{7,t-2})$. It is a natural idea to include $ECASH_t$ and $EFISCAL_t$, which under the alternative of liquidity effects would affect the 3:30pm rate for date t. However, as seen in the previous section (see (i)), those expected cash and fiscal factors for date t will not affect reserves (the 5pm balance) for date t, thanks to the same-day offsetting market operations conducted in date t. Anyway, $ECASH_t$ and $EFISCAL_t$ are not known at 3:30pm of date $t-1$ and therefore cannot be included as regressors.

of the maintenance period to the first day of the next period even under the null of no liquidity effects. So the first days of periods will be dropped from the sample.

The third problem in the test of the martingale hypothesis is that the overnight rate may include a risk premium after the Yamaichi debacle. There were several banks that were rumored to be on the verge of bankruptcy. Those banks were forced to borrow at rates higher than the risk-free rate, which raises the average rate at each point in time within the day. If w_{7t} is the risk premium and i^*_{7t} is the risk-free rate, then the observed rate i_{7t} can be written as $i_{7t} = i^*_{7t} + w_{7t}$. Its change, therefore, is

$$i_{7t} - i_{7,t-1} = (i^*_{7t} + w_{7t}) - (i^*_{7,t-1} + w_{7,t-1}) = (i^*_{7t} - i^*_{7,t-1}) + (w_{7t} - w_{7,t-1}). \tag{5.1}$$

This shows that the change in the observed rate will be serially correlated even if the risk-free rate is a martingale. In particular, if w_{7t} is a white noise process, the first-order autocorrelation coefficient in observed changes is -0.25. We would expect that this problem might be serious for the 3:30pm rate because the market for 5pm funds is very thin. For this reason, we also estimate a specification which drops $i_{7,t-1} - i_{7,t-2}$ and its associated dummy variables from the regression.

Figure 6(a), which plots daily changes in the 3:30pm rate, makes it clear that there are occasionally large changes. As emphasized in, e.g., Hamilton (1997), the OLS estimates may be sensitive to those extreme values. We therefore estimate the regression equation by maximum likelihood, assuming the error distribution described in (4.2). (However, for any of the results reported in this section, there was no essential difference between the estimates by OLS and ML.) The ML estimates are reported in Table 3 for the two subsamples, pre-Yamaichi and post-Yamaichi. Several facts are noteworthy.

(i) For the pre-Yamaichi subsample, where risk premia do not seem important, the lagged dependent variable is significant, which is evidence against the martingale hypothesis. The coefficient is negative, so the 3:30pm rate has a tendency to revert to the mean. This of course is what one would expect if the Desk attempts to guide the rate to a desired level.

(ii) It may appear that the negative coefficient of the lagged reserve surplus ($Z_{3,t-1}$) is hard to explain by the liquidity effect: if an increase in $Z_{3,t-1}$ depresses the overnight rate due to the liquidity effect, then the change in the rate from date $t-1$ to t should increase. The sign of the coefficient, however, can be explained by the endogeneity of the reserve supply. If the Desk sees a surge in the liquidity need for 5pm reserves, it could supply enough reserves to preempt a rate increase. But those reserves will be credited toward required reserves, making it more difficult for the Desk to control the rate in the rest of the maintenance period. For example, if the amount of additional reserves is such that reserve requirements are met for all banks before the settlement day, then the Desk will lose the power to set the rate on the settlement day. The Desk, therefore, would increase reserves but not enough to prevent a rate increase at 5pm. Thus a liquidity effect combined with the endogeneity of reserves can explain the negative coefficient of Z_{3t}.[17]

(iii) For the post-Yamaichi subsample, the coefficient of the lagged dependent variable is near -0.25, which suggests the importance of risk premium.

(iv) For the post-Yamaichi subsample, the reserve surplus $Z_{3,t-1}$ is not significant. It appears that the balance at 5pm is abundant enough to eliminate the liquidity effect.

(v) The ML estimates of τ (the larger of the two standard deviations in the mixed normal distribution) and p (the probability of a draw from the distribution with larger standard deviation) in (4.2) indicate that the tail of the distribution of changes has become far thicker after the Yamaichi debacle.

To be sure, the failure of the hypothesis was already evident in Figure 2, where there are spikes at the end of March and September. The results above shows that the failure occurs regularly, not just on days with seasonal concentration of payments.

We now turn to the unpredictably of the change from 9am to 12:30pm ($i_{4t} - i_{1t}$). The change is plotted in Figure 6(b). The ML estimation of the regression of $i_{4t} - i_{1t}$ indicates that, for either subsample, intra-day changes of the previous day, $i_{4,t-1} - i_{1,t-1}$ (from 9am to 12:30pm) and $i_{7,t-1} - i_{4,t-1}$ (from 12:30pm to 3:30pm), have predictive power, even for the pre-Yamaichi period where risk premia do not seem to have played a role. It is difficult to explain this result, unless expectations are irrational or there is some reason for banks to prefer early or late procurement of 1pm funds in the morning.

6 Formulating the Liquidity Effect

The results in the previous section show that the data are inconsistent with the standard model of perfectly substitutable daily reserves. This section develops a model of reserve management taking into account the transactions demand for reserves. Estimation of the model will be the subject of the next section.

[17] This, however, does not necessarily mean that there should be a positive correlation between the reserve surplus and the rate for 5pm funds, because rate also depends on the expected future rate and the reserve surplus can affect expectations.

6.1 A Model of Liquidity: Settlement is Only Once per Day

6.1.1 The Bank's Optimization Problem

In the standard model of reserve management, the only reason for holding reserves is to meet reserve requirements. The bank's problem then is to distribute required reserves within the reserve maintenance period to minimize the cost of holding reserves. The model of this section generalizes this by allowing liquidity benefits from holding reserves. Let R_t be the reserve balance in date t. The larger is R_t, the lower the probability of an insufficient reserve balance. In the event of an insufficient balance, the bank must ask the BOJ to cover the negative position. This is perceived as costly to the bank. Therefore, the expected cost of an insufficient balance declines with the balance. Let $g(R_t; \eta_t)$ be this expected cost where η_t is a shift parameter. It is a decreasing function of R_t. Put differently, the marginal benefit of additional reserves is $-g'(R_t; \eta_t)$ (where $g'(R_t; \eta_t)$ is the derivative of g with respect to R_t).

Furfine (1998) derived this g function from the distribution of transfers that are not perfectly forecastable at the time of settlement. In his formulation, the marginal benefit $-g'$ can be written as

$$-g'(R_t; \eta_t) = \theta \Phi(-R_t/\eta_t),$$

where θ is the fee imposed by the Fed for overdrafts, η_t is the standard deviation of the unpredictable transfers assumed to be normally distributed, and $\Phi(.)$ is the cumulative density function of the standard normal distribution. This example shows that the marginal benefit of reserves increases with the degree of uncertainty measured by η_t and declines toward zero as R_t increases.

Given a function g representing the expected cost of fund shortage, the bank's optimization problem in date t of the reserve maintenance period is

$$\begin{aligned} \min_{\{R_t, R_{t+1}, \ldots, R_T\}} \quad & \mathrm{E}\Big[c_t\,(i_t R_t + g(R_t; \eta_t)) + \cdots + c_T\,(i_T R_T + g(R_T; \eta_T)) \;\Big|\; \Omega_t\Big] \\ \text{s.t.} \quad & c_t R_t + c_{t+1} R_{t+1} + \cdots + c_T R_T \geq REQ - (c_1 R_1 + \cdots + c_{t-1} R_{t-1}). \end{aligned} \tag{6.1}$$

Here, i_t is the overnight rate and Ω_t is the information set available in date t. The term $i_t R_t$ in the objective function represents the interest cost of reserves R_t. Since this model is a special case of the more general model to be developed in the next subsection, we won't drive it here. We note, however, the role of holidays in the model. The conversion factor c_t enters the constraint because this is how required reserves are calculated. Inclusion of c_t in the objective function can be controversial. For the sake of concreteness, suppose that date t is a Friday and $c_t = 3$. If the bank has access to investment opportunities yielding returns on Saturdays and Sundays, then the interest cost of the Friday balance R_t is indeed $c_t i_t R_t$. Because the BOJ net of interbank fund transfers is closed on Saturdays and Sundays, the expected cost of an insufficient balance should be $g(R_t;\eta_t)$, not $c_t g(R_t;\eta_t)$. The specification of the objective function above assumes that the cost is three times as high on Fridays.

