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The Market Microstructure of Central Bank Intervention

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Abstract

One of the great unknowns in international finance is the process by which new information influences exchange rate behavior. Until recently, data constraints have limited our ability to examine this issue. The Olsen and Associates high-frequency spot market data greatly expand the range of testable hypotheses regarding the influence of information. This paper focuses on one important source of information to the foreign exchange markets, the intervention operations of the G-3 central banks. My previous studies using daily and weekly foreign exchange rate data suggest that central bank intervention operations can influence both the level and variance of exchange rates, but little is known about how exactly traders learn about these operations and whether intra-daily market conditions influence their effectiveness. Using high-frequency data, this paper will examine the relationship between the efficacy of intervention operations and the "state of the market" at the moment that the operation is made public to traders.

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I. Introduction

One of the great unknowns in international finance is the process by which new information influences exchange rate behavior. Standard models of exchange rate determination distinguish the types of information that should influence exchange rate movements, but there has been little focus on the way this information is assimilated by market participants. For example, in most models of exchange rate determination an unanticipated (and exogenous) monetary contraction in the home country, all else equal, leads to an appreciation of the home currency relative to foreign currencies. Our models have little to say about how market participants might learn about the monetary contraction, and they have little to say about how the current state of the foreign exchange market might influence the immediate and longer term reactions of individual foreign exchange traders to the news of such a contraction. One possible explanation for the woefully inadequate empirical performance of standard exchange rate models[1] is that they put so little emphasis on the market microstructure of the foreign exchange market.

This paper focuses on one important source of information to the foreign exchange markets, the intervention operations of the G-3 central banks. Previous studies using daily and weekly foreign exchange rate data suggest that central bank intervention operations can influence both the level and variance of exchange rates,[2] but little is known about how exactly traders learn about these operations and whether intra-daily market conditions influence their effectiveness. This paper will examine the relationship between the efficacy of intervention operations and the "state of the market" at the moment that the operation is made public to traders.

Until recently, data constraints have severely limited our ability to examine market microstructure issues in the foreign exchange market. The Olsen and Associates high-frequency spot market data greatly expand the range of testable hypotheses regarding the influence of information on foreign exchange market

[1] See, for example, Meese and Rogoff (1983) and Rose (1994), and see Lyons (1997) for further discussion of the role of market microstructure in international finance.

[2] See, for example, Dominguez (1992, 1997) and Dominguez and Frankel (1993a,b).

participants. These intra-daily data are used in the paper, and allow me to investigate how intervention news is transmitted to individual traders and across geographic markets, and whether the institutional features of the foreign exchange market help us to better understand the influence of intervention on foreign exchange rate returns and volatility.

Section II of the paper will present stylized facts on the foreign exchange market, central bank interventions, and Reuters news reports. Section III will provide an overview of the role of information in market microstructure models. Section IV will examine the influence of market microstructure on the efficacy of central bank intervention, and section V will present conclusions.

II. Stylized Facts

The Foreign Exchange Market

The foreign exchange market is de-centralized and open 24 hours a day. Even though forex trading occurs at all hours, there appear to be three distinct geographical "markets" defined by daylight hours in Tokyo, London and New York. There is a small overlap between European and Asian trading, no overlap between American and Asian trading and substantial overlap between American and European trading. The main players in the foreign exchange market are dealers, brokers and customers. Dealers are typically located in large commercial banks, trade on their own accounts, and are required upon demand to quote (and transact at) a bid or ask price on the currencies with which they deal. Brokers do not trade on their own accounts, they bring together parties that wish to buy or sell foreign exchange. And finally, customers purchase foreign exchange either directly from dealers or, more typically, with the help of a broker.

Dealers publicize their willingness to deal at certain prices by posting quotes on news services such as the Reuters or Telerate. These quotes appear on computer monitors sitting on the desks of other forex participants. Generally the actual prices at which transactions are carried out will be at narrower spreads than the bids and asks quoted on the computers. The actual transactions prices are proprietary information and are known only by the two participants in the transaction. Consequently, the quotes on the news service screens are the only publicly available information on current prices in the foreign exchange market.[3] Tick-by-tick indicative quotes for the major currencies are available from the Olsen and Associates in their FXFX data series.[4]

In order to get a sense of how the Olsen and Associates indicative quotes (heretofore the FXFX series) compare to actual transactions data, Goodhart, Ito and Payne (1996) obtained one day (June 16, 1993) of transaction data from D2000-2 (a recently developed electronic foreign exchange trading system). They find that: (1) the averages of the bid-ask in both series are almost identical; (2) the time path of indicative quotes is a good and close proxy for the D2000-2 transaction prices; (3) the spreads in the FXFX show clustering among a small number of standard values (e.g. 5,7, and 10 pips for the DEM-$) whereas the spreads "at the touch" (the difference between the best (highest) bid and the lowest ask on offer, usually input be different banks) show no signs of clustering; (4) the FXFX series exhibit stronger negative autocorrelation than the D2000-2 data; and (5) the frequency of quotes on FXFX is a relatively poor predictor of quote frequency on D2000-2.

The data used in this paper are the FXFX series indicative quotes on each day that the Fed intervened in the USD-DEM or USD-JPY markets as well as a control sample of 25 days for each currency on days with no interventions. The data span the period 1987 through 1995. While the Goodhart, Ito and Payne (1996) study suggests that the number of FXFX quotes may not serve as good proxies for transactions volume, their study does suggest that the FXFX data will allow us to analyze the impact of news on price and volatility dynamics. The FXFX data also allow us to examine heterogeneity issues because the names and locations of the quoting banks are included in the dataset. The most severe limitation

[3] Melvin (1997).

[4] The data are collected by Olsen and Associates, Research Institute for Applied Economics, Zurich Switzerland using O&A proprietary real-time data collection software.

of the FXFX data, however is that it does not provide volume information, so that we can not examine the joint dynamics of volume (or order flow) and price.[5]

A plot of the average number of USD-DEM FXFX quotes over the day (figure 1) shows a strong seasonal pattern. There are on average 20 quotes per hour for the mark against the dollar in early Asian trading, quotes reach a daily low at lunch time in Tokyo (3-4:30 GMT; prior to Dec 22, 1994 there existed a Japanese regulation that prohibited trading during this time), market activity then rises in the Asian afternoon and as European trading begins around 7 GMT. The number of quotes hits a daily peak when London and New York trading overlap. The number of quotes falls dramatically with the close of European trading. Figure 2 presents the average daily USD-DEM bid-ask spread which displays a similar pattern to that seen for the number of quotes. Table 1 presents descriptive statistics (means, variance, skewness, kurtosis) of the FXFX data used in this study as well as corresponding statistics on the full sample of FXFX data from 1987-1993 (this data set contains 8,238,532 observations for the USD-DEM rate and 4,230,041 observations for the USD-JPY rate.[6]

Three filters were applied to the FXFX data used in this study. First, all quotes that Olsen and Associates marked as invalid have been excluded. (Quotes are marked as invalid if there is a large discrepancy in the entered quote relative to surrounding quotes presumably due to a typing error or a technical problem with the Reuters reporting system.) A second filter is used to exclude quotes that are repetitions of the immediately preceding ones, but entered by a different institution. (It is often the case that several institutions quasi-simultaneously quote the same bid and ask levels.[7] A third filter excludes any quote where the log-bid or log-ask are such that their percentage difference from both the preceding and the

[5] Lyons (1995, 1996) analyzes data on time-stamped quotes, deals and position for a single USD-DEM dealer at a major New York bank, and the time-stamped price and quantities for transactions mediated by a large New York broker in the same market covering one week in August 1992.

[6] The full sample statistics in the upper panel of Table 1 are reproduced from Table 4 in Guillaume (1997a).

[7] If two institutions enter quotes simultaneously, only one quote is actually kept in the Reuters record. For technical reasons Reuters cannot take more than one quote per six seconds (Dacorogna et al. 1993, Guillaume et al. 1997a).

succeeding log-bid (or respective log-ask) lies outside a specific set of bounds, where the bounds are based on the probability distribution of the USD-DEM and USD-JPY samples.[8]

Central Bank Intervention Stylized facts

Foreign exchange market intervention is any transaction or announcement by an official agent of a government that is intended to influence the value of an exchange rate. In the G-3 countries, intervention operations are implemented by the monetary authority, although the decision to intervene in the U.S. and Japan can also be made by authorities in the U.S. Treasury Department or the Ministry of Finance, respectively. In practice, central banks define intervention more narrowly as any official sale or purchase of foreign assets against domestic assets in the foreign exchange market.

Although each central bank has its own particular set of practices, intervention operations generally take place in the dealer market. During major intervention episodes, the Fed often chooses to deal directly with the foreign exchange desk of several large commercial banks (typically in New York) simultaneously to achieve maximum visibility. Anecdotal evidence suggests that the BOJ also follows this practice. As with any other foreign exchange transaction, trades are officially anonymous. However, most central banks have developed relationships with traders which allow them to inform the market of their presence within minutes of the original transaction, or to keep their intervention operations secret.[9]

The G-3 central banks intervened sporadically over the period 1987 through 1995. There are 273 days in the nine year sample when the Fed intervened in the USD-DEM or the USD-JPY market. Moreover, the Bundesbank and the BOJ frequently intervened on the same days as the Fed, so that our sample includes

[8] The bounds for the percentage differences in USD-DEM quotes are 0.003% and 0.08%. Approximately 1100 USD-DEM quotes are excluded per day (out of a total of approximately 4000) due to the 0.003% cutoff and approximately 70 quotes are excluded per day due to the 0.08% cutoff. These cutoffs were derived from the probability distribution of percentage changes in adjoining quotes. A similar procedure is used to filter USD-JPY quotes. See Nenova (1997) appendix A for further details.

[9] Dominguez and Frankel (1993c) provide a detailed description of this process and the possible reasons that central banks might want to keep their intervention operations secret (the so-called stealth operations).

interventions by all three central banks.[10] In order to analyze the influence of intervention on the intra-daily data, we would ideally like to know the exact time that each central bank entered the market to buy or sell foreign exchange. Unfortunately, this data (to the approximate minute) is only available for the Fed in the last two years of the sample. However, on most days Reuters reports when central banks are in the market, and the time-stamped history of these reports are also available from Olsen and Associates. To illustrate, Figure 3 presents the USD-DEM tick-by-tick FXFX quotes for one of the days in the sample, May 31, 1995, along with an indication of when the Reuters' time-stamped report of Fed intervention appeared. On this particular day the USD-DEM price jumped from .326 to over .345 immediately following the first Fed intervention and there are no signs of mean reversion within the day.

It is possible that some traders in the market will learn that a central bank is in the market before the story appears in a Reuters' report. (It is indeed likely that the bank (or banks) with whom the central bank purchases or sells foreign exchange will know about the intervention before all the other banks.) Therefore, although we can assume that all traders know about the intervention when the Reuters' report is released, it is possible that some (or even the bulk) of the influence of intervention will occur before the Reuters' time-stamp. Based on six weeks of interventions in 1989, Goodhart and Hesse (1993) find that the Reuters announcement lag is no longer than 15 to 30 minutes. However, Peiers (1997) finds Reuter's lags "informed trader" information regarding Bundesbank interventions by as much as 60 minutes in a sample of FXFX data for the period 1992-93. Likewise, Chang and Taylor (1997) find Reuters' reports to lag up to 2 hour lags for BOJ interventions in the same period, 1992-93.

Typically central banks intervene during business hours in their own respective markets. For example, the Fed generally intervenes between 8am and 5pm eastern standard time. According to the Reuters times-stamp, on average the Fed intervenes at 14:57:10 GMT (or 10am EST), the Bundesbank

[10] In 111 days of the 273 days in the sample (or 41%) only one central bank was reported to have intervened; on 80 days (or 29%) two central banks (from among the Fed, Bundesbank and BOJ) were reported to have intervened; on 10 days (or 4%) all three G-3 central banks were reported to have intervened; and on 29 days (11%) more than 3 central banks were reported to have intervened.

intervenes at 11:31:16 GMT (or at 12:30pm in Frankfurt) and the BOJ intervenes at 3:56:36 GMT (or around the Tokyo lunch hour). Figures 4 to 6 present the frequency distributions of intervention times for each central bank. The graphs clearly illustrate that there is a wide range of times at which each of three central banks enter the market.

Reuters news reports stylized facts

The Reuters news reports used in this paper come from the Reuters AAMM Page News (Money Market Headline News). Along with reports of central bank intervention, the Reuters data include announcements of various macroeconomic statistics, statements by central bank and government officials and reports of major economic events. In order to control for the impact of other news on exchange rate returns and volatility, a subsample of these Reuters news reports are also included in the empirical work. In particular, dummy variables were created to indicate the timing of all major macroeconomic announcements and statements regarding exchange rate policy by officials of the G-3 central banks on the intervention sample days. There were no major economic events that occurred on our sample days. Table 2 lists each of the dummy variables created from the Reuters reports and the day-of-week and average time (GMT) when the announcements are made. Unfortunately, the Reuters data is only available starting on August 18, 1989, therefore, many of the empirical tests in this paper will begin in August 1989.[11]

III. The Role of Information in Market Microstructure Models

The market microstructure literature analyzes how specific trading mechanisms affect the price formation process.[12] There are two main branches of microstructure theory: the inventory approach and the information approach.

[11] 101 of the 273 intervention days in our full sample occurred after August 1989.

[12] See, for example, Admati (1991), O'Hara (1995) and Lyons (1997).

The inventory branch of the microstructure literature examines the question of what happens when orders to buy or sell are not always balanced in the selected time period. How does the price change to reflect order flow? In simple versions of these models the dealer's position is purely nonspeculative and there are no information asymmetries. The only uncertainty in these models arises from the arrival of the buy and sell orders. The Garmon (1976) inventory model yields 3 main conclusions: (1) the optimal bid and ask prices are monotone decreasing functions of the dealer's inventory position. As the dealer's inventory increases, he lowers both bid and ask prices, and conversely he raises both prices as inventory falls. (2) The dealer has a preferred inventory position. As the dealer finds his inventory departing from his preferred position, he moves his prices to bring his position back. (3) The optimal bid and ask prices exhibit a positive spread.

