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OF CENTRAL BANK INTERVENTION

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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. 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, but little is known about how exactly traders learn of these operations and whether intra-daily market conditions influence the effectiveness of central bank interventions. This paper uses high-frequency data to 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. The results indicate that some traders know that a central bank is intervening at least one hour prior to the public release of the information in newswire reports. Also, the evidence suggests that the timing of intervention operations matter – interventions that occur during heavy trading volume and that are closely timed to scheduled macro announcements are the most likely to have large effects. Finally, post-intervention mean reversion in both exchange rate returns and volatility indicate that dealer inventories are affected by market reactions to intervention news.

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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 leads to an appreciation of the home currency relative to foreign currencies. Standard models have little to say about how market participants learn of the monetary contraction, or of how the 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 inadequate empirical performance of standard exchange rate models<sup>1</sup> 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,<sup>2</sup> but little is known about how exactly traders learn about these operations and whether intra-daily market conditions influence their effectiveness. This paper uses high-frequency spot market data to 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. The results indicate that some traders know that a central bank is intervening at least one hour prior to the public release of the information in newswire reports. Also, the evidence suggests that the timing of intervention operations matter – interventions that occur during heavy trading volume and that are closely timed to scheduled macro

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<sup>1</sup> See, for example, Meese and Rogoff (1983) and Frankel and Rose (1995), and see Lyons (forthcoming) for a thorough discussion of the role of market microstructure in international finance.

<sup>2</sup> See, for example, Dominguez (1992, 1998) and Dominguez and Frankel (1993a,b).

announcements are the most likely to have large effects. Finally, post-intervention mean reversion in both exchange rate returns and volatility indicate that dealer inventories are affected by market reactions to intervention news.

Section II of the paper presents stylized facts on the foreign exchange market, central bank interventions, and Reuters news reports. Section III reviews the role of inventories and information in market microstructure models. Section IV examines empirically the influence of market microstructure on the efficacy of central bank intervention, and section V is the conclusion.

## 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, instead bringing together dealers that wish to buy or sell foreign exchange. Customers purchase foreign exchange from dealers.

Dealers publicize their willingness to deal at certain prices by posting quotes, typically on one of three news services: Reuters, Telerate or Knight Ridder. These quotes appear on computer monitors located on the desks of other foreign exchange market participants. Generally prices used in actual transactions exhibit narrower spreads than the bids and asks quoted on the computers. Transaction prices are proprietary information known only to the participants in the transaction. Consequently, quotes on news service screens are the only publicly available information on current prices in the foreign exchange

market.<sup>3</sup> Tick-by-tick indicative quotes for the major currencies are available from the Olsen and Associates in their Reuter's FAFX data series.<sup>4</sup>

The data used in this paper are the Reuter's FAFX 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.<sup>5</sup> The data span the period 1987 through 1995.<sup>6</sup> The FAFX data identify a potential source of heterogeneity by including in the data set the names and locations of quoting banks. The most severe limitation of the FAFX data, however is that they do not provide volume information, so it is not possible to examine the joint dynamics of volume (or order flow) and price.<sup>7</sup> Another disadvantage of the data set is that, because it includes only intervention days, it is not possible to measure persistent effects of interventions.

A number of recent studies compare short samples of spot market transactions data with the Olsen and Associates indicative quotes (heretofore the FAFX series). Goodhart, Ito and Payne (1996) use one day (June 16, 1993) of transaction data from the electronic brokerage D2000-2 system and Evans (1998, 1999) uses four months (May – August 1996) of transaction data from the Reuters Dealing D2000-1

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<sup>3</sup> Electronic brokerage and dealing systems can, in principle, provide tick-by-tick transactions prices and order flow but, to date, these data have not been made publicly available.

<sup>4</sup> The data are collected by Olsen and Associates (Research Institute for Applied Economics, Zurich Switzerland) using O&A proprietary real-time data collection software.

<sup>5</sup> The control dates were selected to provide a representative sample of non-intervention days (and days-of-the week) over the period when the intervention operations take place.