6.1.2 Optimality Condition: Case of Binding Reserve Requirements

To derive the first-order condition, consider the following deviation from the solution: increase R_t by $1/c_t$ and reduce reserves for the remaining $T-t$ days of the maintenance period equally by $1/m_{t+1}$. The constraint is still satisfied after this change. The marginal benefit of increasing R_t by $1/c_t$ is

$$c_t(i_t + g'(R_t;\eta_t))/c_t = i_t + g'(R_t;\eta_t),$$

while the marginal cost of the uniform reduction for the remainder of the period is

$$\mathrm{E}\left[c_{t+1}(i_{t+1} + g'(R_{t+1};\eta_{t+1})) + \cdots + c_T(i_T + g'(R_T;\eta_T)) \;\middle|\; \Omega_t\right]/m_{t+1}.$$

So the net change in the value of the objective function is

$$\mathrm{E}\left[i_t + g'(R_t;\eta_t) - \frac{c_{t+1}(i_{t+1} + g'(R_{t+1};\eta_{t+1})) + \cdots + c_T(i_T + g'(R_T;\eta_T))}{m_{t+1}} \;\middle|\; \Omega_t\right]. \tag{6.2}$$

If $(R_t,\ldots,R_T)$ is optimal, then this change should be zero. Therefore, the first-order condition is

$$i_t + g'(R_t;\eta_t) = \overline{i_t} + \mathrm{E}\left[\frac{c_{t+1}g'(R_{t+1};\eta_{t+1}) + \cdots + c_T g'(R_T;\eta_T)}{m_{t+1}} \;\middle|\; \Omega_t\right], \tag{6.3}$$

where $\overline{i_t}$ is the average expected rate defined by

$$\overline{i_t} \equiv \mathrm{E}\left[\frac{c_{t+1}i_{t+1} + c_{t+2}i_{t+2} + \cdots + c_T i_T}{m_{t+1}} \;\middle|\; \Omega_t\right]. \tag{6.4}$$

If there is no liquidity effect so that g' is zero, then $i_t = \overline{i_t}$ and i_t follows a martingale.[18]

[18] The proof of this claim is easier if we consider the following deviation from optimality different from the sort described in the text. Increase R_t by $1/c_t$ and reduce R_T by $1/c_T$. Again, this change doesn't affect the constraint. Setting the marginal benefit equal to the marginal cost, we obtain

$$i_t + g'(R_t;\eta_t) = \mathrm{E}\left[i_T + g'(R_T;\eta_T) \;\middle|\; \Omega_T\right].$$

If $g' = 0$, this becomes

$$i_t = \mathrm{E}\left[i_T \mid \Omega_t\right].$$

Therefore,

$$\mathrm{E}(i_{t+1} \mid \Omega_t) = \mathrm{E}[\mathrm{E}(i_T \mid \Omega_{t+1}) \mid \Omega_t] = \mathrm{E}(i_T \mid \Omega_t) = i_t,$$

implying that i_t is a martingale.

6.1.3 Optimality Condition: Case of Nonbinding Reserve Requirements

We also examine the case where the required reserve constraint is not binding. Excess reserves, although rare in Japan, were observed right after the Yamaichi debacle. Also, as will be shown in the next subsection, a reserve balance at 1pm can be interpreted as excess reserves. Deriving the first-order condition for optimality is easier because the problem reduces to an unconstrained problem. It is

$$i_t = -g'(R_t; \eta_t). \tag{6.5}$$

That is, the demand for reserves R_t is set so that its marginal benefit $-g'$ equals the interest cost of holding reserves. Solving this for R_t gives the demand function for reserves.

6.1.4 An Interpretation of Reserve Surplus

To interpret the reserve surplus, assume that $-g'(R_t, \eta_t)$ takes the following form:

$$-g'(R_t; \eta_t) = \begin{cases} -\beta \cdot (R_t - \eta_t) & (0 \le R_t \le \eta_t), \\ 0 & (\eta_t < R_t). \end{cases} \tag{6.6}$$

Figure 7(a) displays the implied demand curve. Its slope is $-\beta$ when R_t is not large, but the liquidity effect disappears as R_t gets larger than the horizontal intercept η_t. The demand shifter η_t can be interpreted as (what is often described in newspaper accounts) the "market pressure".

Now return to the case of binding reserve requirements and assume that the actual level of reserves is not large enough to eliminate the liquidity effect. In this case the marginal benefit is $-g'(R_t; \eta_t) = -\beta \cdot (R_t - \eta_t)$. Substituting this into the first-order condition (6.3), we obtain

$$i_t = \overline{i_t} - \beta \cdot \left\{ R_t - \mathrm{E}\left[\frac{c_{t+1}R_{t+1} + c_{t+2}R_{t+2} + \cdots + c_T R_T}{m_{t+1}} \,\Big|\, \Omega_t \right] \right\} + \varepsilon_t, \tag{6.7}$$

where

$$\varepsilon_t \equiv \beta \cdot \left(\eta_t - \mathrm{E}\left[\frac{c_{t+1}\eta_{t+1} + c_{t+2}\eta_{t+2} + \cdots + c_T \eta_T}{m_{t+1}} \,\Big|\, \Omega_t \right] \right). \tag{6.8}$$

This term ε_t, representing today's market pressure relative to that for the remaining period, may be called the relative market pressure. (6.7) shows that a permanent increase in the market pressure (η), which leaves the relative pressure unchanged, will not affect how banks allocate reserves within the maintenance period. Substitute the binding constraint $c_{t+1}R_{t+1} + \cdots + c_T R_T = REQ - CUMBAL_t$ (where $CUMBAL_t \equiv c_1 R_1 + \cdots + c_t R_t$) into (6.7), we obtain

$$i_t = \overline{i_t} - \beta \cdot \left\{ R_t - \frac{REQ - CUMBAL_t}{m_{t+1}} \right\} + \varepsilon_t. \tag{6.9}$$

The expression in braces is none other than what we have termed the reserve surplus in Section 2.

Since the equation is linear, we can aggregate it over banks. That is, this equation can be interpreted as giving the equilibrium overnight rate given the level of reserve surplus Z_t determined by the BOJ. This equation shows that there are two factors that determine the overnight rate: the first is the expectations factor represented by $\overline{i_t}$, while the second is the liquidity effect consisting of the reserve surplus and the relative market pressure.

For the binding case, the reserve balance R_t is the value satisfying both the first-order condition and the binding constraint. This balance is given by point A for a given overnight rate in Figure 7(a). This point depends on the relative market pressure. The reserve balance for the non-binding case for the same overnight rate is given by point B. As this figure makes clear, even if the reserve balance that banks would hold without reserve requirements (point B) is less than the required reserve balance (point A), it does not necessarily follow that there is no liquidity effect at the observed level of reserves.

6.2 A Model of Liquidity: Settlement is Twice per Day

The model of the previous subsection ignores the institutional feature that settlement takes place three times (1pm, 3pm, and 5pm) per day. We now extend the model to allow for settlement at two points in time, points a and b. Once this model is developed, allowing more than two settlement points in time will be immediate. Let R_{jt} be the reserve balance at point j $(= a, b)$. Let X_{at} be the net increase of the balance due to the cash, fiscal, and market operations from the beginning of the day to point a, and let X_{bt} be the net increase from a to b (end of the day). The amount of overnight borrowing from a of date t to a of the following day is denoted by F_{at} and the amount of overnight borrowing from b of date t to a of the following day is F_{bt}. Let the associated interest rate be i_{at} and i_{bt}, respectively. These two kinds of borrowing arrangements are enough for the bank to transfer funds between any two points in time, so there is no need to consider other borrowing arrangements.

6.2.1 The Bank's Objective Function

For the sake of simplicity, assume for now that there are only two days left in the maintenance period. If R_{b0} is the balance at the end of the previous day, the budget constraint for day 1 is

$$R_{b0} + X_{a1} + F_{a1} = R_{a1}, \quad R_{a1} + X_{b1} + F_{b1} = R_{b1}. \tag{6.10}$$

(Here, we assume that there is no loans due on day 1, but that is without loss of generality, as it only affects C below.) For day 2, the budget constraint is

$$R_{b1} + X_{a2} + F_{a2} - (1 + i_{a1})F_{a1} - (1 + i_{b1})F_{b1} = R_{a2}, \quad R_{a2} + X_{b2} + F_{b2} = R_{b2}. \tag{6.11}$$

The bank acts to maximize the balance that is left after paying off all the borrowings. That balance is given by

$$R_{b2} - (1 + i_{a2})F_{a2} - (1 + i_{b2})F_{b2}. \tag{6.12}$$

By (6.10) and (6.11), this can be rewritten as

$$C - \Big[(1 + i_{a2})i_{b1}R_{b1} + i_{b2}R_{b2} + (1 + i_{a2})(i_{a1} - i_{b1})R_{a1} + (i_{a2} - i_{b2})R_{a2}\Big], \tag{6.13}$$

where

$$C \equiv (1 + i_{a1})(1 + i_{a2})(R_{b0} + X_{a1}) + (1 + i_{a2})X_{a2} + (1 + i_{b1})(1 + i_{a2})X_{b1} + (1 + i_{b2})X_{b2}. \tag{6.14}$$

The expression in brackets can be rewritten as

$$(i_{b1} + i_{a2}i_{b1})R_{b1} + i_{b2}R_{b2} + (i_{a1} - i_{b1} + i_{a2}i_{a1} - i_{a2}i_{b1})R_{a1} + (i_{a2} - i_{b2})R_{a2}. \tag{6.15}$$

Since C is given to the bank, maximizing the objective function (6.13) is equivalent to minimizing the expression in the brackets. Furthermore, ignoring the second-order terms (such as $i_{a2}i_{b1}$), (6.15) can be approximated by

$$i_{b1}R_{b1} + i_{b2}R_{b2} + (i_{a1} - i_{b1})R_{a1} + (i_{a2} - i_{b2})R_{a2}. \tag{6.16}$$

This shows that the cost of holding a reserve balance at point a, which cannot be credited toward required reserves, is $i_{at} - i_{bt}$,

It should be easy to see that this model can be extended to the case with an arbitrary number of days in the remaining period. If we make the same assumption as in the previous subsection about the effect of holidays, the bank's objective function to be minimized is

$$\mathrm{E}\left[\sum_{s=t}^{T} c_s \left\{(i_{as} - i_{bs})R_{as} + i_{bs}R_{bs}\right\} \,\middle|\, \Omega_{at}\right], \tag{6.17}$$

where Ω_{at} is the information set available at point a of date t. In this optimization problem, R_{as} can be determined on the basis of the information set Ω_{as}. Likewise, R_{bs} is a function of Ω_{bs} (the information set available at point b in date s).