One simple prediction of inventory models is that since a dealer will prefer to sell if he is long inventory and buy if he is short, there should be mean reversion in prices due to inventory effects. Lyons (1996) finds evidence of inventory effects in foreign exchange markets, but little evidence of inventory effects have been found in equity or futures markets.

The information branch of the microstructure literature focuses on the question of how prices may be affected by the fact that traders in the market may have different information sets. In simple versions of these models a dealer's position is purely speculative, there are no inventory costs and no risk aversion. The dealer who is in the middle of many trades, knows that some traders may have better information than he does. These informed traders buy when they know the price is too low and sell when they know it is too high. Moreover, these informed traders have the option not to trade, unlike the dealer, who must always quote prices to buy and sell. Dealers know they will lose when trading with informed traders, so to remain solvent, they must offset these loses by making gains from uninformed traders. These gains arise from the bid-ask spread (Bagehot (1971)).

In the Admati and Pfleiderer (1988) information model, there are three types of traders: informed traders, discretionary liquidity traders (who trade in periods of lowest cost) and nondiscretionary liquidity traders (dealers). Trading costs arise because of the activity of the informed, whose profits are paid by the uninformed liquidity traders. In equilibrium there will be concentrations in volume at arbitrary times because high volume periods attract informed traders (because they can more easily hide their trades) and discretionary liquidity traders (because the cost of trading is lower with increased competition among liquidity traders). So that, periods of high variance correspond to periods of high concentration of informed trading. Volatility U-shaped patterns, therefore, could arise directly from the increased activity by informed traders at open and close.

Bollerslev and Domowitz (1993) document quote arrivals and bid-ask spreads over the trading day, across geographic locations, and across trading participants (using six-weeks of Reuters screen data compiled in 1989 by Charles Goodhart) for the foreign exchange market. They find the U-shaped pattern of trading activity from open to close in the European markets. They also find the U-shape for quote volume for traders who restrict their trading to regional markets within well-defined openings and closings (as opposed to international firms with traders in multiple regional markets). Hsieh and Kleidon (1996) also find the U-shape for quote volume in individual markets, but do not find evidence of volatility spillover in American and European markets when both are open. They find no effect of the NY market open on volatility in London, or the London close on NY volatility. They conclude that the standard information models are, therefore, not consistent with the forex data. "If no new information is reaching the international foreign exchange market -- which is implied by the absence of unusual volatility in quotes generated by traders in one physical location -- then quotes generated by traders in another market show excess volatility relative to that implied by standard information models" (Hsieh and Kleidon, pp. 43). They conclude that market learning about the market structure is important at the start of trading, which results in wide and volatile quotes when traders first enter the market. At the close of trading, inventory management by dealers is the most likely explanation for the higher volatility.

Peiers (1997) examines how interactions between informed (defined to be indications provided by Deutsche Bank (DB)) and uninformed foreign exchange traders (indications given by all other banks) give rise to short-term price leadership during periods of central bank intervention. She finds that during the period October 1992 and September 1993 that volatility increases five minutes prior to Bundesbank interventions and that there is evidence of DB price leadership from 60 to 25 minutes prior to Reuters reports.

Lyons (1996) presents a case study of the motives for trading foreign exchange. Two hypotheses are tested: (1) trading is generated by inventory reasons, and in this case it does not convey information when time between consecutive trades is short; (2) trading is generated by the arrival of new information and intense trading means that an information event has occurred. He finds evidence in favor of the inventory, or "hot-potato" hypothesis, trades occurring when transaction intensity is high are significantly less informative that trades occurring when transaction intensity is low. He also finds evidence that trading occurring when quoting intensity is high are significantly more informative than trades occurring when quoting intensity is low. (He takes this latter result as supportive of Easley and O'Hara's (1992) event-uncertainty version of the information arrival hypothesis.)

Overall, the market microstructure tests using foreign exchange data provide mixed evidence on the relative importance of inventory versus information based models of price behavior. It seems likely that elements of both sorts of models are operative in the foreign exchange market. However, because data on order-flow and inventories are not publicly available for the foreign exchange market, this paper will focus on the influence of information on the forex price formation process. And, in particular, the focus will be on the effects of central bank intervention on prices. The influence of central bank intervention is interesting in its own right and the results in LeBaron (1996) suggest that intervention days may be the source of unusual profits for traders using technical analysis. LeBaron (1996) finds that simple moving average trading rule profits are significant in daily forex data if intervention days are included in the sample -- when interventions are excluded, profits go to zero. An intra-daily examination of trader behavior around intervention events may help us understand why and how intervention days provide these profit opportunities.

IV. Systematic influences of central bank interventions

A fundamental property of high frequency data is that observations can occur at varying time intervals. Irregular spacing of quotes has produced four main directions of empirical research: (1) the use of transaction (rather than clock) time[13]; (2) the mixture of distributions approach to analyzing trade patterns[14]; (3) time-scaling approaches to forecasting price behavior[15]; and (4) the conditional duration approach[16]. Unfortunately there seems to be little consensus in the literature as to which of these approaches works best. An alternative approach to irregularly spaced data, used in this paper, is to create from these data a regularly spaced time series over a discrete time interval. If we define the tick-by-tick price (P) as the average of the bid and ask:

$$P_{t_j} = \frac{\left[logP_{t_j}^{ask} + logP_{t_j}^{bid} \right]}{2}$$

[13] The downside of transaction time is that it may be endogenous and, therefore, transaction prices may suffer from a severe sampling bias (sampling time is not independent of the price process since transactions are more likely to occur when there is new information). This problem is less serious in the bid-ask indicative quote series because these can be updated by a single individual, while transaction prices await the actions of both an active and a passive party (Goodhart and O'Hara (1996).

[14] In this approach the variability of prices and volume are viewed as arising from differences in information arrival rates. Information arrival causes traders to adjust their reservation prices, and this, in turn, causes trade, which changes the market price. In this statistical approach the manner by which information affects traders is not addressed.

[15] Dacorogna et al. (1993) and Muller et al. (1990) construct a new time scale for forex markets that takes into account the three geographical centers of trade (Asia, Europe and New York); it basically expands (clock time) periods with a high mean volatility and reduces periods with low volatility.

[16] Research by Engle and Russel (1995) and Engle (1996) explicitly models the intertemporal correlations of the time interval between events using the autoregressive conditional duration (ACD) model.

where t_j is the sequence of tick recording times which is irregularly spaced, then the regular-space price is defined as:

$$P_{t_i} = P(\Delta t, t_i) = \frac{\left[logP^{ask}_{t_i} + logP^{bid}_{t_i} \right]}{2}$$

where t_i is the sequence of the regular-spaced in time data and Δt is the time interval.[17] Equivalently, the return (R) over a fixed time interval Δt is defined as:

$$R_{t_i} = R(\Delta t, t_i) = P_{t_i} - P_{t_i\text{-}\Delta t}$$

The Influence of Intervention on Returns

I use an "event study" approach to test for the influence of intervention (and other announcements) on exchange rates. If R denotes the 5-minute return series and D^k denotes the (time-stamped to the nearest 5-minute) intervention and other announcement dummy variables, then a general "event study" regression specification is:

$$R_{t_i} - \overline{R_{t_i}} = \alpha_0 + \sum_k \sum_n \alpha^k_{1,n} D^k_{t_{i+n}} + \varepsilon_{t_i}$$

where $\overline{R}$ is set to zero and the intra-daily returns data include only the days on which the Fed intervened in the market over the sample. Using this general regression specification I am able to test a number of different hypotheses: (1) Are the D^ks statistically significant?; (2) Do different central banks have different impacts?; (3) Does the market anticipate the Reuters release of D^k news?; (4) Is there mean reversion (do the n time lags sum to zero)?; (5) Does the volume of trading matter?; (6) Does the day-of-week matter?; (7) Does the time-of-day matter?; (8) Does it matter if intervention is closely timed with other macroeconomic news announcements?

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[17] In practice the 5-minute price series used in this paper is formed by averaging the two immediately adjacent bid and ask (filtered) observations to the round 5-minute mark (T) with weights proportional to the distance from the end of the interval. If we define *wa* as the distance between T and t in seconds, and *wb* as the distance between t-1 and T in seconds, then the price for time T is:

$$P_T = \left[wa \frac{[\log P^{ask}_{t-1} + \log P^{bid}_{t-1}]}{2} + wb \frac{[\log P^{ask}_{t} + \log P^{bid}_{t}]}{2} \right] (wa + wb) \quad \textbf{Error! Main Document Only.}$$

Figure 7 presents a graph of average USD-DEM intra-daily returns. Before presenting the results of the event study tests of the relationship between exchange rate returns, intervention and macro announcements, it is interesting to examine the 25 largest returns over the sample period and the Reuters time-stamped events that surround these unusually large returns. Tables 3 and 4 present this information for USD-DEM returns and USD-JPY returns, respectively. The timing of large returns and the timing of macro announcements tends to be very closely aligned. For example, many of the large returns are timed within 10 seconds of a (scheduled) macroeconomic announcement. In contrast, some of the other large returns are only loosely connected in time with interventions. The Reuters' time stamp typically lag the large returns, sometimes by as much as two hours. Of course, it is possible that the "cause" of the large returns is unrelated to any news event reported by Reuters' (for example, the large returns may instead be related to inventory issues), but it is interesting to note that there are often wide gaps in the timing of large returns and intervention events as reported by Reuters.

Tables 5 and 6 present results of the event-study regression on USD-DEM and USD-JPY data, respectively.[18] In the case of USD-DEM returns, interventions by all three central banks are statistically significant, and in the cases of the Fed and the Bundesbank there is evidence of one hour Reuters' announcement lags. Three of the twelve macro announcements were found to be significant; and lag effects were found up to thirty minutes after the Reuters' time-stamp. There is evidence of mean reversion in the coefficient estimates of Fed intervention, where reversion was, on average, completed in three hours. The impact of the U.S. GNP announcement on USD-DEM returns was the largest by a wide margin, with U.S. consumer credit and Bundesbank intervention ranked second and third.

[18] Various regression specifications were attempted, including imposing a polynomial distributed lag structure on the leads and lags of the intervention variables. Tests of the pdl restrictions suggested that the data do not conform to this specification. Experimentation with various lead and lag combinations indicated that a [-1hr,+2hr] window for the intervention variables and a [0,1hr] window for the macroeconomic announcements was appropriate. In specifications that only included one-time influences (impact effects) of each announcement and intervention variable the right-hand-side variables were generally not found to be significant explanators of returns behavior.

Fed and Bundesbank intervention are also found to significantly influence USD-JPY returns, although Reuters' announcement lags are only found for the Fed. Surprisingly, BOJ intervention was not found to significantly influence USD-JPY returns. Once again, U.S. GNP had the largest impact on USD-JPY returns by a wide margin. There is no evidence of mean reversion in the USD-JPY regression.

In order to test whether interventions that occur during high volume periods have different effects than those in low volume times, a dummy variable distinguishing those Fed interventions that occurred during European trading hours was included in the event-study regressions. The results for both USD-DEM and USD-JPY rates are presented in Table 7. The regression results suggest the influence of intervention on returns is higher during high volume trading hours (defined as European trading hours) relative to low volume periods. Given that 61% of Fed interventions in the sample period occurred during European trading, the Fed seems to have already (perhaps inadvertently) exploited this phenomenon.

The Influence of Intervention on Volatility

A number of studies in the literature find evidence of unconditional leptokurtosis in daily exchange rate changes. This suggests that there exists temporal clustering in the variance of exchange rate changes: large changes are followed by large changes, and small changes by small changes. Hsieh (1989) and Diebold and Nerlove (1989) document that there is strong evidence of autoregressive conditional heteroscedasticity (ARCH) in the one step ahead prediction errors for daily dollar exchange rates. They conclude that the disturbances in the exchange rate process are uncorrelated but not stochastically independent. These studies indicate that the variance of daily and weekly exchange rate changes is forecastable using GARCH models.[19] However, at intra-daily frequencies studies find evidence that the coefficients in the standard GARCH sum to one -- implying that volatility is a random walk and can drift out to infinity or zero -- and that GARCH parameters are not stable.[20]

[19] See Engle, Ito and Lin (1990) and Dominguez (1997) for examples of GARCH studies using daily and weekly exchange rate data.

[20] See Andersen and Bollerslev (1996,1997) and Guillaume et al. (1997a).

Aside from the statistical problems arising in intra-daily GARCH models, conceptually GARCH does not provide an economic explanation for why volatility persists. A key assumption underlying GARCH models is the relative homogeneity of the price discovery process among market participants at the origin of the volatility process. If participants learn about certain types of news at different times (see Nenova (1997) for an example), or if participants have differing operational time horizons, this homogeneity assumption will not be valid.[21] For these reasons intra-daily forex volatility is not modelled using GARCH in this paper.

Figure 8 shows the average USD-DEM 5-minute volatility over the sample of Fed intervention days. The strong seasonal pattern in the volatility data is readily apparent and has been documented by Bollerslev and Domowitz (1993), Dacorogna et al. (1993) and Guillaume et al. (1997b). Failure to take account of these intra-daily seasonals is likely to result in misleading statistical analyses. There are numerous methods available in the literature to de-seasonalize intra-daily forex volatility. Baillie and Bollerslev (1990) suggest using seasonal dummies, Dacorogna et al. (1993) use time-scaling, Engle and Russel (1995) use the intensity of price changes as an alternative measure of volatility, Andersen and Bollerslev (1996) use a Fourier transform, and Ghysels, Gourieroux and Jasiak (1997) use a regression technique based on a stochastic volatility model. In this paper de-seasonalization of the volatility series is achieved using both the simple seasonal dummy approach[22] as well as the Ghysels et al. (1997) regression approach[23]. Figure 9 presents a graph of the de-seasonalized USD-DEM volatility series (using the dummy variable approach).