<sup>6</sup> Only one additional Fed intervention operation has occurred since August 1995. On June 17, 1998 the Fed sold \$833 million against the yen in cooperation with Japanese monetary authorities. "The operation began at 7:55am with the dollar trading at 142.21 yen/\$ and the [Fed] desk operated intermittently until about 9:20am... Over the course of the day the exchange rate climbed over 5 yen and closed at 136.51 yen/\$" (Treasury and Federal Reserve Foreign Exchange Operations, April-June 1998).

<sup>7</sup> There exist at least three intra-daily foreign exchange rate data sets that include volume information, none of which spans the 1987-1995 time period. 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. Goodhart, Ito and Payne (1996) analyze transaction and volume data on June 16, 1993 from the electronic brokerage D2000-2 system. Evans (1998, 1999) and Evans and Lyons (1999) analyze transaction prices and order flow from the Reuters Dealing 2000-1 system over a four month period, May-August 1996.

system.<sup>8</sup> Both studies find that the time path of indicative quotes is a good and close proxy for transaction prices.<sup>9</sup> However, they also find that the FXX data are not good proxies for transaction bid-ask spreads or transaction frequency. The bid-ask spreads in the FXX cluster among a small number of standard values (e.g. 5,7, and 10 pips for the DEM- $\text{\$}$ ), whereas the transaction spreads "at the touch" (the difference between the highest bid and the lowest ask on offer, usually input by different banks) show no signs of clustering. Also, they find that the frequency of quotes on FXX is a relatively poor predictor of transaction volume on D2000-2 and D2000-1.<sup>10</sup>

Table 1 presents descriptive statistics (means, variance, skewness, kurtosis) of the FXX returns data used in this study as well as corresponding statistics on the full sample of FXX returns 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.<sup>11</sup> Mean returns and sample variances on the Fed intervention days are significantly larger than they are over the full sample period or the control sample.<sup>12</sup> Interestingly, mean returns are positive on the Fed intervention days, while they are negative over the full sample and of mixed signs in the control sample depending on the particular sampling frequency used to create the data series. In the full sample, the degree of kurtosis of the returns rises with increasing sample frequency, while for both the Fed intervention days and the control sample the degree of kurtosis is relatively stable over

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<sup>8</sup> See Lyons (forthcoming) and Evans (1998) for details on the Reuters electronic dealing systems.

<sup>9</sup> Martens and Kofman (1998) compare FXX quotes with their matching futures exchange rates from the Chicago Mercantile Exchange over the sample June to August 1993. They find evidence that the futures market prices led the indicative quotes for up to 3 minutes over their sample period, though in the aftermath of prescheduled news announcements, the futures lead was reduced to approximately 1 minute.

<sup>10</sup> This may, in part, be explained by the technical limitations of the FXX transmission process (see footnote 13). It may also be that, especially during high volume periods, traders transact first and then update the Reuters screen quotes.

<sup>11</sup> The full sample statistics in the upper panel of Table 1 are reproduced from Table 4 in Guillaume (1997a).

<sup>12</sup> This is also true at a daily frequency. Chaboud and LeBaron (1999) find a large positive correlation between daily trading volume in currency futures markets and foreign exchange intervention by the Federal Reserve over the period 1979-1996.

sampling frequencies and is less pronounced.

Three filters were applied to the FAFX 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.) The FAFX data also exclude quotes that repeat the values of the immediately preceding quote, but are entered by different institutions. (It is common for several institutions to quasi-simultaneously quote the same bid and ask levels.)<sup>13</sup> A third filter, recommended by Dacorogna et al. (1993), excludes any quote where the log-bid or log-ask are such that their percentage difference from both the preceding and the 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.<sup>14</sup>

#### *Central Bank Intervention Stylized facts*

Foreign exchange market intervention is a 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, the monetary authority implements intervention operations, 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.

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<sup>13</sup> 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). The Reuters DFX indicative quote series is transmitted using a higher speed digital network and is therefore able to take more quotes per second. These data are analyzed in Evans (1998) but are only available for the period May-August 1996.

<sup>14</sup> The outlier filter is recommended by researchers at Olsen and Associates to exclude quotes that are very unlikely to represent trading prices. 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.