6.2.2 Optimality Condition

As in the previous subsection, let $g_j(R_{jt}; \eta_{jt})$ be the expected cost of an insufficient reserve balance at point j $(j = a, b)$. The bank's objective function with this expected cost figured in is

$$\mathrm{E}\left[\sum_{s=t}^{T} c_s \Big\{(i_{as} - i_{bs})R_{as} + g_a(R_{as}; \eta_{as}) + i_{bs}R_{bs} + g_b(R_{bs}; \eta_{bs})\Big\} \;\Big|\; \Omega_{at}\right]. \tag{6.18}$$

If the shift variables η_{at} and η_{bt} are observable at each point in time, then we have $\eta_{at} \in \Omega_{at}$ and $\eta_{bt} \in \Omega_{bt}$. Since only the balance at point b is creditable, the constraint is

$$c_t R_{bt} + c_{t+1} R_{b,t+1} + \cdots + c_T R_{bT} \geq REQ - (c_1 R_{b1} + \cdots + c_{t-1} R_{b,t-1}). \tag{6.19}$$

In this optimization problem, since R_{as} $(s = t, t+1, \ldots, T)$ don't enter the constraint, the first-order condition can be derived easily as in the unconstrained case of the previous subsection:

$$i_{at} - \mathrm{E}\left(i_{bt} \;\middle|\; \Omega_{at}\right) = -g'_a(R_{at}; \eta_{at}) \geq 0. \tag{6.20}$$

If the only reason for holding reserves is to meet reserve requirements, then there is no need to hold a balance at point a. This first-order condition can be interpreted as stating that the overnight rate at a is the sum of the rate at b and a liquidity premium attached to a balance at point a

Regarding R_{bt}, the balance at point b, since the terms involving R_{at} and those involving R_{bt} are additively separable in the objective function(6.18), the first-order condition for R_{bt} is the same as in the previous subsection. Thus,

$$i_{bt} + g'_b(R_{bt}; \eta_{bt}) = \overline{i_{bt}} + \mathrm{E}\left[\frac{c_{t+1} g'_b(R_{b,t+1}; \eta_{b,t+1}) + \cdots + c_T g'_b(R_{bT}; \eta_{bT})}{m_{t+1}} \;\middle|\; \Omega_{bt}\right], \tag{6.21}$$

where

$$\overline{i_{bt}} \equiv \mathrm{E}\left[\frac{c_{t+1} i_{b,t+1} + c_{t+2} i_{b,t+2} + \cdots + c_T i_{bT}}{m_{t+1}} \;\middle|\; \Omega_{bt}\right]. \tag{6.22}$$

The reason the conditional expectation is taken conditional on Ω_{bt}, not on Ω_{at}, is that R_{bt} can be chosen based on Ω_{bt}.

6.2.3 The Reserve Surplus

Assume, as in the previous subsection, that the demand functions for balances at the two settlement points, $-g'_j(R_{jt}; \eta_{jt})$ $(j = a, b)$, are given by (6.6). Then (6.20) becomes

$$i_{at} - \mathrm{E}\left(i_{bt} \;\middle|\; \Omega_{at}\right) = \begin{cases} -\beta_a \cdot (R_{at} - \eta_{at}) \geq 0 & (0 \leq R_{at} \leq \eta_{at}), \\ 0 & (\eta_{at} < R_{at}), \end{cases} \tag{6.23}$$

where β_a is the β at a. The demand curve for reserves at a is drawn in Figure 7(b), with the horizontal axis measuring R_{at} and the vertical axis measuring i_{at}. This is obtained by just shifting the demand curve in Figure 7(a) by the expected rate $\mathrm{E}\left(i_{bt} \mid \Omega_{at}\right)$.

Assuming that $R_{bt} \leq \eta_{bt}$ for the remainder of the maintenance period, the first-order condition (6.21) can be rewritten as

$$i_{bt} = \overline{i_{bt}} - \beta_b Z_{bt} + \varepsilon_{bt}, \tag{6.24}$$

where

$$Z_{bt} \equiv R_{bt} - \frac{REQ - (CUMBAL_{t-1} + c_t R_{bt})}{m_{t+1}} \tag{6.25}$$

$$CUMBAL_{t-1} \equiv c_1 R_{b1} + \cdots + c_{t-1} R_{b,t-1} \tag{6.26}$$

$$\varepsilon_{bt} \equiv \beta_b \cdot \left(\eta_{bt} - \mathrm{E}\left[\frac{c_{t+1}\eta_{b,t+1} + c_{t+2}\eta_{b,t+2} + \cdots + c_T \eta_{bT}}{m_{t+1}} \;\middle|\; \Omega_{bt} \right] \right). \tag{6.27}$$

Here, Z_{bt} is the reserve surplus and ε_{bt} is the relative market pressure at point b.

7 Estimation of the Liquidity Effect

We have derived equations (6.23) and (6.24) for individual banks. Since they are linear, the same equations hold with R_{at} and Z_{bt} aggregate variables for the banking sector as a whole, as long as a liquidity effect exists for each bank. In this section, we will estimate these equations (or equations derivable from these) using aggregate data. We take the settlement point a to be 1pm when about 70% of the transfers in the BOJ net take place. As in the model, we take point b to be the end of the day, namely 5pm. Accordingly, i_{at} is taken to be the overnight rate for delivery at 1pm and i_{bt} is the rate for delivery at 5pm. These rates are exact empirical counterparts because the overnight rates ovserved before 1pm are for contracts starting at 1m and maturing at 1pm of the following day and the rates observed before 5pm (e.g., the 3:30pm rate) are for contracts starting at 5pm and maturing at 1pm of the following day.

7.1 Balances at 1pm and their Liquidity Premium

We first examine (6.23), which explains the difference between the rate for 1pm funds and the rate for 5pm funds. As clear from (6.20), the difference can be interpreted as a premium attached to balances at 1pm and its expected value should be nonnegative. Figure 8(a) plots this difference $i_{4t} - i_{7t}$. It is easy to see from this figure that the premium rose dramatically after the Yamaichi debacle.

If there is a liquidity effect, (6.23) can be written as $i_{at} - \mathrm{E}(i_{bt} \mid \Omega_{at}) = -\beta_a \cdot (R_{at} - \eta_{at})$. Denoting the forecast error for i_{bt}, $i_{bt} - \mathrm{E}(i_{bt} \mid \Omega_{at})$, by ξ_t, this equation can be rewritten as

$$i_{at} - i_{bt} = -\beta_a R_{at} + (\beta_a \eta_{at} - \xi_t), \quad \xi_t \equiv i_{bt} - \mathrm{E}(i_{bt} \mid \Omega_{at}). \tag{7.1}$$

If we are to estimate β_a from this equation, there are two problems to be overcome. First, there is no data on the reserve balances at time point a (1pm). Second, there is a simultaneity problem due to the endogeneity of R_{at}. To jump ahead, it was not possible to obtain reliable estimates of β_a probably due to these problems.

Regarding the first problem (of the lack of data on R_{at}), we could calculate R_{at} under some assumptions. Since borrowings between banks add up to zero for the banking sector as a whole, the aggregate balance R_{at} equals the balance at the end of previous day $R_{b,t-1}$ plus the cash and fiscal factors and market operations up to 1pm. The net fund inflow due to market operations can be calculated from a table in a BOJ publication (*Bank of Japan Monthly Statistics*) which lists individual operations with their *start* and *end*. In this calculation, we can ignore same-day operations because their start is either 3pm or 5pm. The problem in the calculation of R_{at} is that we don't have information of the distribution within days of payments and receipts for the cash and fiscal factors. As already mentioned, cash withdrawals (a debit item in the cash factor) occurs at 9am and deposits occurs at 3pm, but we do not have the breakdown of the cash factor between withdrawals and deposits. The same holds true for the fiscal factor. If we make the herioc assumption that the cash factor is concentrated in the morning and the fiscal factor is concentrated in the afternoon, then R_{at} can be calculated as:

$$R_{at} = R_{b,t-1} + CASH_t + \text{ relevant operations notified prior to date } t, \tag{7.2}$$

where $R_{b,t-1}$ is reserves at the end of date $t-1$. Figure 8(b) plots R_{at} thus calculated.