[21] Hogan and Melvin (1994) add the standard deviation of survey responses on forthcoming US Trade Balance data to a GARCH model of foreign exchange rates subsequent to that announcement. They find evidence that heterogenous expectations are a source of limited volatility spill-over effects (meteor showers).

[22] Tick-by-tick returns are regressed on 288 five-minute dummy variables, de-seasonalized volatility is computed as the squared deviation of returns from the fitted values of this regression. The de-seasonalized volatility is then transformed into a 5-minute series as described in footnote 17.

[23] In brief, the Ghysels et al. (1997) procedure involves regressing squared returns from the intervention sample on the number of quotes, spread and returns in the control sample data. The de-seasonalized volatility is then computed as the deviation of the squared returns from the fitted values from the regression.

I use two approaches to examine the influence of central bank intervention (and other macro announcements) on exchange rate volatility. The first approach is analogous to the "event study" test on exchange rate returns. The general regression specification is:

$$V^s_{t_i} = \alpha_0 + \sum_k \sum_n \alpha^k_{1,n} D^k_{t_{i+n}} + \varepsilon_{t_i}$$

where V^s is the de-seasonalized 5-minute volatility.

Table 8 presents the results of the volatility event-study regression using USD-DEM data. Significant one hour leads were found for intervention operations by all three central banks. There is evidence of mean reversion in the case of BOJ interventions. Seven of the twelve macro announcements are also found to be significant, with the significant lags varying from impact to one hour after the Reuters' time-stamp. Again, the announcement with the largest influence on USD-DEM variability is U.S. GNP.

The results of the USD-JPY volatility event-study regression are presented in Table 9. In contrast to the analogous USD-JPY returns regression, BOJ interventions are now significant and Bundesbank interventions are not. There is evidence of one hour Reuters' announcement lags for both the Fed and the BOJ, and there is no evidence of mean reversion. Six of twelve macro announcements are significant. U.S. GNP again has the largest effect, but less dramatically than in the USD-DEM regressions.

Table 10 presents results of returns and volatility event-study regressions that include interactive day-of-the-week dummy variables. These regressions allow me to test whether interventions on a particular day-of-week are more (or less) significant than operations on other days. The motivation for this set of regressions is the lore among central bankers that interventions on Fridays are less likely to be effective. The results suggest that day-of-week effects exist, but that they differ depending on the currency, central bank and dependent variable. Moreover, if anything, the results suggest that interventions on Friday are the most likely to be statistically significant. The frequency distributions of G-3 interventions is approximately evenly spread among the five days of the week, suggesting that central bankers did not put much stake on the "friday effect".

In table 11 the hypothesis that interventions in the morning have different effects than those in the afternoon is tested. Three interactive dummies are included in the event-study regressions distinguishing those days on which Fed interventions occurred in the morning, the afternoon, or over the full day. These additional variables were only found to be significant in the volatility regressions. In the USD-DEM volatility regression days on which the Fed only intervened in the morning, and days on which they intervened over the full day, are found to be significant. Results for the remaining variables in the regression were little changed by the inclusion of the interactive dummies. These results suggest that days on which the Fed intervened in the morning or throughout the day were more effective than Fed interventions on days when they only entered the forex market in the afternoon. Since the days on which the Fed was in the market throughout the day necessarily involved multiple interventions, this suggests that multiple (intra-daily) interventions are more effective, at least relative to interventions that only occur in the afternoon. This result is somewhat surprising in that we might have expected interventions to be less effective on days when the Fed needed to intervene on multiple occasions during the day.

The regression specification presented in Table 12 allows me to test whether interventions that are timed close to a (scheduled) macro announcement have different effects than those that are not. The dummy variable distinguishing those interventions that occurred within ninety minutes ahead or thirty minutes behind a macro announcement is significant in both the USD-DEM and USD-JPY volatility regressions. (The variable was not found to be significant in the returns regressions.) The relative size of the coefficients on the interactive dummy suggests that these interventions have larger effects than interventions that are not timed close to other announcements (although these continue to be significant in the regressions). One possible explanation for this result is that traders are more sensitive to news (including intervention news) in times when other major announcements are released.

A second approach I use to examine the influence of intervention on volatility arranges squared returns around interventions according to the intervention event rather than clock time. So that the first observation before an intervention report is the return recorded five minutes before the intervention report. I select a two-hour (before and after) window surrounding each G-3 intervention operation in the two currency markets, USD-DEM and USD-JPY. Intervention reports which follow a previous report within the two-hour window are excluded from the sample.[24] I then compare squared 5-minute returns from this "intervention sample" with a control sample of matched (by time-of-day and day-of-week) 5-minute volatility observations when no intervention was reported. (This sample comes from the control group of 25 days for each currency when no intervention occurred.) So, for example, if the BOJ intervened in the USD-JPY market on a Monday at 3:55 GMT, then the five minutes returns two hours before and after this event are included in the BOJ intervention sample. The matched control sample will likewise include an average of returns on all Mondays in the two hour window around 3:55 GMT.

The differences between exchange rate volatility surrounding the two-hour intervention and non-intervention periods can be seen in figures 10 through 15. There are a total of 47 (five-minute) volatility observations for each intervention: 23 before the report, one for the time that the report appears on the Reuters screen, and 23 volatility observations after the report. The figures indicate that volatility surrounding intervention periods is from five to twenty-five times (depending on the central bank and the currency) that during non-intervention periods in the interval [-30,+30] minutes. The average variance in the intervention sample typically remains higher than in the non-intervention period for over an hour before and after the intervention reports. Further, the peak difference in volatility occur between five and twenty minutes before the Reuters' time-stamp (0:00 on the graphs).

In order to test the equality of return variances through time in the period surrounding the intervention event versus the matched non-intervention sample a Brown-Forsythe (1974) modified Levene

[24] In the case of Fed interventions this criteria disqualified 151 out of 268 Fed interventions; for the BOJ this disqualified 37 out of 145 BOJ interventions; and for the Bundesbank the criteria disqualified 24 out of 83 Bundesbank interventions.

test is used.[25] The null hypothesis is that the variances at five-minute intervals surrounding the two samples are homoskedastic. The test statistic is approximately distributed as $F_{J-1,N-J}$ under the null (where j (j=1 to J) is the intraday period and N is the number of observations in the sample averages).[26] Results of these tests are presented in table 13. The return variance of both the USD-DEM and USD-JPY rates are found to vary significantly around Fed interventions. And, for the BOJ and the Bundesbank we can reject the hypothesis that return variances are constant in the interventions samples for the USD-JPY and USD-DEM, respectively. In the cases of the two control samples for Fed and BOJ intervention, we cannot reject the hypothesis of equal variances. However, in the case of the Bundesbank there is evidence of unequal return variance in both the USD-DEM and USD-JPY control samples.

In addition to analyzing whether average volatility in the period surrounding interventions is significantly higher than volatility during matched non-intervention periods, the FXFX data allow us to test whether the variance of quotes from specific banks is responsible for any significant differences. In other words, we can test whether quotes from the major banks that deal in the USD-DEM and USD-JPY markets are more variable around intervention events than is typical at the same times of day on non-intervention days. If certain banks systematically receive information regarding intervention before other banks, we might expect to find that it is these banks that drive up volatility around intervention events. Table 14 presents F-statistics for equality of variance in the two hours surrounding G-3 interventions using quotes from individual banks. The banks selected were those listed by Euromoney magazine as the most popular among corporate customers in the New York market for the Fed, the Tokyo market for the BOJ and the

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[25] The Brown and Forsythe (1974) test is robust to departures of the underlying data from normality. The test is also used by Chang and Taylor (1997) to examine the intra-day effects of BOJ intervention on USD-JPY volatility.

[26] The test statistic is:

$$F = \frac{\sum_{j=1}^{J} n_j \left(\overline{D_{.j}} - \overline{D_{..}}\right)^2}{\sum_{j=1}^{J}\sum_{i=1}^{n_j}\left(D_{ij} - \overline{D_{.j}}\right)^2} \frac{(N - J)}{(J - 1)}$$ **Error! Main Document Only.**

where $D_{ij} = |R_{ij} - M_{.j}|$; R_{ij} is the return for day i intraday period j; $M_{.j}$ is the sample median return for period j computed over the n_j days included in the test; $D_{.j}$ is the mean absolute deviation from the median for period j; and $D_{..}$ is the grand mean, where $N=\Sigma n_j$.

London market for the Bundesbank.[27] The statistics generally do not support the hypothesis that it is individual banks that systematically influence return variance surrounding intervention events. It is said that the G-3 central banks generally attempt to use a wide and variable selection of banks for their intervention transactions in order not to give any one bank unfair advantage. The results in Table 14 suggest that these attempts have been quite successful.[28]

IV. Conclusions

The tests in this paper explore whether the "state of the forex market" at the moment that central bank intervention operations (and macro announcements) are made public to traders matters. Using an event-study style regression and intra-daily FXFX data on each day that the Fed intervened in the USD-DEM and USD-JPY markets eight hypotheses were examined. The results of these regressions suggest that: (1) Fed intervention significantly influenced both USD-DEM and USD-JPY returns and volatility; (2) Bundesbank intervention significantly influenced USD-DEM returns and volatility. And, BOJ interventions significantly influenced USD-DEM and USD-JPY volatility. There is little evidence that BOJ operations influenced USD-JPY returns. (However, it is important to note that the days included in the sample were chosen on the basis of Fed interventions. So that the observations on Bundesbank and BOJ interventions are only those that occurred on days on which the Fed was also in the market.); (3) some traders know at least one hour prior to the Reuters' report that a central bank is intervening, and the effects of interventions generally persist, at least to the end of the day; (4) There is evidence of intra-daily mean reversion for Fed intervention on the USD-DEM returns, and BOJ interventions on USD-DEM volatility; (5) Fed interventions that occurred during European trading (a proxy for relatively heavy trading volume periods)

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[27] Euromoney magazine publishes its survey on the foreign exchange market annually. The banks selected appeared regularly (from 1989 to 1995) in the list of the five most popular banks in each market.

[28] Alternatively it may be that we will not be able to pick up individual bank effects in the indicative quote data. During heavy information periods such as the period surrounding an intervention event it may be that banks are less conscientious about updating quotes (recall that Goodhart, Ito and Payne (1996) find that the frequency of quotes is a relatively poor predictor of transaction frequency on D2000-2).

had relatively larger effects than those that occurred in low volume periods; (6) interventions that occur on particular days-of-the-week are relatively more influential than others. However, the days differ depending on the currency and central bank. There is no evidence (of the Central Banker lore) that interventions on Fridays are less effective than those on other days; (7) those days on which Fed interventions occurred in the morning, or in both the morning and afternoon were found to be more effective than those that occurred only in the afternoon; (8) those G-3 interventions that were closely timed to a scheduled macro announcement were more effective than those that were not; and (9) there is little evidence in the FXFX data that specific large banks in the USD-DEM and USD-JPY markets systematically act as price leaders in reaction to news of central bank intervention.

Overall, the tests in the paper support the hypothesis that central bank intervention influences intra-daily forex returns and volatility,[29] and the hypothesis that the efficacy of central bank intervention depends on the characteristics of the forex market at the time the operations become known to traders. Moreover, these results suggest that further empirical and theoretic exploration of the role of market microstructure in the determination of exchange rate behavior is warranted.

[29] This confirms LeBaron's (1996) result that profit opportunities exist on intervention days.

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Table 1 FXFX Descriptive Statistics

Full Sample of FXFX data 1987-1993 (based on 8,238,532 obs for DEM and 4,230,041 obs for JPY)

rate	time int.	mean	variance	skewness	kurtosis
USD/DEM	10 m	$-2.73 . 10^{-7}$	$2.62 . 10^{-7}$	0.17	35.10
	1 h	$-1.63 . 10^{-6}$	$1.45 . 10^{-6}$	0.26	23.55
	6 h	$-9.84 . 10^{-6}$	$9.20 . 10^{-6}$	0.24	9.44
	24 h	$-4.00 . 10^{-5}$	$3.81 . 10^{-5}$	0.08	3.33
USD/JPY	10 m	$-9.42 . 10^{-7}$	$2.27 . 10^{-7}$	-0.18	26.40
	1 h	$-5.67 . 10^{-6}$	$1.27 . 10^{-6}$	-0.09	25.16
	6 h	$-3.40 . 10^{-5}$	$7.63 . 10^{-6}$	-0.05	11.65
	24 h	$-1.37 . 10^{-4}$	$3.07 . 10^{-5}$	-0.15	4.81

Fed Intervention Days 1987-1995 (based on 1,169,684 obs for DEM and 438,039 obs for JPY)

rate	time int.	mean	variance	skewness*	kurtosis*
USD/DEM	5 m	$4.94 . 10^{-6}$	$6.85 . 10^{-9}$	0.33	2.31
	10 m	$9.89 . 10^{-6}$	$1.20 . 10^{-8}$	-0.17	3.23
	1 h	$5.42 . 10^{-5}$	$5.13 . 10^{-8}$	1.22	3.98
	24 h	$1.05 . 10^{-3}$	$5.95 . 10^{-5}$	-0.32	1.93
USD/JPY	5 m	$9.90 . 10^{-6}$	$5.02 . 10^{-9}$	0.58	0.66
	10 m	$1.98 . 10^{-5}$	$9.23 . 10^{-9}$	0.41	-2.63
	1 h	$1.14 . 10^{-4}$	$6.56 . 10^{-8}$	0.57	-0.32
	24 h	$2.99 . 10^{-3}$	$2.95 . 10^{-5}$	0.01	-3.14

Control Sample: 25 days 1987-1993 (based on 108,973 obs for DEM and 49,132 obs for JPY)

rate	time int.	mean	variance	skewness*	kurtosis*
USD/DEM	5 m	$-6.84 . 10^{-7}$	$1.52 . 10^{-9}$	0.95	5.75
	10 m	$-1.37 . 10^{-6}$	$3.15 . 10^{-9}$	1.21	1.79
	1 h	$1.13 . 10^{-6}$	$2.61 . 10^{-8}$	0.46	2.80
	24 h	$1.10 . 10^{-3}$	$2.16 . 10^{-5}$	2.29	8.53
USD/JPY	5 m	$-3.26 . 10^{-7}$	$1.07 . 10^{-9}$	0.27	1.66
	10 m	$-6.53 . 10^{-7}$	$1.96 . 10^{-9}$	0.50	-2.54
	1 h	$1.42 . 10^{-5}$	$2.73 . 10^{-9}$	-0.53	0.59
	24 h	$2.25 . 10^{-4}$	$1.37 . 10^{-5}$	0.61	0.42

The top panel of data are reproduced from Table 4 in Guillaume et al. (1997b).
** The skewness and kurtosis formulas are from Kendall and Stuart (1958).