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 banks (typically in New York) simultaneously to achieve high visibility.<sup>15</sup> 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 that allow them to inform the market of their presence within minutes of the original transaction, or to keep their intervention operations secret.<sup>16</sup>

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 the sample of Fed intervention days also includes interventions by all three central banks.<sup>17</sup> In order to analyze the influence of intervention on the intra-daily data, ideally one would like to know the exact time that each central bank entered the market to buy or sell foreign exchange. Unfortunately, such data (rounded to the nearest minute) are only available for the Fed in the last two years of the sample. However, on most days when central banks are in the market, Reuters reports the timing of their interventions and the time-stamped history of these reports are also available from Olsen and Associates. To illustrate, Figure 1 presents the DEM–USD tick-by-tick FAFX quotes for one of the last 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 natural log of the DEM-USD price jumped from .326 to over .345 immediately following the first Fed

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<sup>15</sup> Prior to 1992 the Fed conducted its foreign exchange transactions exclusively with commercial bank dealers, but in 1992 the Federal Reserve authorized relationships (for intervention purposes) with securities dealers (Federal Reserve Bank of New York, 1992).

<sup>16</sup> Dominguez and Frankel (1993b) 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).

<sup>17</sup> In 111 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.

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 trading desks in the first bank (or banks) with which 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 FFX data for the period 1992-93. Likewise, Chang and Taylor (1998) 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 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). Figure 2 presents the frequency distribution of intervention times for the Fed. The graph clearly illustrates that there is a wide range of times at which the Fed enters the market.

Quite apart from the decision of when and how to intervene, central banks have varied goals for their intervention operations. The Fed describes four different reasons for its interventions in foreign exchange markets: to influence trend movements in exchange rates, to calm disorderly markets, to rebalance its foreign exchange reserve holdings, and to support fellow central banks in their exchange rate operations. Unfortunately, central banks rarely provide traders (or researchers) information regarding their specific goals for particular intervention operations. This lack of information, in turn, makes it difficult to access the "success" of individual intervention operations. Further, the magnitude and persistence of intervention's influence are likely to depend importantly on the interaction of the central bank's goals and

the market's perception of those goals.

Market participants react differently to the foreign exchange transactions of central banks than they do to trades between dealers or customers. One reason for the difference is that central banks are likely to have more information than the market about their own future policy intentions, and interventions may serve to convey (or signal) this private information.<sup>18</sup> Naranjo and Nimalendran (1998) hypothesize that interventions create significant adverse selection problems for dealers. They find evidence that dealers increase exchange rate spreads around interventions and suggest that in doing so they protect themselves against the greater informational asymmetry around interventions.

A recent survey of market participants indicates that central bank intervention activity is taken seriously by traders. Moreover, the survey results suggest that traders expect interventions to both increase volatility and “restore equilibrium exchange rates” (Cheung and Wong, *forthcoming*). The empirical work that follows measure the impact of intervention operations on foreign exchange rate prices and volatility, and the extent to which this impact, and subsequent effects of intervention, depend on the “state of the market”.<sup>19</sup> In particular, the evidence indicates the degree to which the forcefulness of intervention is affected by the volume of trading (proxied by time-of-day), the day-of-the week, and the proximity to the release of other macroeconomic news. In addition, it is possible to examine whether different central banks have different impacts on currencies, whether the market anticipates Reuters' reports of intervention operations, and whether exchange rates exhibit intra-daily mean reversion in reaction to intervention news.

#### *Reuters news reports stylized facts*

The Reuters news reports are available from the Reuters AAMM Page News (Money Market

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<sup>18</sup> See Mussa (1980) and Dominguez (1992) for further discussion of the intervention signalling hypothesis. Montgomery and Popper (*forthcoming*) suggest that central bank intervention may also serve to aggregate and disseminate traders' information and thereby serve an informational sharing role for a heterogeneously informed market.

<sup>19</sup> Of the four reasons that the Fed intervenes, only one (when the goal is to rebalance its portfolio) does not involve a desired change in the level or volatility of exchange rates. The tests in this paper are predicated on the assumption that relatively few interventions take place for this reason.