The second problem, simultaneity, arises for the following reason. The second component of the error term $\beta_a \eta_{at} - \xi_t$ in (7.1) is a forecast error, and so uncorrelated with the regressor R_{at}. However, the first component η_{at}, which represents the market pressure, is likely to be correlated with the regressor. The Desk is obligated to conduct market operations so that the average overnight rate is close to the level set by the directive. Since the overnight rate for delivery at point a, when most of the transactions take place, has a strong influence on the average rate, the Desk's main interest is to control that rate. Now, as (7.1) indicates, the balance at point a, R_{at}, affects the rate at a through the liquidity effect. Although it is not possible for the Desk to influence R_{at} by same-day operations since their *start* (delivery time) is 3pm or 5pm, it is possible to do so by pre-arranged operations notified to the dealers prior to date t whose *start* is point a of date t. Therefore, if the Desk anticipates an increase in the market pressure in date t, it will conduct pre-arranged operations to increase R_{at}. (In fact, as Figure 4 indicates, after the Yamaichi debacle, the open market operations were arranged to create a large balance at 1pm.) For this reason, there will be a positive correlation between R_{at} and the forecastable component of the market pressure η_{at}, and hence η_{at} itself.

Because of this positive correlation, the OLS estimate of the R_{at} coefficient (the negative of β_a) obtained from regressing $i_{at} - i_{bt}$ on a constant and R_{at} turned out to be positive (a wrong sign), probably due to the positive correlation just mentioned.

The standard remedy is to use instrumental variables, and it appears that for the problem at hand there is an ideal instrument: the unexpected cash and fiscal factors which can reasonably be assumed to be uncorrelated with the market pressure and which do affect the balance at 1pm. However, the instrumental variables estimator using these as instruments, too, picked up a wrong sign and was very imprecisely estimated.

7.2 Estimation using Morning Rates

We now turn to an alternative strategy, which is to use the change in the morning rates. The basic idea is the following. Since the rates observed before 1pm are forward rates for funds deliverable at 1pm, the difference between the 9am and 12:30pm rates should reflect new and relevant information that hits the market in the morning. If there are no liquidity effects, then $UCASH_t$ and $UFISCAL_t$ are not relevant information because, as seen in Section 4, they are temporary liquidity shocks having no effect on the future paths of reserves.

We begin by deriving an equation explaining the level of the rate for 1pm funds by taking the expectation of both sides of (6.24) conditional on Ω_{at} and then substitute the resulting equation into (7.1):

$$i_{at} = -\beta_a R_{at} - \beta_b \, \mathrm{E}(Z_{bt} \mid \Omega_{at}) + \mathrm{E}(\overline{i_{bt}} \mid \Omega_{at}) + u_t, \quad u_t \equiv \beta_a \eta_{at} - \mathrm{E}(\varepsilon_{bt} \mid \Omega_{at}). \tag{7.3}$$

(Here, $\overline{i_{bt}}$ is the average expected 5pm rate for the remainder of the maintenance period, see (6.22).) This equation shows that the overnight rate for delivery at a depends on the liquidity effect ($\beta_a R_{at}$), the ex-ante reserve surplus ($\mathrm{E}(Z_{bt} \mid \Omega_{at})$), and the expectation effect($\mathrm{E}(\overline{i_{bt}} \mid \Omega_{at})$), and the market pressure.

The rate at 9am, denoted i_{1t}, is a forward rate for funds deliverable at 1pm. It should therefore be equal to the expected value of i_{at}. Writing $\mathrm{E}(x \mid 9\mathrm{am})$ for the expectation as of 9pm of a variable x in question, and taking the expectation of both sides of (7.3), we obtain

$$i_{1t} = -\beta_a \, \mathrm{E}(R_{at} \mid 9\text{am}) - \beta_b \, \mathrm{E}(Z_{bt} \mid 9\text{am}) + \mathrm{E}(\overline{i_{bt}} \mid 9\text{am}) + \mathrm{E}(u_t \mid 9\text{am}). \tag{7.4}$$

We can do the same for the 12:30 rate to obtain

$$i_{4t} = -\beta_a \, \mathrm{E}(R_{at} \mid 12{:}30\text{pm}) - \beta_b \, \mathrm{E}(Z_{bt} \mid 12{:}30\text{pm}) + \mathrm{E}(\overline{i_{bt}} \mid 12{:}30\text{pm}) + \mathrm{E}(u_t \mid 12{:}30\text{pm}). \tag{7.5}$$

Now define, for a random variable x, an operator $\mathcal{D}$ by

$$\mathcal{D}(x) \equiv \mathrm{E}(x \mid 12{:}30\text{pm}) - \mathrm{E}(x \mid 9\text{am}) \tag{7.6}$$

This represents the revision of expectation from 9am to 12:30pm. Taking the difference between (7.4) and (7.5), we obtain

$$i_{4t} - i_{1t} = -\beta_a \mathcal{D}(R_{at}) - \beta_b \mathcal{D}(Z_{bt}) + \mathcal{D}(\overline{i_{bt}}) + \mathcal{D}(u_t). \tag{7.7}$$

In estimating this equation, we will treat $\mathcal{D}(\overline{i_{bt}})$ and $\mathcal{D}(u_t)$ as errors. For the pre-Yamaichi period, as clear from Figure 8(a), there seems to be no liquidity effects for 1pm funds. So we set $\beta_a = 0$. Regarding $\mathcal{D}(Z_{bt})$, we can relate it to observable variables as follows. Note from (2.10) that Z_{bt} can be written as

$$\begin{aligned} Z_{bt} &= R_{bt} - \frac{REQ - (CUMBAL_{t-1} + c_t R_{bt})}{m_{t+1}} \\ &= \frac{m_t}{m_{t+1}} R_{nt} - \frac{1}{m_{t+1}} \Big(REQ - CUMBAL_{t-1} \Big) \\ &= \frac{m_t}{m_{t+1}} \left(R_{b,t-1} + CASH_t + FISCAL_t + \sum_{i=0}^{3} OPER_{it} \right) - \frac{1}{m_{t+1}} \Big(REQ - CUMBAL_{t-1} \Big), \end{aligned} \tag{7.8}$$

where $OPER_{it}$ ($i = 0, 1, 2, 3$) are the operations defined in (2.4). Since $OPER_{0t}$, $R_{b,t-1}$, $CUMBAL_{t-1}$ and REQ are known at 9am, their $\mathcal{D}$ is zero. Therefore,

$$\mathcal{D}(Z_{bt}) = \frac{m_t}{m_{t+1}} \mathcal{D}(CASH_t) + \frac{m_t}{m_{t+1}} \mathcal{D}(FISCAL_t) + \frac{m_t}{m_{t+1}} \mathcal{D}(\sum_{i=1}^{3} OPER_{it}) \tag{7.9}$$

As already noted, credit and debit items of the cash and fiscal factors occur between 9am and 3pm (inclusive). So it is not realistic to assume that $CASH_t$ and $FISCAL_t$ are known by 1pm. If their forecasts as of 9am are $ECASH_t$ and $EFISCAL_t$ and if only a constant fraction of their unexpected changes is known by 1pm, we have

$$\mathcal{D}(CASH_t) = \lambda_c \cdot UCASH_t, \quad \mathcal{D}(FISCAL_t) = \lambda_f \cdot UFISCAL_t. \tag{7.10}$$

Substituting this and (7.9) into (7.7) and setting $\beta_a = 0$, we obtain

$$i_{4t} - i_{1t} = -\beta_b\lambda_c \cdot \left(\frac{m_t}{m_{t+1}} UCASH_t\right) - \beta_b\lambda_f \cdot \left(\frac{m_t}{m_{t+1}} UFISCAL_t\right) + \left\{ -\beta_b \frac{m_t}{m_{t+1}} \mathcal{D}\left(\sum_{i=1}^{3} OPER_{it}\right) + \mathcal{D}(\overline{i_{bt}}) + \mathcal{D}(u_t) \right\} \tag{7.11}$$

For the pre-Yamaichi subsample, we estimate this equation, treating the expression in the braces as the error term. The regressors are therefore $\frac{m_t}{m_{t+1}} UCASH_t$ and $\frac{m_t}{m_{t+1}} UFISCAL_t$ and the regression coefficients are $-\beta_b\lambda_c$ and $\beta_b\lambda_f$.