Table 2 Selected Reuters Announcements (1989-1995)

News Event	Day-of-week	average time (GMT)
Fed Intervention	various	14:57:10
US Employment	Friday	12:30(DST);13:30
US CPI/PPI	Friday	12:30(DST);13:30
US M1	Thursday	20:30(DST);21:30
US Trade	various	12:30(DST);13:30
US Consumer Credit	various	19:30(DST)20:30
US Retail Sales	various	12:30(DST);13:30
US Leading Indicators	Wed or Fri	12:30(DST);13:30
US GNP	various	12:30(DST);13:30
FOMC news	Friday	20:30(DST);21:30
exchange rate comments by US officials	various	14:48:12
Bundesbank Intervention	various	11.31:16
Bundesbank Meeting	Thursday	11:30(DST):12:30
German M3	various	6:30(DST);7:30
exchange rate comments by German officials	various	10:27:13
BOJ Intervention	various	3:56:36
Japanese Current Account	various	6:30(DST);7:30
exchange rate comments by Japanese officials	various	6:51:07

DST denotes daylight savings time; otherwise, times are GMT.

Table 3 The 25 Largest 5-min USD-DEM Returns (1989-95)

DATE	TIME	RETURN	EVENT*	REUTERS TIME-STAMP
9/15/89	12:35:00	0.009458	CPI;Trade	12:36;12:36
9/15/89	18:20:00	0.005188	Fed	13:56
9/15/89	18:25:00	0.011564	BB	14:28
10/5/89	13:05:00	0.005004	BB	12:09 and 13:11
10/6/89	12:35:00	0.005968	Employment	12:34
1/10/90	15:15:00	0.006123	Fed	19:05
3/19/91	13:10:00	0.00525	Fed;BB	16:00-16:13
3/19/91	13:40:00	0.00514	CPI;Housing Starts	13:33
3/19/91	14:35:00	0.005161	Fed;BB	16:00-16:13
3/19/91	14:40:00	0.005647	Fed;BB	16:00-16:13
3/19/91	14:45:00	0.008245	Fed;BB	16:00-16:13
5/17/91	14:30:00	0.007094	Fed;BB	19:15-20:53
5/17/91	14:35:00	0.005674	Fed;BB	19:15-20:53
5/17/91	15:05:00	0.005492	Fed;BB	19:15-20:53
7/12/91	13:25:00	0.005715	Fed;BB	13:27
7/20/92	14:20:00	0.005532	Fed;BB	14:30
7/20/92	14:30:00	0.006298	Fed;BB	14:30
8/11/92	12:20:00	0.005553	Fed;BB	12:30
8/21/92	13:25:00	0.006027	Fed;BB	13:35
4/29/94	14:30:00	0.006037	Fed	14:40
11/2/94	16:05:00	0.007848	Fed	16:13-18:53
5/31/95	12:40:00	0.010738	Fed	12:49
5/31/95	12:45:00	0.005854	BB	12:45
5/31/95	12:55:00	0.006077	Fed	12:51-12:54
8/15/95	12:20:00	0.008128	BB;Fed;BOJ	12:49-12:58

NOTE: Fed Intervention Occurred on Each of These (69) Days

* Events are defined as any macro announcement or central bank intervention that occurred within a [-1hr,5hr] window of the large return.

Table 4 The 25 Largest 5-min USD-JPY Returns (1989-95)

DATE	TIME	RETURN	EVENT*	REUTERS TIME-STAMP
9/15/89	12:35:00	0.005344	CPI;Trade;Fed;BB	12:36;12:36;13:56;14:28
9/15/89	18:20:00	0.007393	Fed;BB	13:56;14:28
9/15/89	18:25:00	0.005687	Fed;BB	13:56;14:28
9/15/89	18:35:00	0.006791	Fed;BB	13:56;14:28
10/6/89	12:35:00	0.005976	Employment;Fed	12:34;13:42
1/17/92	18:35:00	0.005997	Fed	18:38
1/17/92	19:10:00	0.005314	BOJ	19:14
1/17/92	19:15:00	0.004613	BOJ	19:14
4/27/93	12:55:00	0.004626	Fed	13:05-14:15
8/19/93	12:35:00	0.005207	Trade	12:30
8/19/93	14:30:00	0.005635	Fed	14:39
8/19/93	15:05:00	0.005217	Fed	15:07
4/29/94	13:10:00	0.005025	Fed	14:38-16:08
5/4/94	12:30:00	0.005113	Fed;BB	12:33;12:34
6/24/94	13:15:00	0.005839	Fed;BB;BOJ	13:45-16:59
6/24/94	13:35:00	0.005378	Fed;BB;BOJ	13:45-16:59
11/2/94	16:05:00	0.007266	Fed	16:13-18:58
5/31/95	12:40:00	0.008712	Fed	12:49
5/31/95	12:45:00	0.008348	BB	12:45
5/31/95	12:55:00	0.007176	Fed	12:51-12:54
5/31/95	14:30:00	0.004466	Fed	13:47
8/2/95	13:10:00	0.005012	Fed;BOJ	13:13;13:30
8/15/95	12:20:00	0.005948	BB;Fed;BOJ	12:49;12:58
8/15/95	23:25:00	0.004811	Fed;BB;US Retail Sales	14:28;14:24;19:06
8/15/95	24:00:00	0.004664	Fed;BB;US Retail Sales	14:28;14:24;19:06

NOTE: Fed Intervention Occurred on Each of These (66) Days
Events are defined as any macro announcement or central bank intervention that occurred within a [-1hr,5hr] window of the large return.

Table 5 USD-DEM RETURNS

$$R_{t_i} = \alpha_0 + \sum_k \sum_n \alpha^k_{1,n} D^k_{t_{i+n}} + \varepsilon_{t_i}$$

where R is the 5-min USD-DEM return; D^k includes the intervention and macro announcements; n=-1 to +2hrs for the G-3 intervention variables and official announcements and n=0 to +1hr for the macro announcements; t_i is the sequence of the regular-spaced (every 5 minutes) intra-daily data for all the days on which the Fed intervened against the mark from 1989 to 1995 (69 days). The (max) coefficient is multiplied by 1000.

Intervention or Macro Announcement	Significant leads	Significant lags	max coeff	robust t-stat	corresponding lead or lag	Mean Reversion
Fed Intervention	1hr-15min	55min-2hrs	0.69	2.20	1hr lead	yes
Bundesbank Intervention	1hr-5min	5min-40min	2.32	4.13	1hr lead	no
BOJ Intervention		50min-2hrs	0.64	2.15	2hr lag	no
US Employment						
Bundesbank Meeting						
German M3						
US CPI						
US M1						
US Trade						
US Consumer Credit		15min-30min	3.74	2.28	30min lag	no
US Retail Sales						
US Leading Indicators						
US GNP		5min-10min	37.52	1.70	5min lag	no
Japanese Current Account		15min-25min	1.91	1.85	15min lag	no
FOMC news						
Japanese official						
US official*						
German official		35min-1hr	0.80	1.72	15min lag	no

Number of observations= 19,833; R^2=0.022; D.W.=1.88. * In some specifications 30min to 2hr lags on US official announcements are significant, with the maximum coefficient at the 2hr lag.

Table 6 USD-JPY RETURNS

$$R_{t_i} = \alpha_0 + \sum_k \sum_n \alpha_{1,n}^k D_{t_{i+n}}^k + \varepsilon_{t_i}$$

where R is the 5-minute USD-JPY return; D^k includes the intervention and macro announcements; n=-1 to +2hrs for the G-3 intervention variables and official announcements and n=0 to +1hr for the macro announcements; t_i is the sequence of the regular-spaced (every 5 minutes) intra-daily data for all the days on which the Fed intervened against the yen from 1989 to 1995 (66 days). The (max) coefficient is multiplied by 10000.

Intervention or Macro Announcement	Significant leads	Significant lags	max coeff	robust t-stat	corresponding lead or lag	Mean Reversion
Fed Intervention	1hr-5min	0-40min	0.11	3.71	1hr lead	no
Bundesbank Intervention		45min-2hrs	1.04	2.18	2hr lag	no
BOJ Intervention						
US Employment						
Bundesbank Meeting						
German M3		15min-30min	13.39	1.75	30min lag	no
US CPI						
US M1						
US Trade						
US Consumer Credit		15min-30min	2.52	1.76	30min lag	no
US Retail Sales		20min-30min	6.80	1.96	30min lag	no
US Leading Indicators						
US GNP		5min-10min	23.77	1.72	5min lag	no
Japanese Current Account						
FOMC news						
Japanese official	1hr-5min	0-40min	0.96	2.35	1hr lead	no
US official		35min-2hrs	1.92	2.68	2hr lag	no
German official						

Number of observations=18,969; R^2=0.015; D.W.=1.90.

Table 7 INFLUENCE OF EUROPEAN TRADING HOURS

$$R_{t_i} \;=\; \alpha_0 \;+\; \sum_k \sum_n \alpha_{1,n}^{k} D_{t_{i+n}}^{k} \;+\; \sum_n \alpha_{2,n} E_{t_{i+n}} \;+\; \varepsilon_{t_i}$$

where R is the 5-minute return; D^k includes the intervention and macro announcements that were found to be significant in tables x or x; n=-1 to +1hr for the intervention variables and n=0 to +1hr for the macro announcements; E is a dummy variable distinguishing those Fed interventions that occurred during European trading hours; t_i is the sequence of the regular-spaced (every 5 minutes) intra-daily data for all the days on which the Fed intervened against the mark or yen from 1989 to 1995 (69 or 66 days). The (max) coefficient is multiplied by 10^{-5}.

USD-DEM RETURNS

Intervention or Macro Announcement	Significant leads	Significant lags	max coeff	robust t-stat	corresponding lead or lag
Europe*Fed	1hr-15min	1hr-2hrs	0.75	1.81	1hr lead
Fed Intervention	none	none			
Bundesbank Intervention	1hr-5min	0-45min	2.37	4.06	1hr lead
BOJ Intervention	1hr-40min		0.62	1.72	1hr lead
US Consumer Credit		20min-30min	3.75	2.31	30min lag
US GNP	0	36.47	1.69	impact	
Japanese Current Account		20min-25min	1.83	1.84	20min lag

Number of observations= 19,833; R^2=0.014; D.W.=1.88.

NOTE: 61% of Fed interventions occurred during European trading hours. Fed interventions during European trading hours are also found to be significant in the USD-DEM volatility regression.

USD-JPY RETURNS

Europe*Fed	1hr-5min	0-35min	1.37	2.61	1hr lead
Fed Intervention	none	none			
Bundesbank Intervention	1hr-5min	0-45min	2.06	2.95	1hr lead
German M3		15min-20min	6.82	1.77	15min lag
US Consumer Credit		20min-30min	2.26	1.72	30min lag
US GNP	0	22.76	1.69	impact	
Japanese official	25min-5min	0	0.54	1.75	25min lead

Number of observations=18,969; R^2=0.012; D.W.=1.90.

NOTE: 61% of Fed interventions occurred during European trading hours. Fed interventions during European trading hours are not found to be significant in the USD-JPY volatility regression.

Table 8 USD-DEM VOLATILITY

$$V^{s}_{t_i} = \alpha_0 + \sum_k \sum_n \alpha^{k}_{1,n} D^{k}_{t_{i+n}} + \varepsilon_{t_i}$$

where V^s is the de-seasonalized 5-minute volatility; D^k includes the intervention and macro announcements; n=-1 to +2hrs for the G-3 intervention variables and official announcements and n=0 to +1hr for the macro announcements; t_i is the sequence of the regular-spaced (every 5 minutes) intra-daily data for all the days on which the Fed intervened against the mark from 1989 to 1995 (69 days). The (max) coefficient is multiplied by 10^{-5}.

Intervention or Macro Announcement	Significant leads	Significant lags	max coeff	robust t-stat	corresponding lead or lag	Mean Reversion
Fed Intervention	1hr-5min	0-1hr	0.80	5.26	1hr lead	no
Bundesbank Intervention	1hr-5min	0-1hr	1.22	3.16	1hr lead	no
BOJ Intervention	1hr-10min	50min-1hr	0.38	2.16	1hr lead	yes
US Employment						
Bundesbank Meeting		20min-1hr	2.29	2.04	1hr lag	no
German M3		0-10min	0.95	2.30	impact	no
US CPI		20min-35min	7.43	1.70	20min lag	no
US M1		0-45min	0.07	2.19	impact	no
US Trade						
US Consumer Credit						
US Retail Sales						
US Leading Indicators		0-15min	0.96	2.93	impact	no
US GNP		0-30min	27.37	1.67	impact	no
Japanese Current Account		5min-1hr	0.43	2.42	1hr lag	no
FOMC news						
Japanese official		10min-2hrs	0.32	2.70	2hrs lag	no
US official	10min-5min	0-2hrs	2.07	1.68	2hrs lag	no
German official						

Number of observations=19,833; R^2=0.057; D.W.=1.77.

Table 9 USD-JPY VOLATILITY

$$V^s_{t_i} = \alpha_0 + \sum_k \sum_n \alpha^k_{1,n} D^k_{t_{i+n}} + \varepsilon_{t_i}$$

where V^s is the de-seasonalized 5-min volatility; D^k includes the intervention and macro announcements; n=-1 to +2hrs for the G-3 intervention variables and official announcements and n=0 to +1hr for the macro announcements; t_i is the sequence of the regular-spaced (every 5 min) intra-daily data for all the days on which the Fed intervened against the mark from 1989 to 1995 (66 days). The (max) coefficient is multiplied by 10^{-5}.