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 are 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. No major economic events occurred on the 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 are only available starting on August 18, 1989; consequently, many of the empirical tests in this paper use data starting in August 1989.<sup>20</sup>

### III. The Role of Information in Market Microstructure Models

The market microstructure literature analyzes ways in which specific trading mechanisms affect the price formation process.<sup>21</sup> There are two main branches of microstructure theory: the inventory approach and the information approach.

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 buy and sell orders.

One simple prediction of inventory models is that since a dealer prefers to sell if he is long inventory, and to buy if he is short inventory, there should be mean reversion in prices due to inventory

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<sup>20</sup> 101 of the 273 intervention days in the full sample occurred after August 1989.

<sup>21</sup> See, for example, Admati (1991), O'Hara (1995) and Lyons (forthcoming).

effects.<sup>22</sup> Lyons (1996) finds evidence of inventory effects in foreign exchange markets, but little evidence of inventory effects has appeared 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. In simple versions of these models a dealer's position is purely speculative, there are no inventory costs and no risk aversion. A 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 losses 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. 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). Consequently, periods of high variance correspond to periods of high concentration of informed trading. Daily U-shaped volatility 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

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<sup>22</sup> 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.

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 to September 1993, 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, thereby not conveying information when time between consecutive trades is short; (2) trading is generated by the arrival of new information, in which case intense trading means that an information event has occurred. He finds evidence in favor of the

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inventory, or "hot-potato" hypothesis, in that trades occurring when transaction intensity is high are significantly less informative than trades occurring when transaction intensity is low. He also finds evidence that trades 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. This paper examines the intra-daily effects of central bank intervention on currency prices. Evans (1999) and Peiers (1997) describe central bank intervention as an example of fundamental private information in the foreign exchange market. One might, therefore, expect to see some of the predictions of the information approach (increased volume and volatility) to appear on intervention days. It is also possible that market reactions to interventions influence dealer inventories, leading to post intervention mean reversion in prices. The paper examines both these hypotheses. Further, 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. Intra-daily examination of trader behavior around intervention events offers the prospect of explaining 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 resulting in irregular spacing of quotes. Standard econometric techniques require regularly spaced data. The 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.<sup>23</sup> Defining the tick-by-tick price (P) as the average of the bid and ask:

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

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

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

where  $t_i$  is the sequence of the regular-spaced in time data and  $\Delta t$  is the time interval.<sup>24</sup> Equivalently, the return (R) over a fixed time interval  $\Delta t$  is defined as:

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

### *The Influence of Intervention on Returns*

The empirical work uses 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

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<sup>23</sup> Irregular spacing of quotes has produced four main directions of empirical research: (1) the use of transaction (rather than clock) time. (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 (1997).) (2) the mixture of distributions approach to analyzing trade patterns; (3) time-scaling approaches to forecasting price behavior (Dacorogna et al. (1993) and Muller et al. (1990); and (4) the conditional duration approach (Engle and Russel (1998) and Engle (forthcoming)). Unfortunately there seems to be little consensus in the literature as to which of these approaches works best.

<sup>24</sup> 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. Defining  $wa$  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:

$$P_T = \left[ wa \frac{\left[ \log P_{t-1}^{ask} + \log P_{t-1}^{bid} \right]}{2} + wb \frac{\left[ \log P_t^{ask} + \log P_t^{bid} \right]}{2} \right] (wa + wb)$$

"event study" regression specification is:

$$R_{t_i} - \bar{R}_{t_i} = \mathbf{a}_0 + \sum_k \sum_n \mathbf{a}_{l,n}^k D_{t_i+n}^k + \mathbf{e}_{t_i}$$

where  $\bar{R}$  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 it is possible to test a number of different hypotheses which follow from the inventory and information approaches to modeling market microstructure.