For the OLS and ML estimates of the regression coefficients to be consistent, the error term has to be uncorrelated with the regressors. It is reasonable to suppose that this condition is satisfied for the pre-Yamaichi period. As was mentioned as stylized fact (ii) in Section 4, $UCASH_t$ and $UFISCAL_t$ are to be offset by defensive operations in the following day. So it cannot affect the market's expectation about future overnight rates, $\mathcal{D}(\overline{i_{bt}})$. Also as mentioned as stylized fact (v), the amount of same-day operations at 9:20am, $OPER_{1t}$, are uncorrelated with $UCASH_t$ and $UFISCAL_t$ and there were hardly any additional same-day operations. Therefore, under the assumption that $UCASH_t$ and $UFISCAL_t$ are uncorrelated with the market pressure $\mathcal{D}(u_t)$, the regressors are uncorrelated with the error term.[19]

As was seen in Section 5, the change in the morning rates are related to the intra-day changes in the previous day, so in the actual estimation we include a constant and $i_{7,t-1} - i_{4,t-1}$, and $i_{4,t-1} - i_{1,t-1}$.[20] Put differently, the only difference from the Table 4 regressions is the addition of $\frac{m_t}{m_{t+1}} UCASH_t$ and $\frac{m_t}{m_{t+1}} UFISCAL_t$. Table 5 displays the ML estimation of the regression (see regressions #1). Now for both regressors, the coefficient estimates have the right sign. The $\frac{m_t}{m_{t+1}} UFISCAL_t$ coefficient is highly significant. This result is consistent with the conclusions we drew from Table 3 that the martingale hypothesis can be rejected for the pre-Yamaichi subsample.[21]

[19] This assumption is eminently sensible because the cash and fiscal factors are "hard to control by the central bank or by individual banks, at least in the short run, because they are a reflection of the decisions by such diverse agents as firms, households, the government, and nonresidents. For this reason, as in most other central banks, the Desk treats them as exogenous" (Miyanoya (2000)).

[20] Those additional regressors didn't affect the estimates of the coefficients of $\frac{m_t}{m_{t+1}} UCASH_t$ and $\frac{m_t}{m_{t+1}} UFISCAL_t$.

[21] As seen in Section 3, the forecasts of the cash and fiscal factors published by the BOJ are not rational. We also used modified forecasts derived from rolling regressions. For example, to obtain $CASH_t$ for Jaunary 4, 1999, we estimate

$$CASH_t = \lambda ECASH_t + \gamma_0 + \gamma_1(CASH_{t-1} - ECASH_{t-1}) \tag{7.12}$$

using the data since a year prior to the date. The fitted value from this regression is the modified $ECASH_t$ and $UCASH_t$ is calculated from this modified value. The same procedure is taken for $UFISCAL_t$. The ML estimates based on this modified data were similar to those reported in the table.

Regression #3 of Table 5 show the ML estimate of the same regression for the post-Yamaichi period. Since there appears to be a liquidity effect in 1pm funds as shown in Figure 8(a), the $UCASH_t$ and $UFISCAL_t$ regressors pick up the effect of $\mathcal{D}(R_{at})$ as well. So it is difficult to interprete their regression coefficients except that their joint significance is evidence for liquidity effects at either 1pm or 5pm. However, if $UFISCAL_t$ rather than $UCASH_t$ is more closely related to the reserve surplus, then the infignificance of the $\frac{m_t}{m_{t+1}} UFISCAL_t$ coefficient is consistent with the other conclusion from Table 3 that there seems to be no liquidity effect for 5pm funds after the Yamaichi debacle. To the extent that same-day operations (whose *start* is either 3pm or 5pm) in the post-Yamaichi period offset a large fraction of $UCASH_t$ after 1pm but by 5pm (as suggested by stylized fact (vii) of Section 4, the large $UCASH_t$ coefficient represents a substantial liquidity effect at 1pm. The coefficient, however, is not statistically significant.

Finally, we added the change in the reserve surplus, $Z_{1t} - Z_{1,t-1}$ as an additional regressor. The ML estimates are reported in Table 5 as regressions #2 (pre-Yamaichi) and #4 (post-Yamaichi). As mentioned in Section 4 (see stylized fact (iii)), it is hard to predict the change in the reserve surplus. So the actual change should be a good estimate of $\mathcal{D}(Z_{bt})$. But because a change in the reserve surplus is taken by the market as a signal of a change in policy, $\mathcal{D}(Z_{bt})$ will be correlated with $\mathcal{D}(\overline{i_{bt}})$. Therefore, the change in Z_{1t} is endogenous in the regression, and for this reason its estimated coefficient is hard to interpret. But it does document the significant effect of the reserve surplus on the overnight rate. In particular, for the post-Yamaichi sample where there seems to be no liquidity effect at 5pm, the fact that the change is significant shows that the effect on the overnight rate is not through the liquidity effect but through the expectations effect.[22]

8 Conclusion

This paper has studied the liquidity effect in the Japanese interbank market for overnight loans using daily and intra-day data for a recent period. Main conclusions are as follows.

1. According to a model of reserve management with multiple settlement points developed in this paper, the overnight rate at each point in the day depends on reserve balances and the so-called reserve surplus if there is a liquidity effect.

2. Since the Desk conducts open market operations so that the overnight rate trades at a range close to the target level, reserve balances are endogenous in equations explaining the overnight

[22] Note that same-day operations cannot affect the balance at 1pm, so a change in the reserve surplus can affect the morning rates either through the 5pm liquidity effect or through the expectations effect (see (7.3)).

rate. In this paper, we resolved this problem by exploiting the fact that the overnight rates observed in the morning are forward rates. Our estimates suggest that a liquidity effect existed for reserve balances at 5pm but not at 1pm before the Yamaichi debacle. After the Yamaichi debacle, a liquidity effect existed at 1pm but not at 5pm. The large supply of reserves by the BOJ designed to build up a balance at 1pm was not enough to eliminate the liquidity effect.

3. As clear from (6.20) and (6.21) and also from the discussion of the first-order condition in footnote 18, the overnight rates at various points within the day are the expected value of the 5pm rate on the settlement day. As stated in Okina (1993), the Desk can determine the 5pm rate on the settlement day by arranging the path of reserves so that there is a shortage of reserves on the settlement day. Since the social cost of providing reserves is zero, the optimal market operation in the class of market operations desinged for controlling the overnight rate is to supply enough reserves to eliminate liquidity effects at any points in time except for 5pm on the settlement day. This, however, might not be feasible because the cash and fiscal factors are not perfectly predictable. For example, a large infusion of those factors on the settlement day would create excess reserves. This may force the Desk to not provide enough reserves at 5pm on some days before the settlement day. Since 1pm balances are not creditable toward required reserves, it is a necessary condition for optimal market operations to provide enough reserves at 1pm to eliminate liquidity effects. However, the amount of funds the Desk can provide may be constrained by the availability of collaterals. The evidence found in this paper is consistent with the view that the Desk behaved optimally before and after the Yamaichi debacle.

9 References

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Figure 1: Overnight Rate (weighted averages)

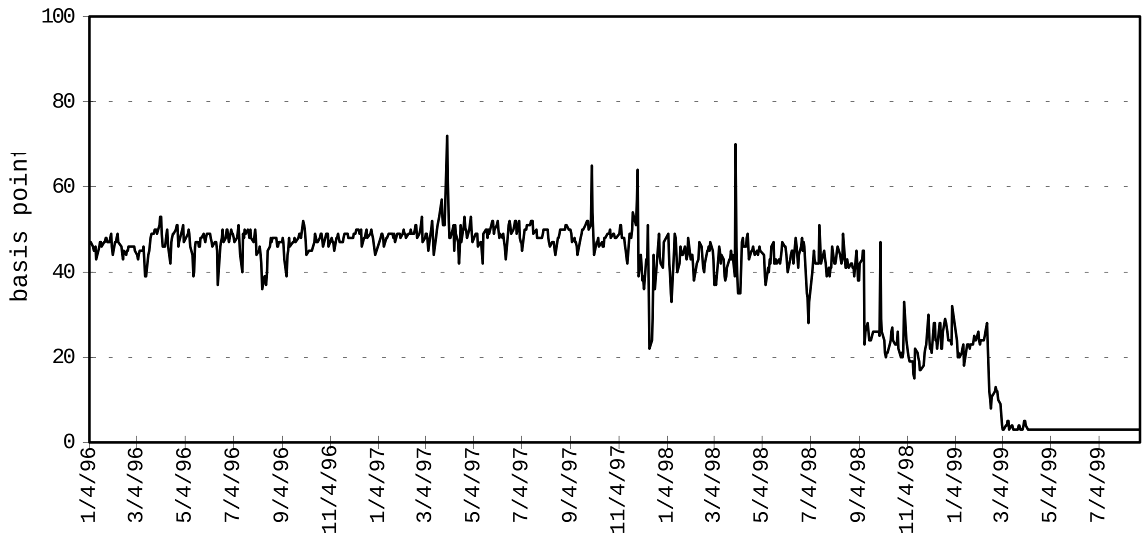

Figure 2: Overnight Rate (weighted averages)