Intervention or Macro Announcement	Significant leads	Significant lags	max coeff	robust t-stat	corresponding lead or lag	Mean Reversion
Fed Intervention	1hr-5min	0-1hr15min	0.30	3.41	1hr lead	no
Bundesbank Intervention						
BOJ Intervention	1hr-5min	0-1hr	0.30	4.15	1hr lead	no
US Employment						
Bundesbank Meeting						
German M3		5min-1hr	0.29	2.72	1hr lag	no
US CPI						
US M1		5min-1hr	0.08	1.84	1hr lag	no
US Trade						
US Consumer Credit		15min-1hr	0.48	2.20	1hr lag	no
US Retail Sales		5min-45min	0.31	1.76	5min	no
US Leading Indicators						
US GNP		25min-30min	1.74	1.72	25min lag	no
Japanese Current Account		30min-1hr	0.09	2.03	1hr lag	no
FOMC news		0-1hr	0.29	1.99	1hr lag	no
Japanese official*						
US official		15min-2hrs	1.23	2.31	2hr lag	no
German official						

Number of observations=18,969; R^2=0.005; D.W.=1.91.* In some specifications 1hr to 2hr lags on Japanese official announcements are significant, with the maximum coefficient at 2 hours.

Table 10 DOES IT MATTER ON WHAT DAY-OF-THE WEEK INTERVENTION OCCURS?

$$A_{t_i} = \alpha_0 + \sum_g \sum_n \alpha^g_{1,n} D^g_{t_{i+n}} + \sum_d \sum_n \alpha^d_{2,n} D^j_{t_{i+n}} * W^d_t + \varepsilon_{t_i}$$

where A is the 5-minute return or the de-seasonalized 5-minute volatility; D^g includes the macro announcements and two of the G-3 intervention variables; D^j is the remaining G-3 intervention variable (such that $D^g+D^j=D^k$); W^d is a dummy variable for each day of week d=1,..,5; n=-1 to +2hrs for the intervention variable and n=0 to +1hr for the macro announcements; t_i is the sequence of the regular-spaced (every 5 minutes) intra-daily data for all the days on which the Fed intervened against the mark or yen from 1989 to 1995 (69 or 66 days).

Currency	Dependent Variable	Intervention Variable	Mon	Tues	Wed	Thurs	Fri
USD-DEM	Returns	Fed			x		x
		Bundesbank	x	x			x
		BOJ		x			x
	Volatility	Fed			x	x	x
		Bundesbank	x			x	
		BOJ					
USD-JPY	Returns	Fed	x		x		x
		Bundesbank	x	x			x
		BOJ					
	Volatility	Fed		x	x	x	x
		Bundesbank		x	x	x	
		BOJ		x	x	x	x

x denotes that interventions by the indicated central bank on this day-of-week significantly influenced the dependent variable (returns or volatility) in the regression.

Table 11 INFLUENCE OF TIME OF DAY (MORNING vs AFTERNOON)

$$V^s_{t_i} = \alpha_0 + \sum_k \sum_n \alpha^k_{1,n} D^k_{t_{i+n}} + \sum_n \alpha_{2,n} M_{t_{i+n}} + \varepsilon_{t_i}$$

where V^s is the de-seasonalized 5-minute volatility; D^k includes the intervention and macro announcements that were found to be significant in tables x or x; n=-1 to +1hr for the intervention variables and n=0 to +1hr for the macro announcements; AM is a dummy variable distinguishing days on which Fed interventions occurred before noon EST; PM is a dummy variable distinguishing days on which Fed interventions occurred after noon EST; and AMPM is a dummy variable distinguishing days on which the Fed intervened in both the morning and afternoon; t_i is the sequence of the regular-spaced (every 5 min) intra-daily data for all the days on which the Fed intervened against the mark or yen from 1989 to 1995 (69 or 66 days). The (max) coefficient is multiplied by 10^{-5}.

USD-DEM VOLATILITY

Intervention or Macro Announcement	Significant leads	Significant lags	max coeff	robust t-stat	corresponding lead or lag
AM*Fed	1hr-5min	0-1hr40min	0.85	2.40	1hr lead
PM*Fed		30-2hrs	0.29	2.17	2hr lag
AMPM*Fed	25min-5min	0-30min	0.45	1.68	25min lead
Fed Intervention		20min-1hr	0.68	4.05	1hr lag
Bundesbank Intervention	1hr-5min	0-30min	1.30	2.85	1hr lead
BOJ Intervention	1hr-30min	40min-1hr	0.38	4.07	1hr lag
Bundesbank Meeting		20min-1hr	0.23	2.09	20min lag
German M3		0-5min	0.51	2.52	impact
US CPI		20min-35min	7.35	1.68	20min lag
US M1		0-45min	0.06	2.09	impact
US GNP		0-30min	27.1	1.69	impact
Japanese Current Account		0-1hr	0.47	2.51	1hr lag

Number of observations=19,833; R^2=0.052; D.W.=1.78.

USD-JPY VOLATILITY

Intervention or Macro Announcement	Significant leads	Significant lags	max coeff	robust t-stat	corresponding lead or lag
AM*Fed					
PM*Fed					
AMPM*Fed	1hr-5min	0-40min	0.80	2.37	1hr lead
Fed Intervention	1hr-5min	0-25min	1.36	4.03	1hr lead
BOJ Intervention	1hr-5min	0-10min	0.37	4.51	1hr lead
German M3		0-1hr	0.27	2.62	1hr lag
US M1		15min-1hr	0.11	2.80	1hr lag
US Consumer Credit		15min-1hr	0.50	2.32	1hr lag
US Retail Sales		5min-45min	0.33	1.76	5min lag
US GNP		30min	1.63	1.67	20min lag
Japanese Current Account		0-35min	0.92	1.70	20min lag
FOMC news		0-25min	0.21	3.21	impact

Number of observations=18,969; R^2=0.038; D.W.=1.90.
In the USD-DEM data 43% of Fed interventions occurred in the am; 13% in the pm; and 44% over the full day. In the USD-JPY data 57% of Fed interventions occurred in the am; 16% in the pm; and 24% over the full day.

Table 12 INFLUENCE OF PROXIMITY OF A MACRO ANNOUNCEMENT

$$V^s_{t_i} = \alpha_0 + \sum_k \sum_n \alpha^k_{1,n} D^k_{t_{i+n}} + \sum_n \alpha_{2,n} M_{t_{i+n}} + \varepsilon_{t_i}$$

where V^s is the de-seasonalized 5-minute volatility; D^k includes the intervention and macro announcements that were found to be significant in tables x or x; n=-1 to +1hr for the intervention variables and n=0 to +1hr for the macro announcements; M is a dummy variable distinguishing those interventions that occurred within 90min ahead or 30min behind a macro announcement; t_i is the sequence of the regular-spaced (every 5 minutes) intra-daily data for all the days on which the Fed intervened against the mark or yen from 1989 to 1995 (69 or 66 days). The (max) coefficient is multiplied by 10^{-5}.

USD-DEM VOLATILITY

Intervention or Macro Announcement	Significant leads	Significant lags	max coeff	robust t-stat	corresponding lead or lag
Fed Intervention	1hr-5min	0-25min	1.07	5.23	1hr lead
Bundesbank Intervention	1hr-5min	0-30min	1.15	2.48	1hr lead
BOJ Intervention		10min-1hr	0.16	5.03	1hr lag
Bundesbank Meeting		20min-1hr	0.17	1.83	20min lag
German M3		0-5min	0.51	2.52	impact
US CPI		20min-30min	5.56	1.67	20min lag
US M1		0-45min	0.17	2.16	impact
US GNP	0	23.82	1.69	impact	
Japanese Current Account		0-1hr	0.95	3.00	1hr lag
Macro Dummy	1hr-5min	0-55min	2.58	2.29	1hr lead

Number of observations=19,833; R^2=0.057; D.W.=1.76.

USD-JPY VOLATILITY

Fed Intervention	1hr-5min	0-1hr	0.35	2.57	1hr lead
BOJ Intervention	1hr-5min	0-10min	0.34	4.81	1hr lead
German M3		0-1hr	0.27	2.62	1hr lag
US M1		15min-1hr	0.11	2.87	1hr lag
US Consumer Credit		35min-1hr	0.44	1.84	1hr lag
US Retail Sales		5min-45min	0.31	1.76	5min lag
US GNP	25min-30min	2.08	1.69	25min lag	
Japanese Current Account		0-35min	0.57	1.73	impact
FOMC news		0-1hr	0.50	2.06	1hr lag
Macro Dummy	1hr-5min	0-45min	1.38	1.78	1hr lead

Number of observations=18,969; R^2=0.039; D.W.=1.90.
7% of interventions are timed close to a macro announcement in the USD-DEM market; 10% of interventions are timed close to a macro announcement in the USD-JPY market.

Table 13 Tests of the Equality of Return Variances
Two Hours Before and After Interventions by the G-3
and in Matched Control Samples

I Fed Intervention	Intervention Sample	Control Sample
USD-DEM	3.4509**	0.9034
USD-JPY	1.7147**	0.8851
critical values F(38,2691) = 1.4094 (5%) and 1.6202 (1%)		
II. BOJ Intervention		
USD-DEM	1.2057	0.8762
USD-JPY	1.9372**	0.9618
critical values F(38,1716) = 1.4119 (5%) and 1.6213 (1%)		
III. Bundesbank Intervention		
USD-DEM	2.8319**	1.4569*
USD-JPY	1.0242	1.5015*
critical values F(38,1209) = 1.4149 (5%) and 1.6268 (1%)		

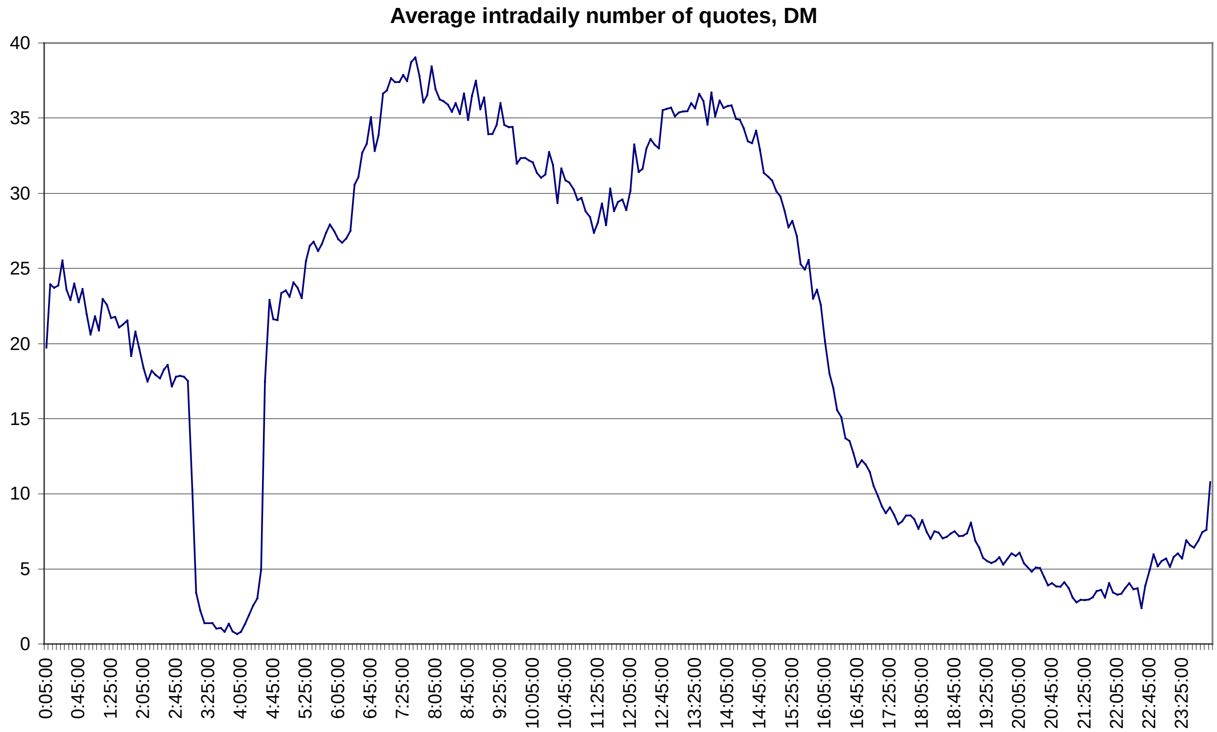
The Fed intervention sample includes 70 Reuters reports; the BOJ intervention sample includes 45 Reuters reports; and the Bundesbank intervention sample includes 32 intervention reports. The F-test statistics are for the equality of variance over the [-120,+120] interval.

Table 14 Tests of the Equality of Return Variances
Two Hours Before and After Interventions by the G-3
Using Individual Banks' Quotes

I Fed Intervention	USD-DEM	USD-JPY
Chemical Bank	0.7657	1.4175*
Morgan Guaranty	0.7	0.9438
Citibank	1.3546	1.108
critical values F(38,2691) = 1.4094 (5%) and 1.6202 (1%)		
II. BOJ Intervention		
Chemical Bank	0.83	0.9733
Morgan Guaranty	1.7785**	1.0454
Deutsche Bank	0.8153	0.8705
BHF	0.9328	0.9732
Bank of Tokyo	0.9419	1.2888
critical values F(38,1716) = 1.4119 (5%) and 1.6213 (1%)		
III. Bundesbank Intervention		
Chemical Bank	0.9354	0.931
Morgan Guaranty	1.4264*	0.8585
Deutsche Bank	0.9084	1.0059
Dresdner Bank	1.0111	1.2307
critical values F(38,1209) = 1.4149 (5%) and 1.6268 (1%)		

The Fed intervention sample includes 70 Reuters reports; the BOJ intervention sample includes 45 Reuters reports; and the Bundesbank intervention sample includes 32 intervention reports. The F-test statistics are for the equality of variance over the [-120,+120] interval.