If intervention operations provide “fundamental private information” to market participants, microstructure theory suggests that the volume of trade, the bid-ask spread, and volatility of prices (and possibly the level of prices) will rise in reaction to the public release of this information. The FXFX data allow us to analyze the intra-day influence of intervention on both prices and volatility, but not spreads or volume. Using the event study regression specification, it is possible to test for the impact and intra-day effects of intervention (and other macro news) by examining whether the  $D^k$ s are statistically significant. Further, the specification can be adjusted to test whether market participants react to the intervention operations of different central banks similarly by including these operations separately in the regression. The possibility that certain market participants know about the interventions before others can be tested by looking for evidence of price effects prior to the time-stamped Reuters release of  $D^k$  news. The influence of the “state of the market” can be measured by examining information releases during specific days-of-the-week and times-of-day. It is also possible to measure whether the effects of interventions that are closely timed with other macroeconomic news announcements differ from those that occur in low news times. Finally, in order to investigate whether dealer inventories are influenced by intervention news, a test for mean reversion can be constructed by checking whether the  $n$  time lags on the  $D^k$ s sum to zero.

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 lags 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.) Nonetheless, 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.<sup>25</sup> 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. 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. There is evidence of mean reversion in the coefficient estimates of Fed intervention, where reversion was, on average, completed in three hours

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.<sup>26</sup>

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<sup>25</sup> Various regression specifications were attempted, including imposing a polynomial distributed lag (pdl) 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.

<sup>26</sup> Interestingly, LeBaron (1996) also finds that the influence of intervention days on technical trading rule

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*

The strong seasonal pattern in the average USD-DEM 5-minute volatility over the sample of Fed intervention days is readily apparent. Intradaily foreign exchange volatility seasonals have been documented by Bollerslev and Domowitz (1993), Dacorogna et al. (1993) and Guillaume et al. (1997b).<sup>27</sup> Failure to take account of these intra-daily seasonals is likely to result in misleading statistical analyses.<sup>28</sup> In this paper de-seasonalization of the volatility series is achieved using both the simple seasonal dummy approach<sup>29</sup> as well as the Ghysels et al. (1998) regression approach<sup>30</sup>.

I use two approaches to examine the influence of central bank intervention (and other macro

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profitability to be lower in the USD-JPY market than in the USD-DEM market.

<sup>27</sup> The variance of daily and weekly exchange rate changes is forecastable using GARCH models. However, at the intra-daily frequency 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 (Andersen and Bollerslev (1997,1998), Guillaume et al. (1997a)).

<sup>28</sup> There are numerous methods available in the literature to de-seasonalize intra-daily forex volatility. Baillie and Bollerslev (1991) suggest using seasonal dummies, Dacorogna et al. (1993) use time-scaling, Engle and Russel (1998) use the intensity of price changes as an alternative measure of volatility, Andersen and Bollerslev (1997) use a Fourier transform, and Ghysels, Gouriou and Jasiak (1998) use a regression technique based on a stochastic volatility model.

<sup>29</sup> Tick-by-tick returns are regressed on 288 five-minute dummy variables, and 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 24.

<sup>30</sup> In brief, the Ghysels et al. (1998) 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.

announcements) on exchange rate volatility. The first approach is analogous to the "event study" test on exchange rate returns. The general regression specification is:

$$V_{t_i}^s = \mathbf{a}_0 + \sum_k \sum_n \mathbf{a}_{l,n}^k D_{t_i+n}^k + \mathbf{e}_{t_i}$$

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, suggesting that some traders know about intervention well before the Reuters new release. 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 average 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 permit a test of whether interventions on a particular day-of-the-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 it 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 resulted in higher volatility than Fed interventions on days when it 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 associated with higher levels of market volatility, at least relative to interventions that only occur in the afternoon.

The regression specification presented in Table 12 serves as a test of 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 on volatility 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) at times when other major announcements are released.

A second approach to examining the influence of intervention on volatility arranges squared returns around interventions according to the intervention event rather than clock time. In this approach, 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.<sup>31</sup> 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 Fed intervened in the USD-JPY market on a Monday at 3:55 GMT, then the five minute returns two hours before and after this event are included in the Fed intervention sample. The matched control sample likewise includes 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 Fed intervention and non-intervention periods can be seen in figures 3 and 4. 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 occurs 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 test is used.<sup>32</sup> 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  $j$

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<sup>31</sup> 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.

<sup>32</sup> 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 (1998) to examine the intra-day effects of BOJ intervention on USD-JPY volatility.