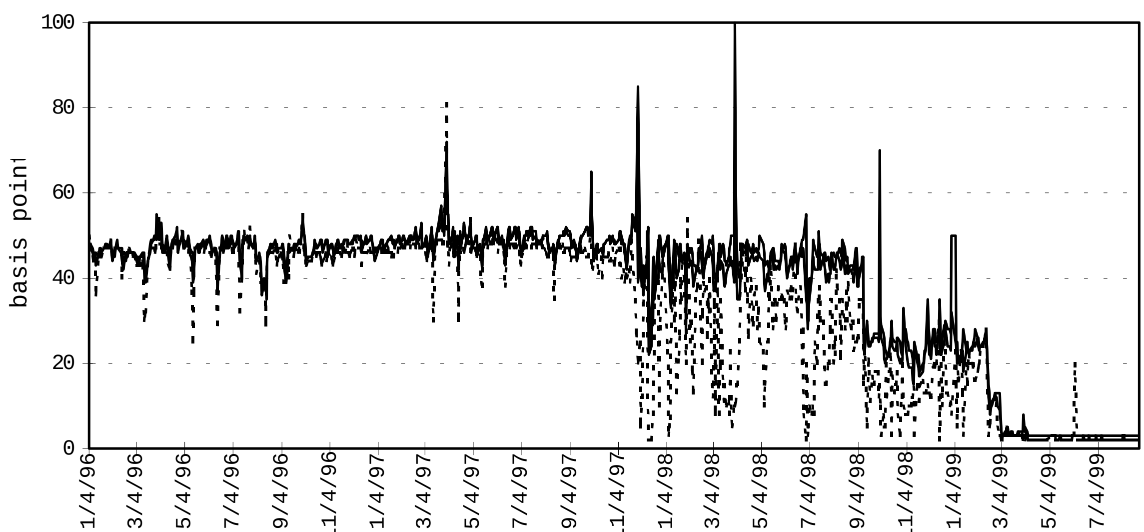

Figure 3: Forecast Errors for Cash and Fiscal Factors

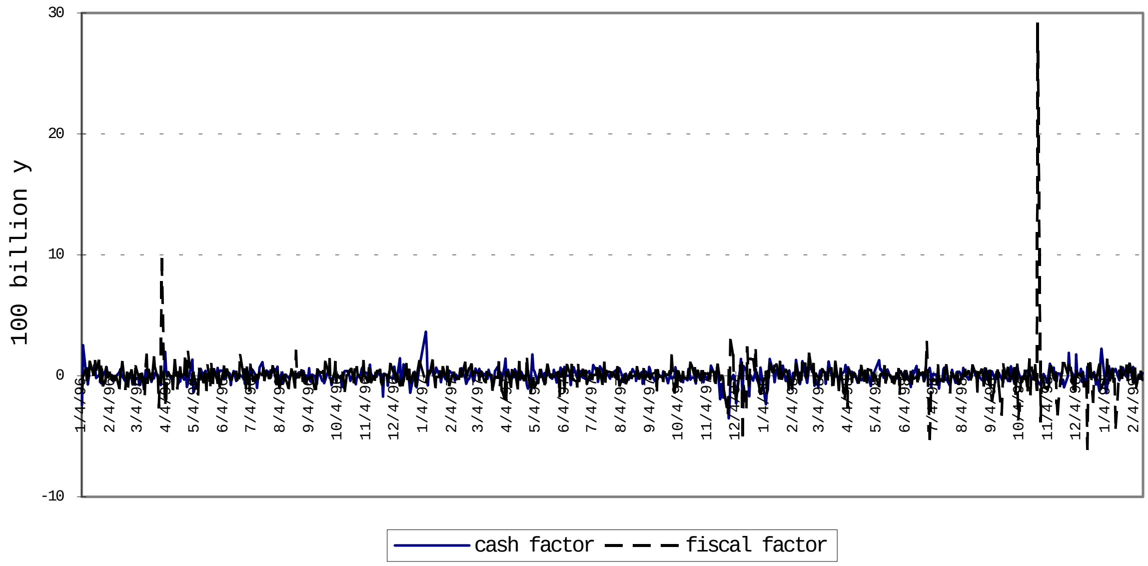

Figure 4: Ex-ante Reserve Surplus

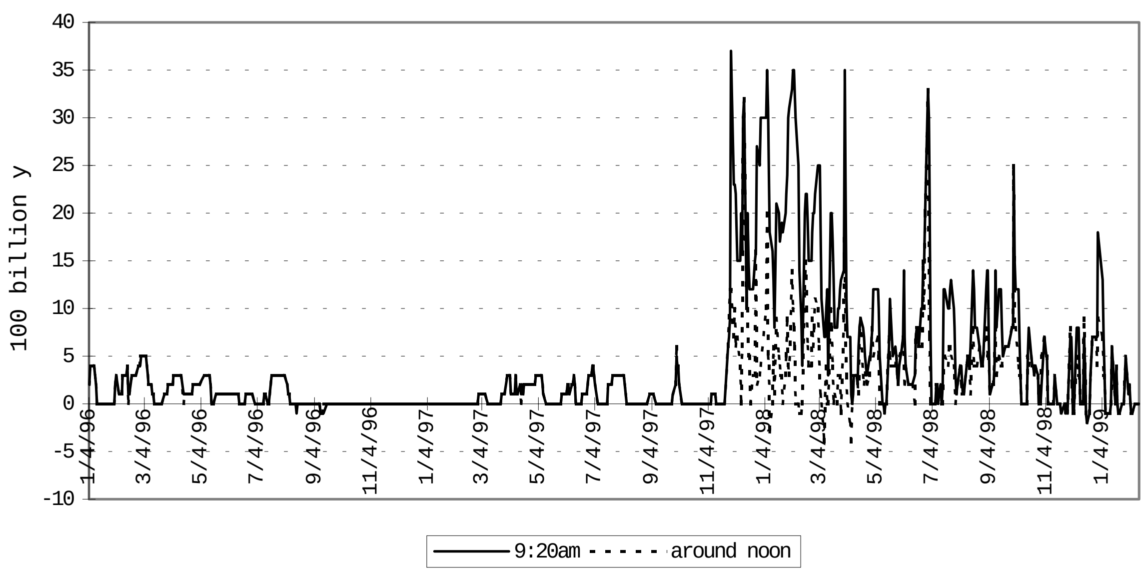

Figure 5: Open Market Operations by Settlement Time

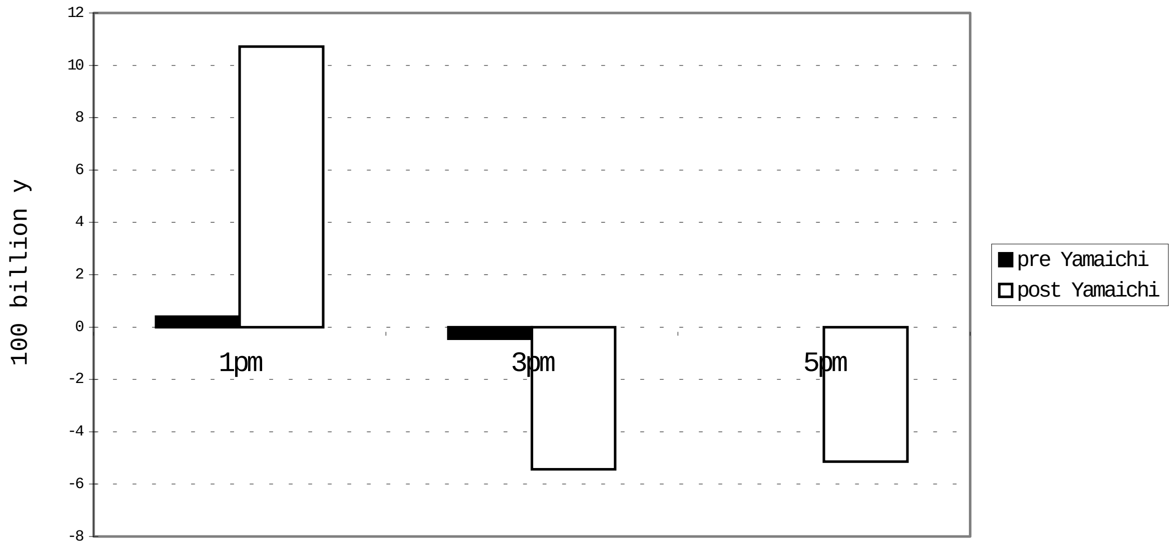

Figure 6(a): Daily Changes, 5pm Overnight Rate

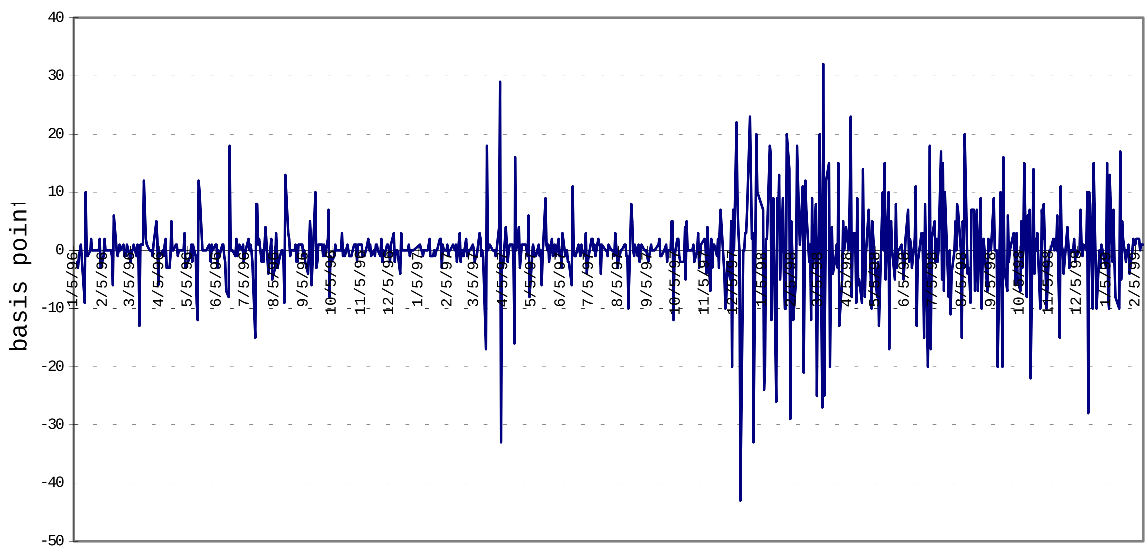

Figure 6(b): Rate Differentials

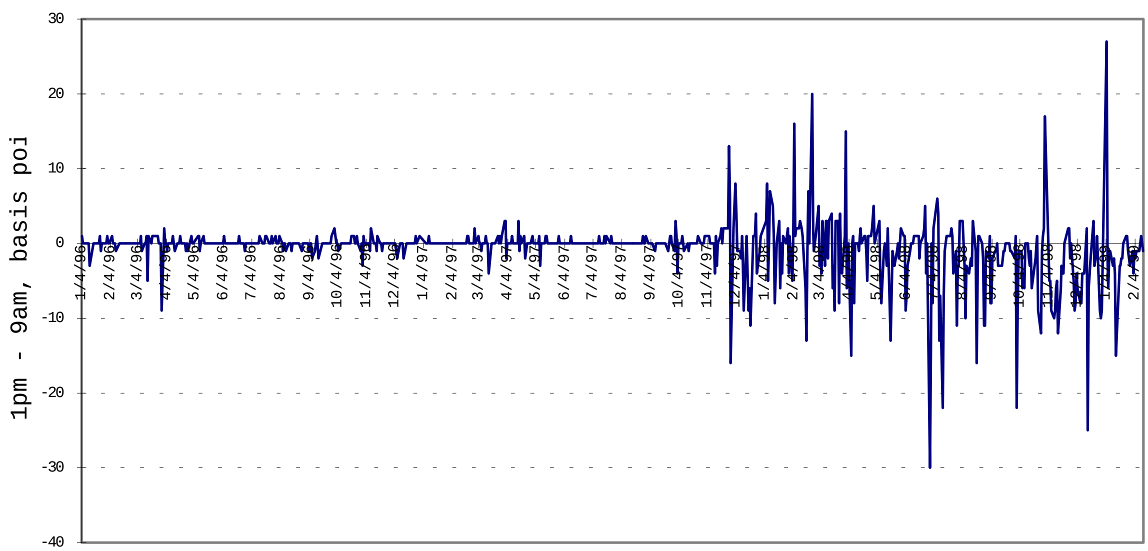