FIGURE 1



Average intradaily number of quotes, DM
40
35
30
25
20
15
10
5
0
0:05:00
0:45:00
1:25:00
2:05:00
2:45:00
3:25:00
4:05:00
4:45:00
5:25:00
6:05:00
6:45:00
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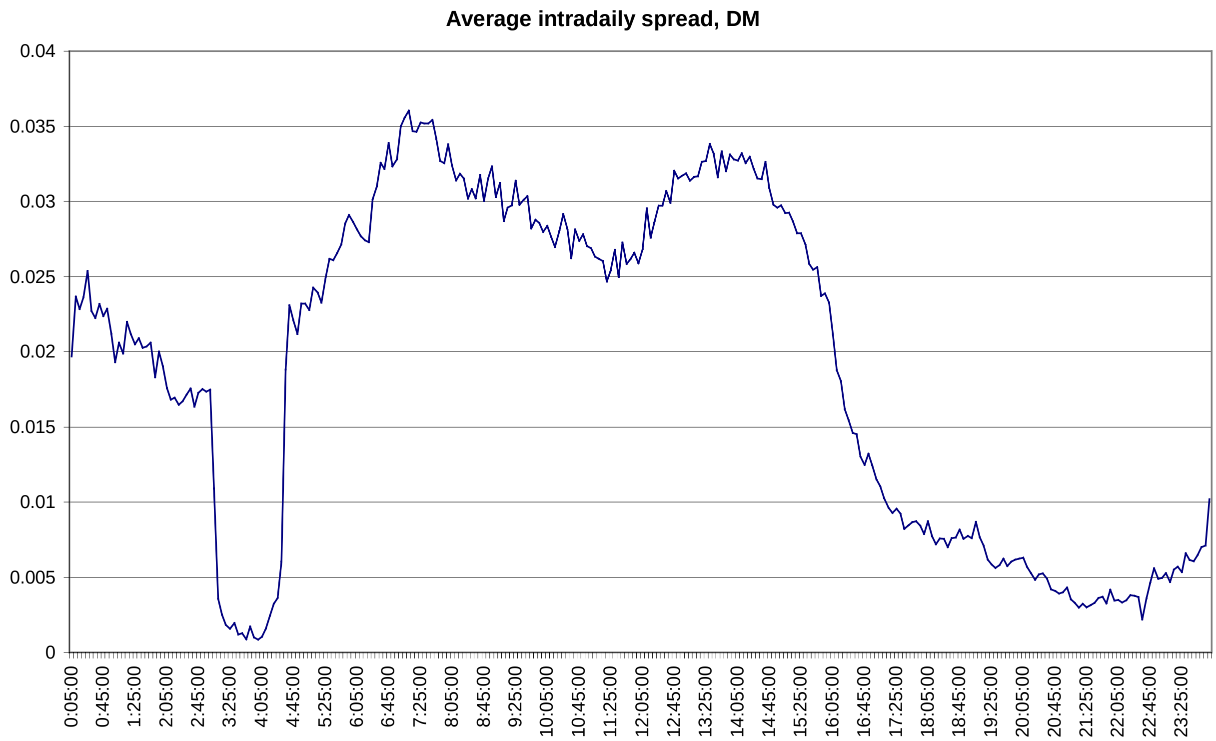
14:05:00
14:45:00
15:25:00
16:05:00
16:45:00
17:25:00
18:05:00
18:45:00
19:25:00
20:05:00
20:45:00
21:25:00
22:05:00
22:45:00
23:25:00

FIGURE 2


Average intradaily spread, DM
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0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
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0:45:00
1:25:00
2:05:00
2:45:00
3:25:00
4:05:00
4:45:00
5:25:00
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18:45:00
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23:25:00

FIGURE 3

$/dm on May 31, 1995

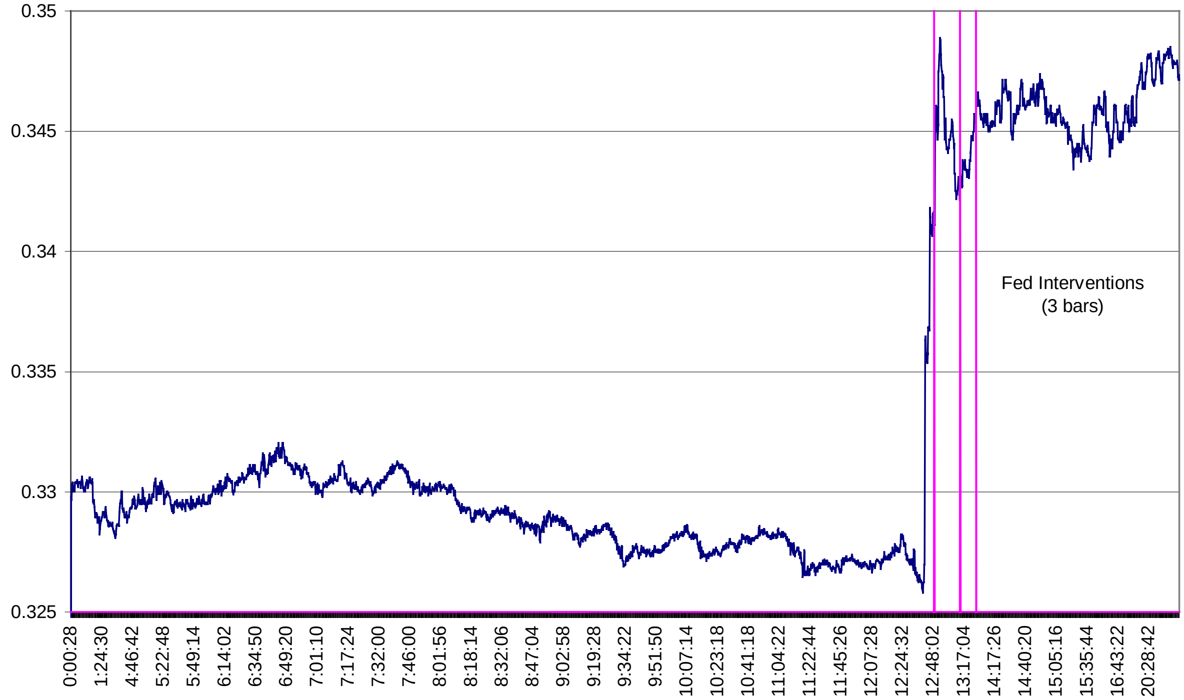
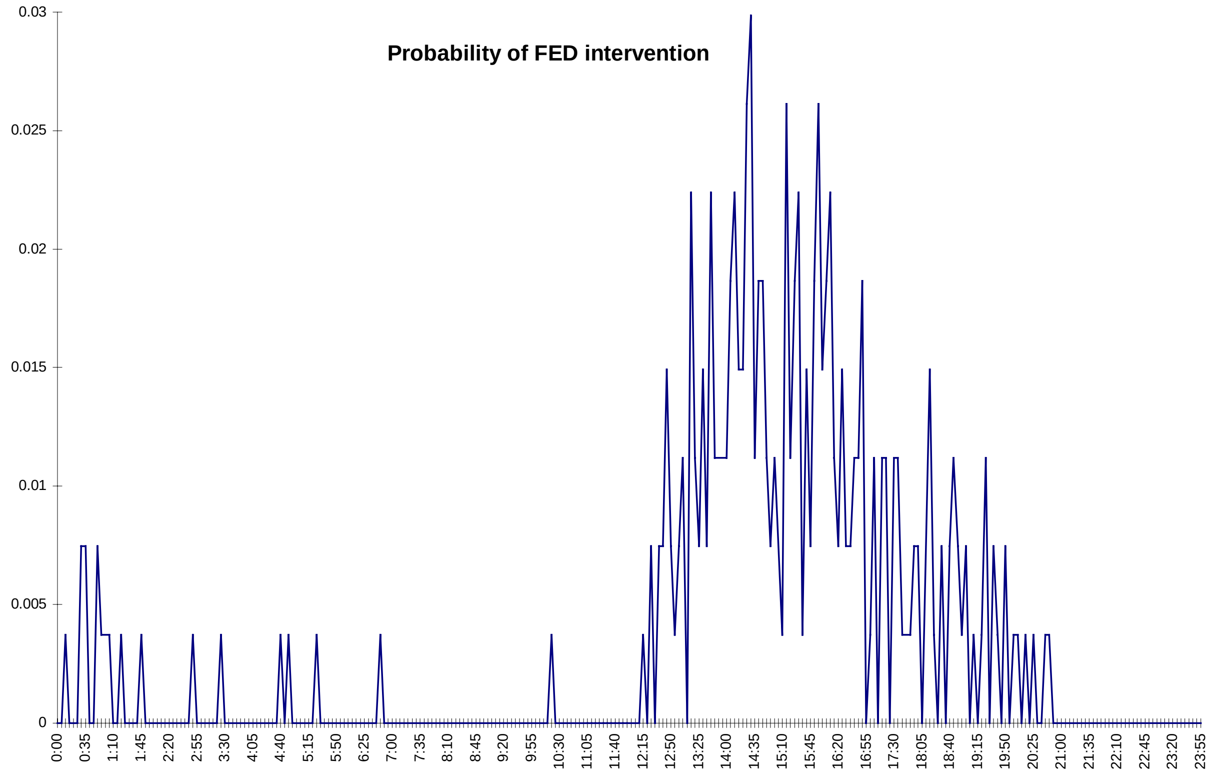
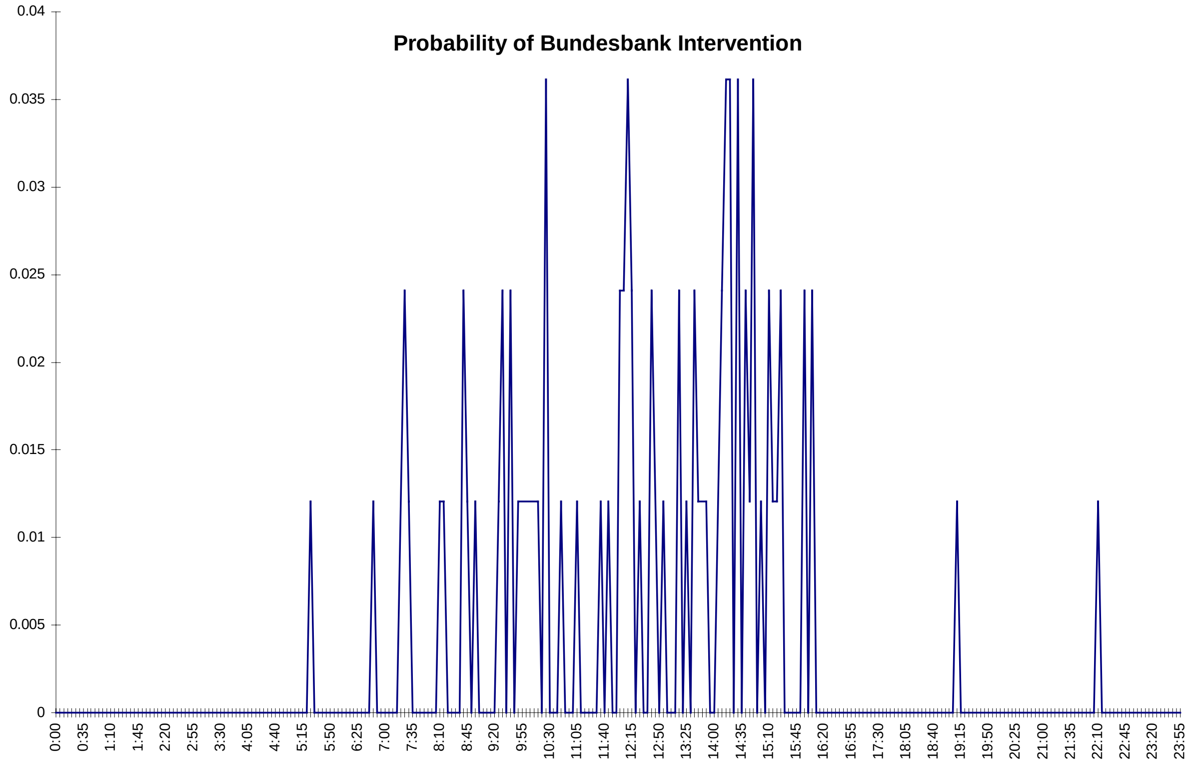


FIGURE 4



Probability of FED intervention
0.03
0.025
0.02
0.015
0.01
0.005
0
0:00
0:35
1:10
1:45
2:20
2:55
3:30
4:05
4:40
5:15
5:50
6:25
7:00
7:35
8:10
8:45
9:20
9:55
10:30
11:05
11:40
12:15
12:50
13:25
14:00
14:35
15:10
15:45
16:20
16:55
17:30
18:05
18:40
19:15
19:50
20:25
21:00
21:35
22:10
22:45
23:20
23:55