(j=1 to J) is the intraday period and N is the number of observations in the sample averages).<sup>33</sup> 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, it is possible to 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, it is not possible to reject the hypothesis of equal variances. However, in the case of the matched control sample for the Bundesbank intervention days there is evidence of unequal return variance in both the USD-DEM and USD-JPY markets.

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 permit a test of whether the variance of quotes from specific banks is responsible for any significant differences. In other words, the test consists of examining quotes from the major banks that deal in the USD-DEM and USD-JPY markets to see if they 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, then these banks are likely to 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 London market for the Bundesbank.<sup>34</sup> The statistics generally do not support the hypothesis that it is

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<sup>33</sup> The test statistic is:

$$F = \frac{\sum_{j=1}^J n_j (\overline{D_{.j}} - \overline{D_{..}})^2}{\sum_{j=1}^J \sum_{i=1}^{n_j} (D_{ij} - \overline{D_{.j}})^2} \frac{(N - J)}{(J - 1)}$$

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;  $\overline{D_{.j}}$  is the mean absolute deviation from the median for period  $j$ ; and  $\overline{D_{..}}$  is the grand mean, where  $N = \sum n_j$ .

<sup>34</sup> 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.

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.<sup>35</sup>

#### IV. Conclusions

The tests in this paper explore whether aspects of market microstructure influence the effectiveness of central bank intervention. In particular, this study examines the importance of the "state of the foreign exchange market" at the moment that central bank intervention operations (and macro announcements) are made public to traders. Using an event-study style regression and intra-daily FFX data on each day that the Fed intervened in the USD-DEM and USD-JPY markets, a number of hypotheses were examined. The results of these regressions provide evidence that central bank intervention is considered fundamental private information by market participants and that dealer inventories are influenced by the release of intervention news.

Specifically, the empirical evidence indicates that Fed intervention operations significantly influenced both USD-DEM and USD-JPY intra-day returns and volatility. Bundesbank intervention significantly influenced USD-DEM intra-day returns and volatility. And, BOJ interventions significantly influenced intra-day USD-DEM and USD-JPY volatility. There is little evidence that BOJ operations influenced intra-day USD-JPY returns. (However, it is important to note that the observations on Bundesbank and BOJ interventions are only those that occurred on days on which the Fed was also in the market.) The evidence also suggests that 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. There is evidence of intra-daily mean reversion for Fed intervention on the USD-DEM returns, and

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<sup>35</sup> Alternatively it may be that the indicative quote data are too noisy to pick up individual bank effects. 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).

BOJ interventions on USD-DEM volatility. Fed interventions that occurred during European trading (a proxy for relatively heavy trading volume periods) had relatively larger effects than those that occurred in low volume periods. 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. Those days on which Fed interventions occurred in the morning, or in both the morning and afternoon, were found to be associated with higher volatility than those that occurred only in the afternoon. Those G-3 interventions that were closely timed to a scheduled macro announcement were more effective than those that were not. And, 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 foreign exchange returns and volatility,<sup>36</sup> and the hypothesis that the efficacy of central bank intervention depends on the characteristics of the foreign exchange 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.

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<sup>36</sup> This confirms LeBaron's (1996) result that profit opportunities exist on intervention days.

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Table 1 Descriptive Statistics of the FFX price change distribution