Figure 7(a): Reserve Demand

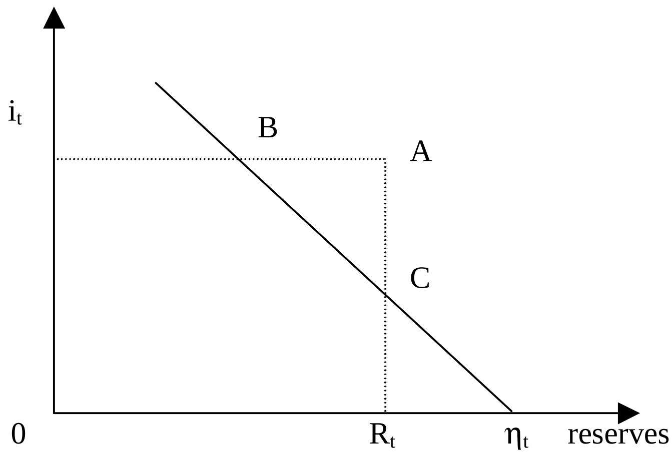

Figure 7(b): Demand for 1pm Reserves

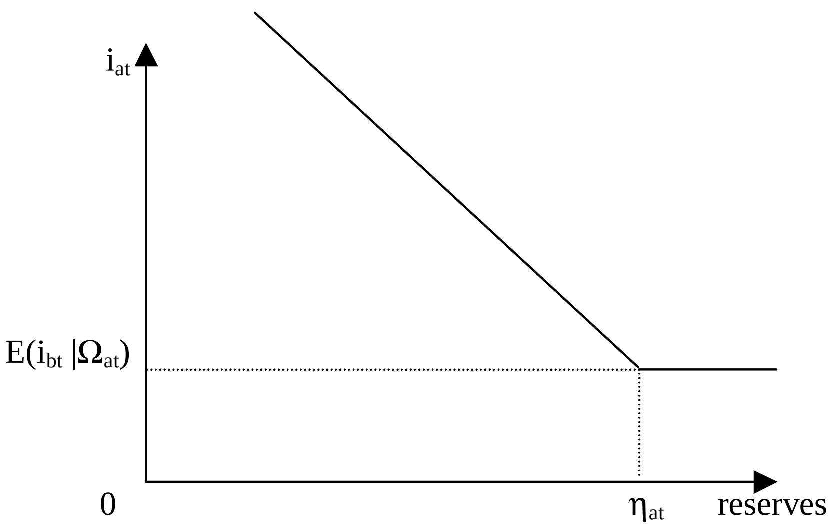

Figure 8(a): Rate DIfferentials

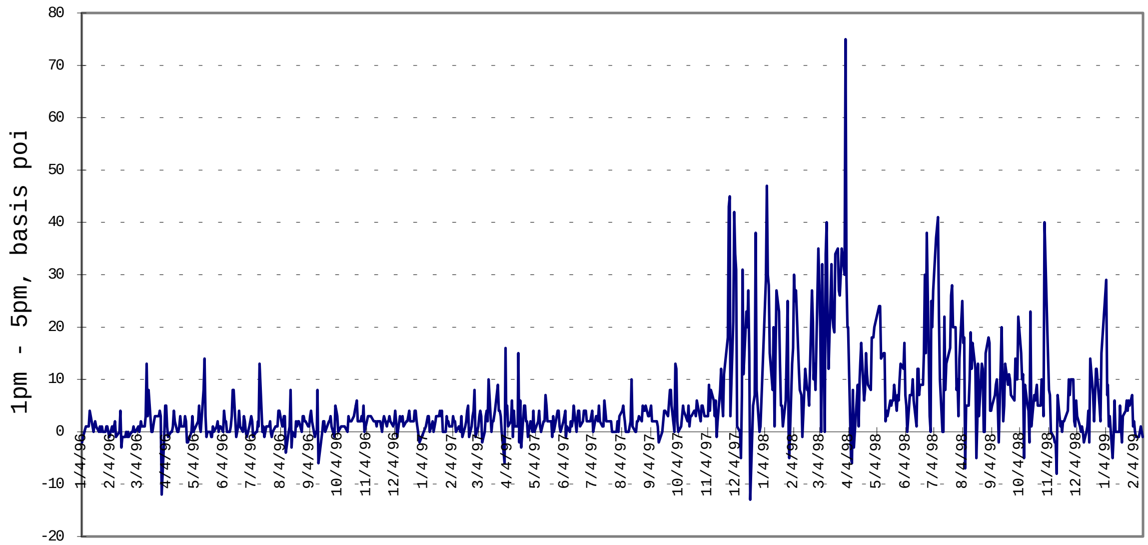

Figure 8(b): Reserve Balance at 1pm

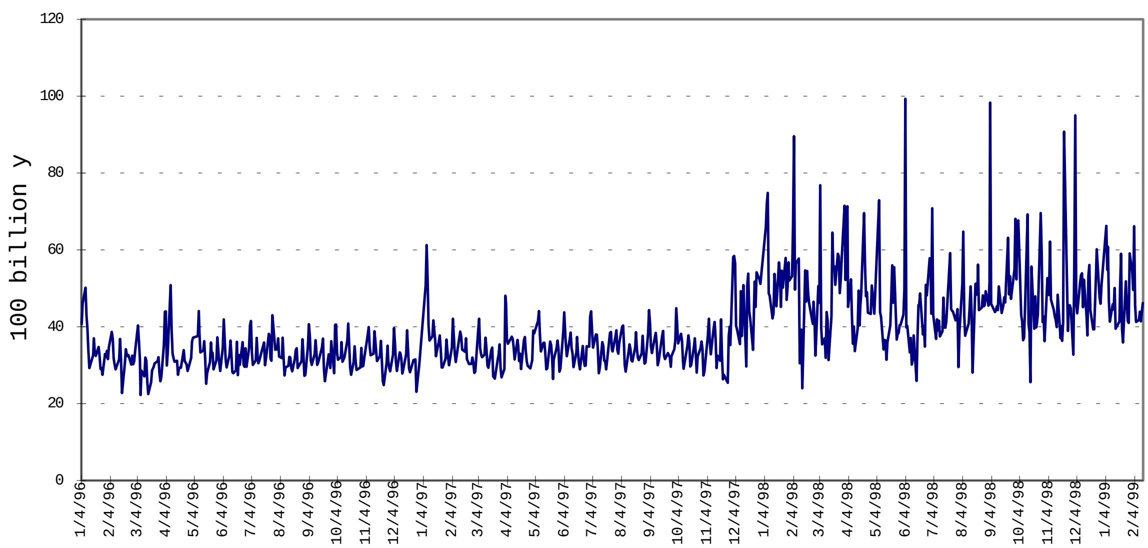

Table 1 : Serial Correlation in UCASH, UFISCAL

	1st-order correlation	Q(12)
UCASH	0.23 (0.036)	61.6 [p=0.0%]
UFISCAL	-0.098 (0.036)	11.6 [p=2.2%]