FIGURE 5



Probability of Bundesbank Intervention
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0:00
0:35
1:10
1:45
2:20
2:55
3:30
4:05
4:40
5:15
5:50
6:25
7:00
7:35
8:10
8:45
9:20
9:55
10:30
11:05
11:40
12:15
12:50
13:25
14:00
14:35
15:10
15:45
16:20
16:55
17:30
18:05
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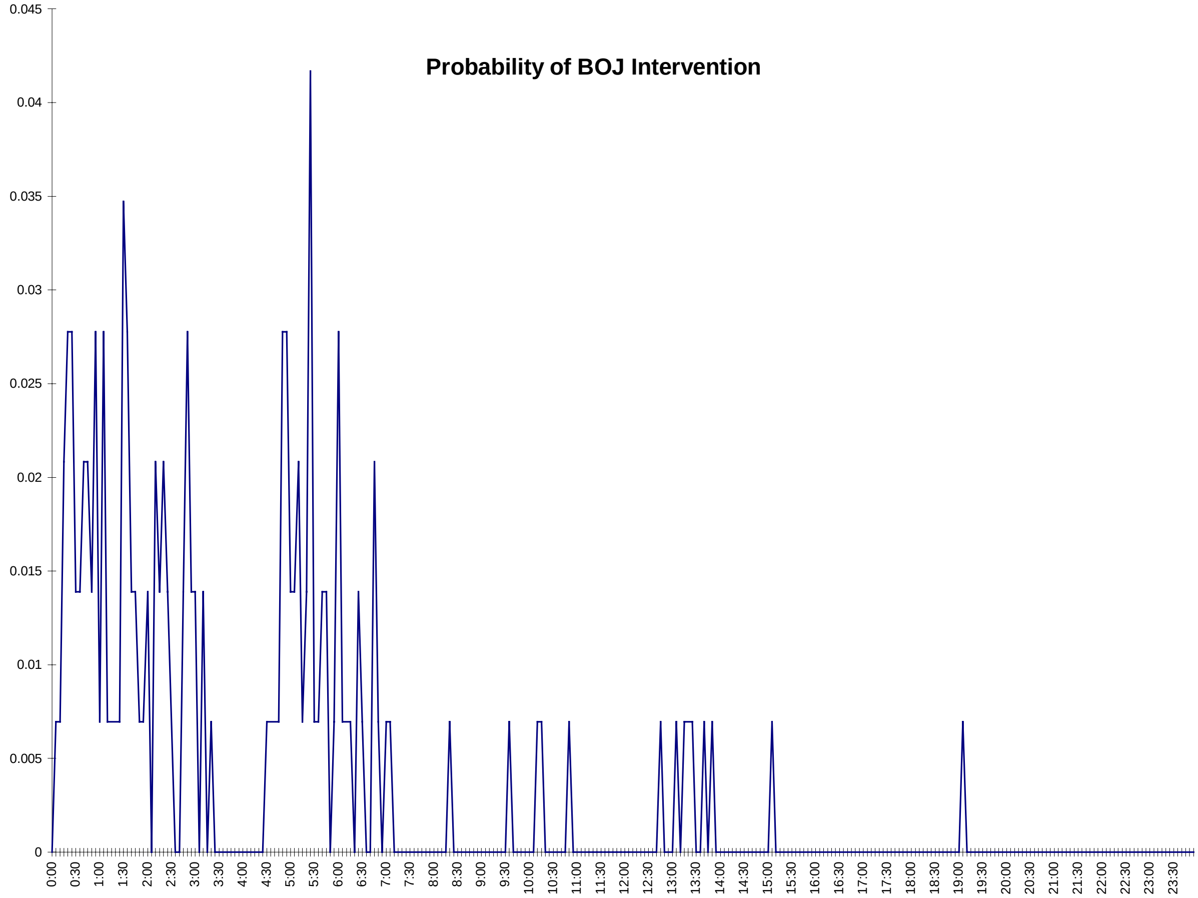
21:00
21:35
22:10
22:45
23:20
23:55

FIGURE 6



Probability of BOJ Intervention
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0:00
0:30
1:00
1:30
2:00
2:30
3:00
3:30
4:00
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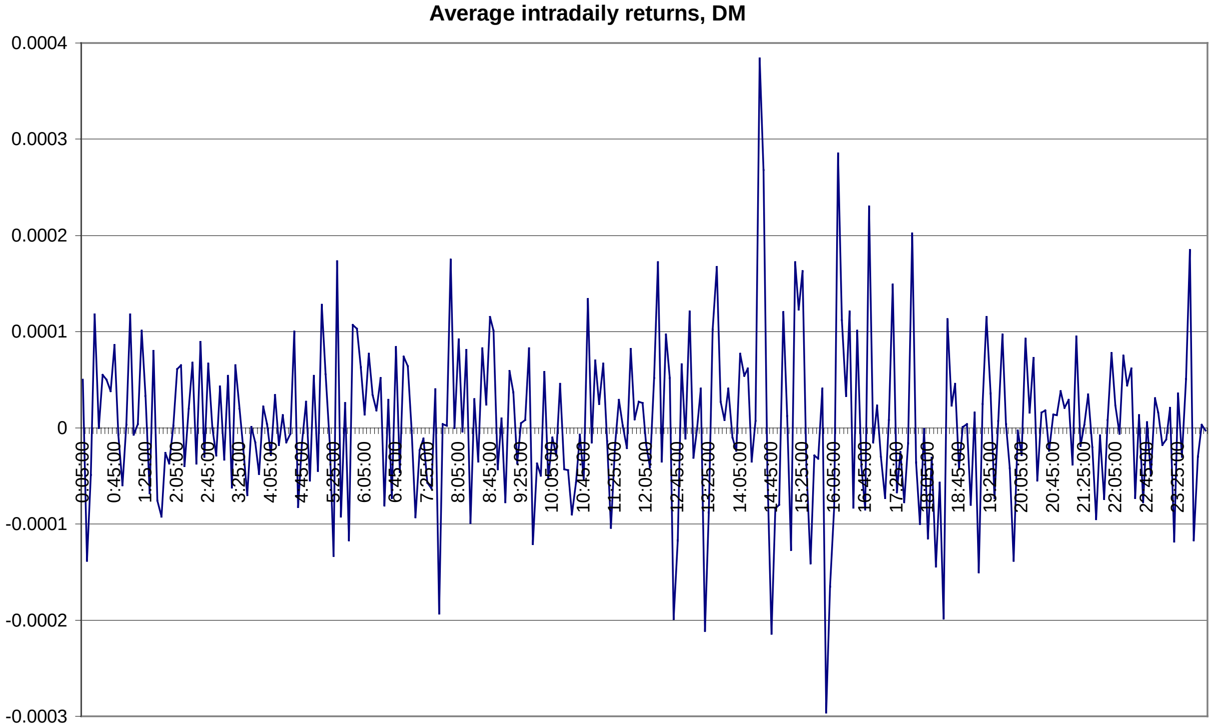
23:00
23:30

FIGURE 7



Average intradaily returns, DM
0.0004
0.0003
0.0002
0.0001
0
-0.0001
-0.0002
-0.0003
0:05:00
0:45:00
1:25:00
2:05:00
2:45:00
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4:05:00
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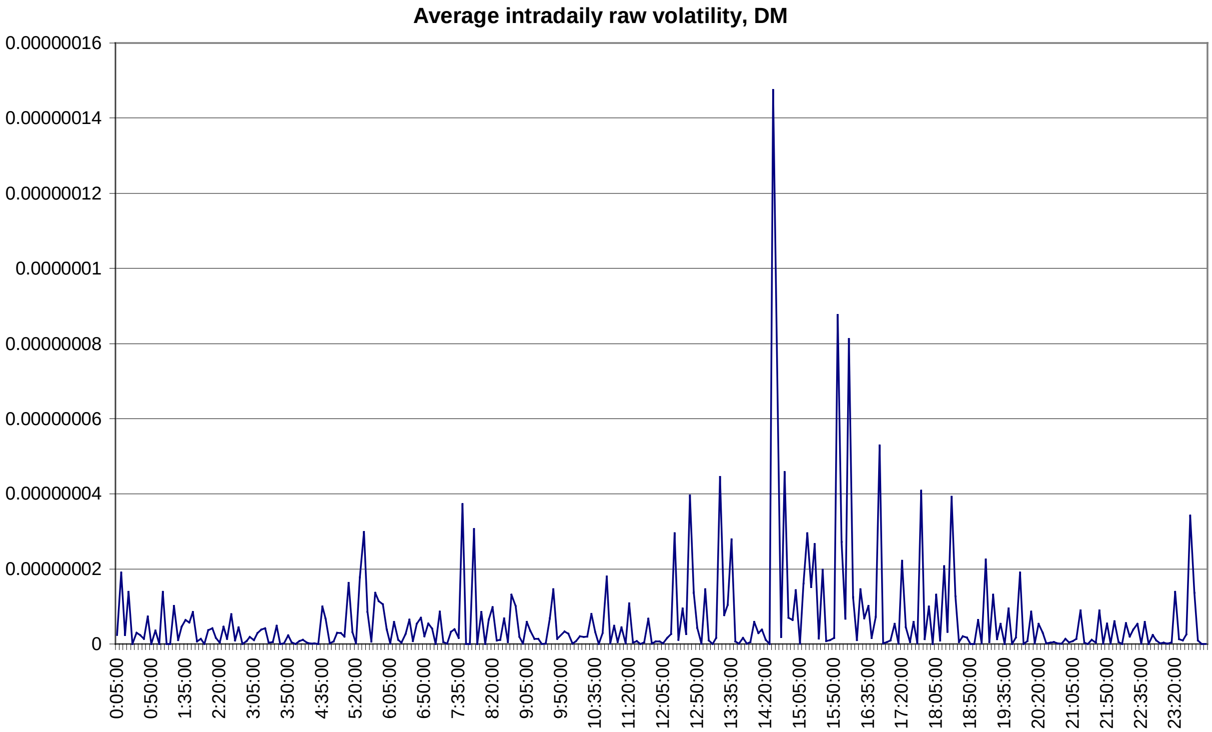
18:45:00
19:25:00
20:05:00
20:45:00
21:25:00
22:05:00
22:45:00
23:25:00

FIGURE 8



Average intradaily raw volatility, DM
0.00000016
0.00000014
0.00000012
0.0000001
0.00000008
0.00000006
0.00000004
0.00000002
0
0:05:00
0:50:00
1:35:00
2:20:00
3:05:00
3:50:00
4:35:00
5:20:00
6:05:00
6:50:00
7:35:00
8:20:00
9:05:00
9:50:00
10:35:00
11:20:00
12:05:00
12:50:00
13:35:00
14:20:00
15:05:00
15:50:00
16:35:00
17:20:00
18:05:00
18:50:00
19:35:00
20:20:00
21:05:00
21:50:00
22:35:00
23:20:00

FIGURE 9

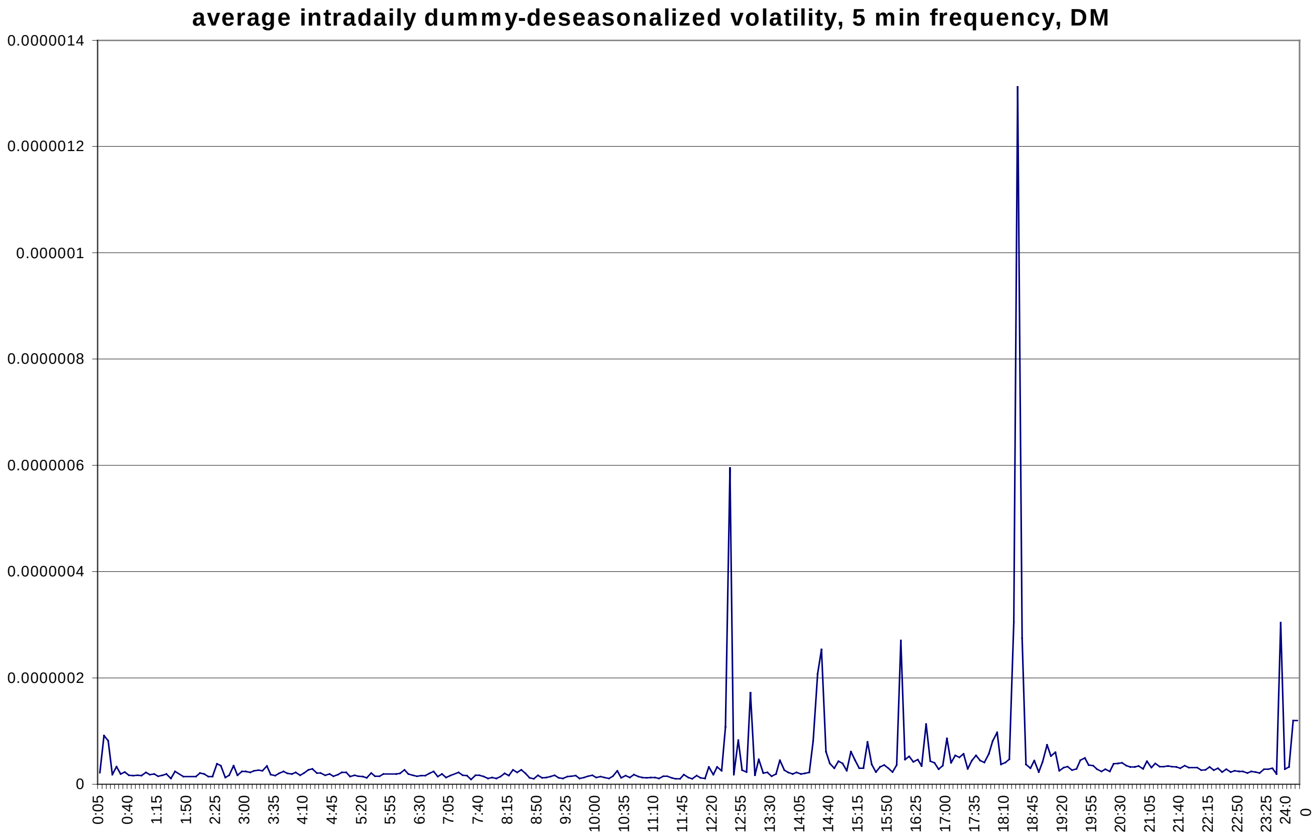

average intradaily dummy-deseasonalized volatility, 5 min frequency, DM
0.0000014
0.0000012
0.000001
0.0000008
0.0000006
0.0000004
0.0000002
0
0:05
0:40
1:15
1:50
2:25
3:00
3:35
4:10
4:45
5:20
5:55
6:30
7:05
7:40
8:15
8:50
9:25
10:00
10:35
11:10
11:45
12:20
12:55
13:30
14:05
14:40
15:15
15:50
16:25
17:00
17:35
18:10
18:45
19:20
19:55
20:30
21:05
21:40
22:15
22:50
23:25
24:0
0