Note: The sample is from January 4, 1996 to February 12, 1999. The sample size is 767. Figures in parentheses are standard errors. Those in brackets are p-values. The Q(12) statistic is distributed asymptotically as ch-squared with 12 degrees of freedom under the null of no serial correlation.

Table 2: Desk's Reaction Function

reg. no.	sample period, sample size(n)	regressors									R^2	Breusch-Godfrey statistic with p-value
		lagged dep. var.	ECASH	EFISCAL	lagged UCASH	lagged UFISCAL	deviation from the target of 9am rate	UCASH	UFISCAL	deviation from the target of morning rates excluding 9am rate		
(a) the dependent variable is the reserve surplus as of 9:20am												
#1	1996/1/4 to 1997/11/21 n = 420	0.93 (0.020)	-0.0021 (0.0047)	-0.0024 (0.0017)	-0.044 (0.035)	-0.016 (0.025)	0.049 (0.011)	----	----	----	0.85	25.7 [0.0%]
#2		0.93 (0.020)	-0.0037 (0.0047)	-0.0025 (0.0017)	-0.051 (0.035)	-0.014 (0.025)	0.047 (0.011)	0.084 (0.040)	-0.029 (0.028)	-----	0.85	25.2 [0.0%]
#3	1997/11/25 to 1999/2/12 n = 272	0.96 (0.024)	-0.086 (0.036)	0.017 (0.013)	-0.33 (0.21)	-0.038 (0.077)	0.33 (0.039)	----	----	-----	0.87	20.8 [0.1%]
#4		0.96 (0.024)	-0.088 (0.037)	0.018 (0.013)	-0.31 (0.22)	-0.044 (0.078)	0.33 (0.039)	-0.026 (0.28)	-0.069 (0.091)	-----	0.87	21.1 [0.1%]
(b) the dependent variable is the reserve surplus as of noon												
#5	1997/11/25 to 1999/2/12 n = 272	0.67 (0.050)	-0.051 (0.035)	0.023 (0.013)	-0.46 (0.22)	-0.073 (0.077)	0.11 (0.049)	-0.66 (0.28)	-0.19 (0.088)	0.086 (0.052)	0.60	14.9 [1.1%]

Note: Figures in parentheses are standard errors. Settlement days and the final days of settlement periods are dropped from the sample. The Breusch-Godfrey statistic is asymptotically chi-squared with 5 degrees of freedom under the null of no serial correlation. The coefficients of a constant and seasonal dummies are not reported to save space. UCASH, UFISCAL, ECASH, EFISCAL enter the regressions after multiplication by the factor described in (4.1)

Table 3: Is the 5pm Rate a Martingale?

sample period (n = sample size)	regressors		σ	τ	p
	lagged dependent variable	lagged reserve surplus			
1996/1/4 to 1997/11/21 n = 442	-0.062 (0.026)	-0.14 (0.063)	1.3 (0.072)	5.7 (0.057)	0.16 (0.028)
	-----	-0.12 (0.20)	1.2 (0.070)	5.7 (0.55)	0.17 (0.029)
1997/11/25 to 1999/2/12 n = 286	-0.26 (0.048)	-0.018 (0.084)	1.8 (0.29)	6.3 (1.0)	0.67 (0.050)
	-----	-0.009 (0.033)	1.5 (0.36)	7.5 (1.7)	0.73 (0.051)

Note: For the definition of (σ, τ, p), see (4.2) of the text. Standard errors in parentheses. The reserve surplus is as of noon. The dependent variable is the change in the overnight rate from 3:30pm of the previous day to 3:30 of the day. The first days of settlement periods are dropped from the sample because the change from the previous day to the first day of the period need not be unpredictable. The coefficients of a constant and seasonal dummies are not reported.

Table 4: Are Changes in the Morning Unpredictable?

sample period (n = sample size)	regressors			σ	τ	p
	constant	lagged $i_7 - i_4$	lagged $i_4 - i_1$			
1996/1/4 to 1997/11/21 n = 466	0.063 (0.077)	0.11 (0.026)	0.11 (0.038)	0.95 (0.062)	4.1 (0.45)	0.16 (0.037)
1997/11/25 to 1999/2/12 n = 300	-0.71 (0.49)	0.16 (0.029)	0.31 (0.041)	4.4 (0.35)	4.2 (0.57)	0.14 (0.044)

Note: For definition of (σ, τ, p), see (4.2) of the text. Standard errors in parentheses. i_4 is the rate for 1pm fund, observed at 12:30pm. i_1 is the rate for1pmfund,observed at 9am. The dependent variable is $i_4 - i_1$.

Table 5: Liquidity Effects at Settlement Points

regression no.	sample period (n =sample size)	regressors						σ	τ	p
		constant	lagged $i_7 - i_4$	lagged $i_4 - i_1$	UCASH	UFISCAL	change in reserve surplus			
#1	1996/1/4 to 1997/11/21 n = 443	0.10 (0.070)	0.13 (0.024)	0.13 (0.038)	-0.060 (0.083)	-0.28 (0.071)	-----	0.92 (0.052)	4.0 (0.49)	0.13 (0.033)
#2		0.10 (0.070)	0.012 (0.023)	0.14 (0.037)	-0.030 (0.11)	-0.26 (0.071)	-0.49 (0.12)	0.95 (0.049)	4.4 (0.60)	0.10 (0.028)
#3	1997/11/25 to 1999/2/12 n = 286	-0.64 (0.49)	0.17 (0.029)	0.31 (0.041)	-0.81 (0.53)	0.24 (0.31)	-----	4.1 (0.41)	4.1 (0.56)	0.15 (0.054)
#4		-0.21 (0.45)	0.18 (0.027)	0.38 (0.038)	-0.84 (0.45)	0.27 (0.30)	-0.33 (0.070)	3.6 (0.41)	3.7 (0.45)	0.22 (0.067)

Note: For definition of (σ, τ, p), see (4.2). Standard errors in parentheses. The dependent variable is the $i_4 - i_1$, the 1pm rate observed at 12:30pm less the 1pm rate observed at 9am. Settlement days are dropped from the sample. UCASH, UFISCAL enter the regression with the multiplier indicated in (7.11) of the text.

Appendix Table 1: the Desk's Reaction Function

regression no. corresponding to those in Table 2	sample period	regressors									σ	τ	p
		lagged dep. var.	ECASH	EFISCAL	lagged UCASH	lagged UFISCAL	deviation from the target of 9am rate	UCASH	UFISCAL	deviation from the target of morning rates excluding 9am rate			
(a) the dependent variable is reserve surplus as of 9:20am													
#3	1997/11/25 to 1999/2/12	0.96 (0.019)	-0.025 (0.032)	0.017 (0.011)	-0.27 (0.20)	-0.072 (0.049)	0.29 (0.046)	----	----	-----	1.9 (0.21)	3.0 (0.36)	0.27 (0.082)
#4		0.97 (0.019)	-0.023 (0.032)	0.018 (0.012)	-0.27 (0.20)	-0.070 (0.052)	0.29 (0.045)	0.098 (0.22)	-0.013 (0.16)	-----	1.9 (0.22)	3.1 (0.36)	0.27 (0.087)
(b) the dependent variable is reserve surplus as of noon													
#5	1997/11/25 to 1999/2/12	0.65 (0.045)	0.006 (0.025)	0.015 (0.008)	0.14 (0.17)	-0.020 (0.050)	0.083 (0.040)	-0.84 (0.19)	-0.003 (0.083)	0.13 (0.034)	1.7 (0.11)	5.5 (0.92)	0.10 (0.029)

Note: For definition of (σ, τ, p), see (4.2) of the text. Standard errors in parentheses. Settlement days and first days of settlement periods are dropped from the sample. The sample size is 272. The coefficients of a constant and seasonal dummies are not reported to save space. UCASH, UFISCAL, ECASH, EFISCAL enter the regressions with multipliers indicated in (4.1).