FIGURE 10

FED intervention on DM data - variance comparison on 5-min returns

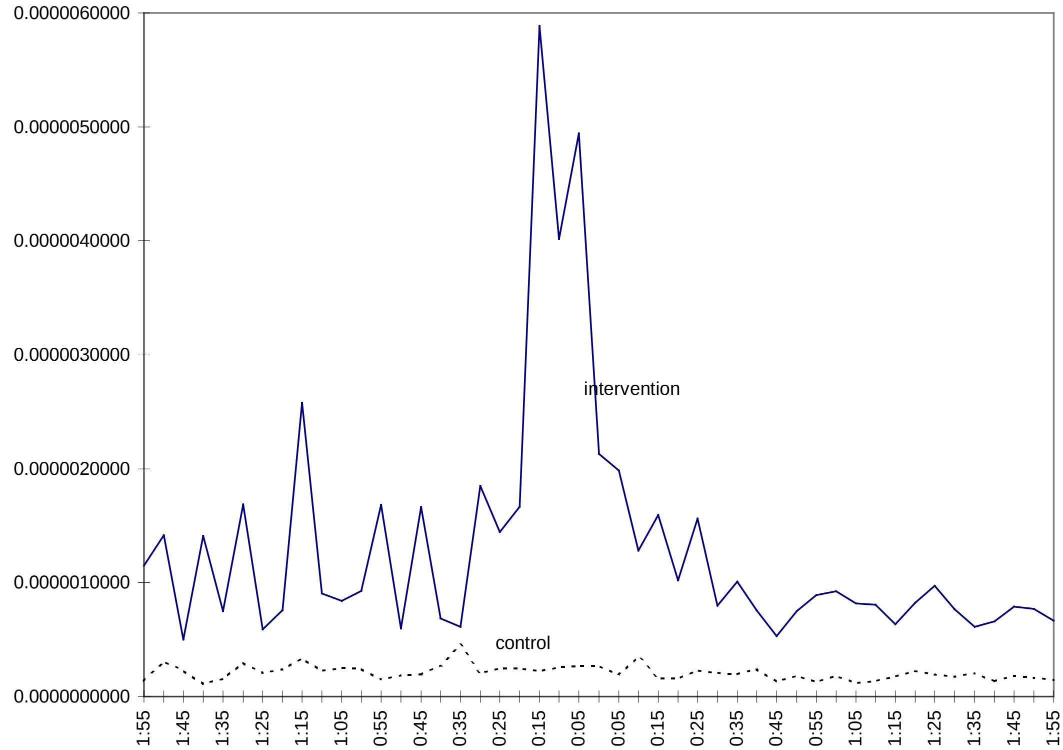


FIGURE 11

BB intervention on DM data - variance comparison on 5-min returns

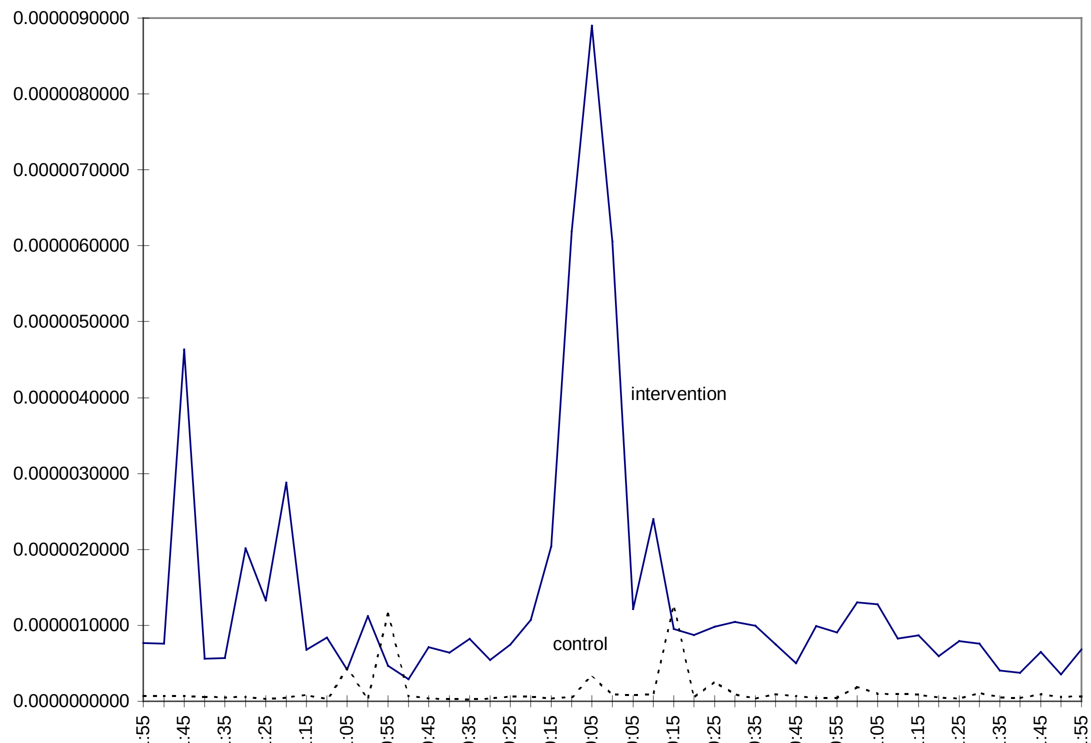


FIGURE 12

BOJ intervention on DM data - variance comparison on 5-min returns

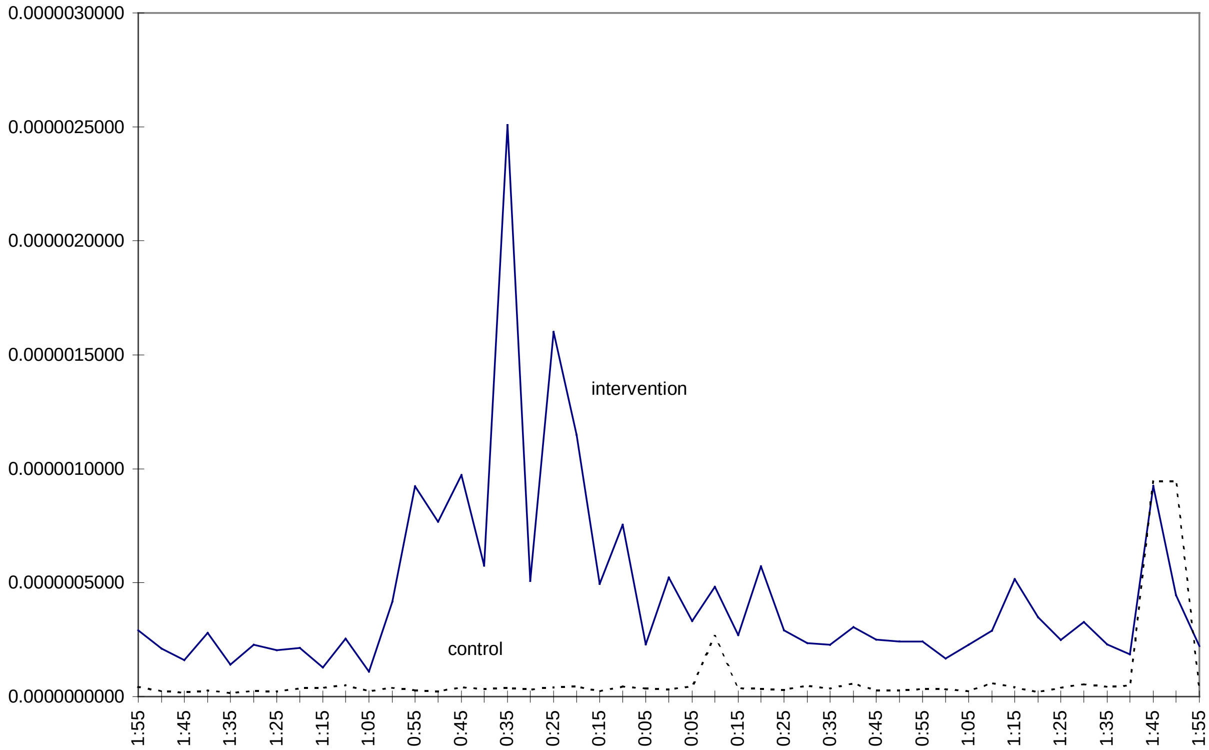


FIGURE 13

FED intervention on JPY data - variance comparison of 5-min returns

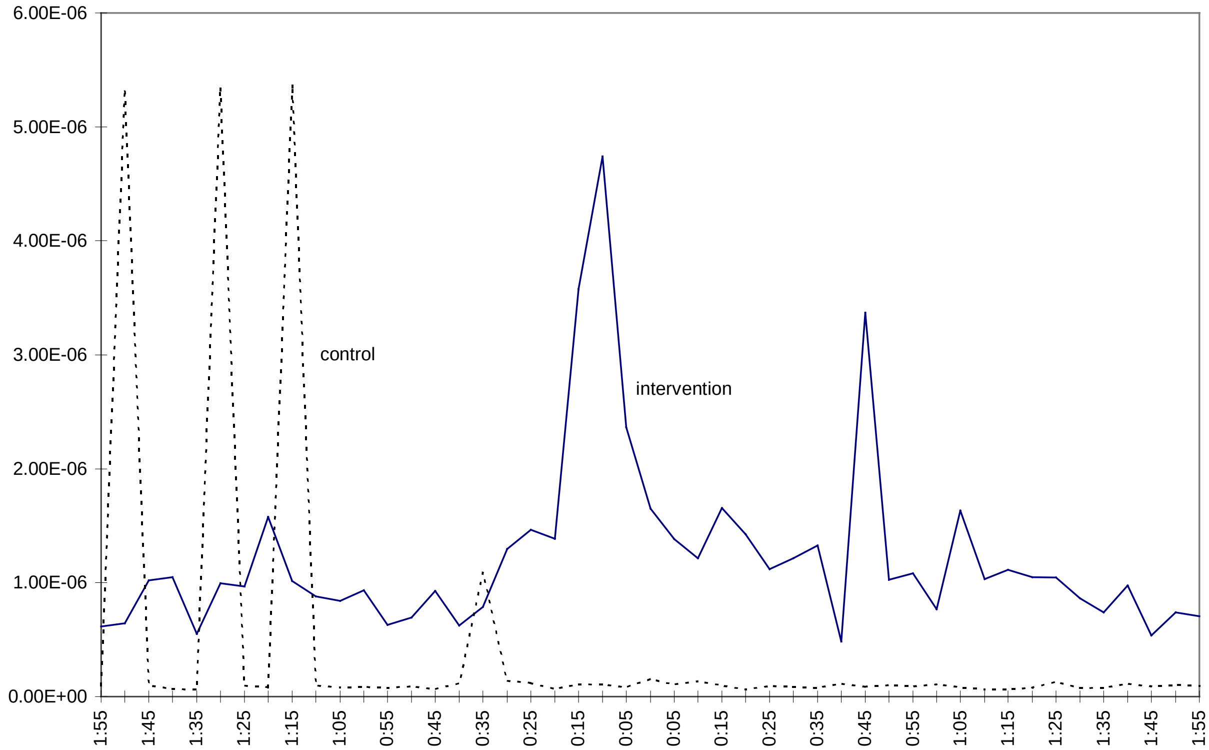


FIGURE 14

BB intervention on JPY data - variance comparison on 5-min returns

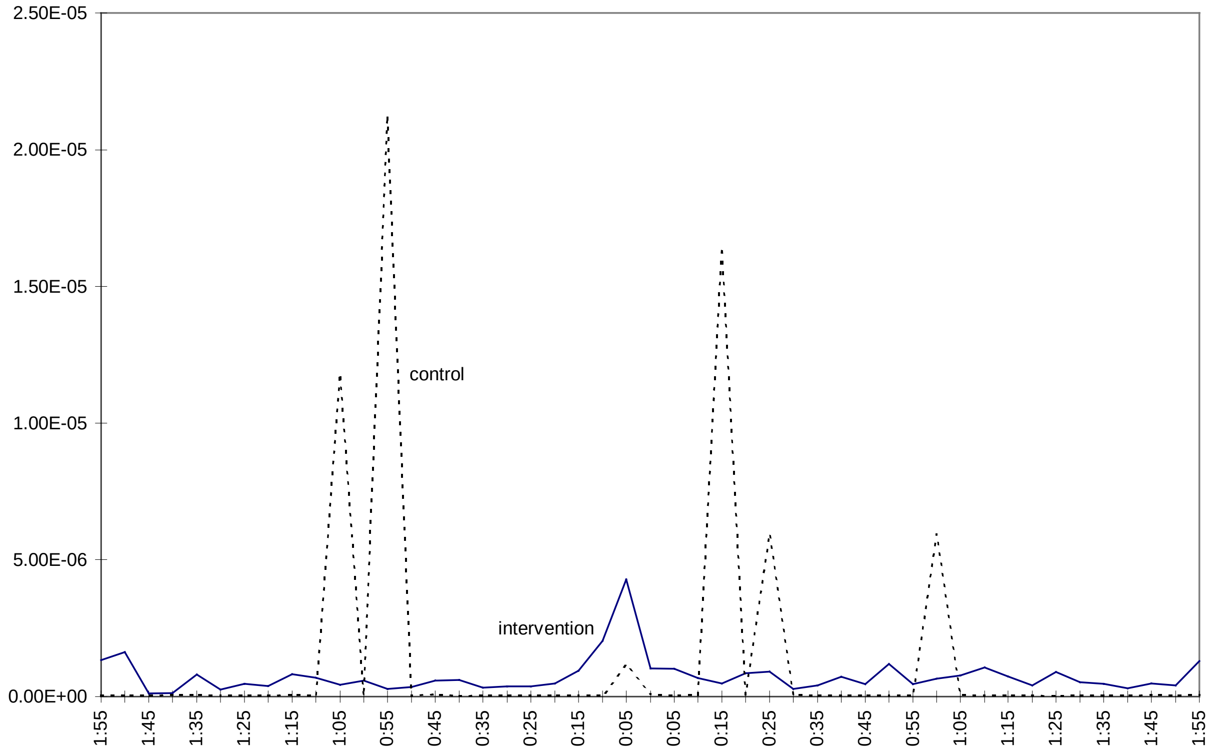


FIGURE 15

BOJ intervention on JPY data - variance comparison on 5-min returns