Full Sample of FFX 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	$-2.73 \cdot 10^{-7}$	$2.62 \cdot 10^{-7}$	0.17	35.10
	1 h	$-1.63 \cdot 10^{-6}$	$1.45 \cdot 10^{-6}$	0.26	23.55
	6 h	$-9.84 \cdot 10^{-6}$	$9.20 \cdot 10^{-6}$	0.24	9.44
	24 h	$-4.00 \cdot 10^{-5}$	$3.81 \cdot 10^{-5}$	0.08	3.33
USD/JPY	10 m	$-9.42 \cdot 10^{-7}$	$2.27 \cdot 10^{-7}$	-0.18	26.40
	1 h	$-5.67 \cdot 10^{-6}$	$1.27 \cdot 10^{-6}$	-0.09	25.16
	6 h	$-3.40 \cdot 10^{-5}$	$7.63 \cdot 10^{-6}$	-0.05	11.65
	24 h	$-1.37 \cdot 10^{-4}$	$3.07 \cdot 10^{-5}$	-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	$4.94 \cdot 10^{-6}$	$6.85 \cdot 10^{-9}$	0.33	2.31
	10 m	$9.89 \cdot 10^{-6}$	$1.20 \cdot 10^{-8}$	-0.17	3.23
	1 h	$5.42 \cdot 10^{-5}$	$5.13 \cdot 10^{-8}$	1.22	3.98
	24 h	$1.05 \cdot 10^{-3}$	$5.95 \cdot 10^{-5}$	-0.32	1.93
USD/JPY	5 m	$9.90 \cdot 10^{-6}$	$5.02 \cdot 10^{-9}$	0.58	0.66
	10 m	$1.98 \cdot 10^{-5}$	$9.23 \cdot 10^{-9}$	0.41	-2.63
	1 h	$1.14 \cdot 10^{-4}$	$6.56 \cdot 10^{-8}$	0.57	-0.32
	24 h	$2.99 \cdot 10^{-3}$	$2.95 \cdot 10^{-5}$	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	$-6.84 \cdot 10^{-7}$	$1.52 \cdot 10^{-9}$	0.95	5.75
	10 m	$-1.37 \cdot 10^{-6}$	$3.15 \cdot 10^{-9}$	1.21	1.79
	1 h	$1.13 \cdot 10^{-6}$	$2.61 \cdot 10^{-8}$	0.46	2.80
	24 h	$1.10 \cdot 10^{-3}$	$2.16 \cdot 10^{-5}$	2.29	8.53
USD/JPY	5 m	$-3.26 \cdot 10^{-7}$	$1.07 \cdot 10^{-9}$	0.27	1.66
	10 m	$-6.53 \cdot 10^{-7}$	$1.96 \cdot 10^{-9}$	0.50	-2.54
	1 h	$1.42 \cdot 10^{-5}$	$2.73 \cdot 10^{-9}$	-0.53	0.59
	24 h	$2.25 \cdot 10^{-4}$	$1.37 \cdot 10^{-5}$	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

$$R_{t_i} = \mathbf{a}_0 + \sum_k \sum_n \mathbf{a}_{I,n}^k D_{t_i+n}^k + \mathbf{e}_{t_i}$$

where R is the 5-min USD-DEM return;  $D^k$  includes the intervention and macro announcements;  $n=-1$  to  $+2$ hrs for the G-3 intervention variables and official announcements and  $n=0$  to  $+1$ hr 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

$$R_{t_i} = \mathbf{a}_0 + \sum_k \sum_n \mathbf{a}_{I,n}^k D_{t_i+n}^k + \mathbf{e}_{t_i}$$

where R is the 5-minute USD-JPY return; D<sup>k</sup> 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<sub>i</sub> 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<sup>2</sup>=0.015; D.W.=1.90.

Table 7 INFLUENCE OF EUROPEAN TRADING HOURS

$$R_{t_i} = \mathbf{a}_0 + \sum_k \sum_n \mathbf{a}_{1,n}^k D_{t_i+n}^k + \sum_n \mathbf{a}_{2,n} E_{t_i+n} + \mathbf{e}_{t_i}$$

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

$$V_{t_i}^s = \mathbf{a}_0 + \sum_k \sum_n \mathbf{a}_{I,n}^k D_{t_i+n}^k + \mathbf{e}_{t_i}$$

where  $V^s$  is the de-seasonalized 5-minute volatility;  $D^k$  includes the intervention and macro announcements;  $n=-1$  to  $+2$ hrs for the G-3 intervention variables and official announcements and  $n=0$  to  $+1$ hr 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

$$V_{t_i}^s = \mathbf{a}_0 + \sum_k \sum_n \mathbf{a}_{k,n}^k D_{t_i+n}^k + \mathbf{e}_{t_i}$$

where  $V^s$  is the de-seasonalized 5-min volatility;  $D^k$  includes the intervention and macro announcements;  $n=-1$  to  $+2$ hrs for the G-3 intervention variables and official announcements and  $n=0$  to  $+1$ hr 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?

$$A_{t_i} = \mathbf{a}_0 + \sum_g \sum_n \mathbf{a}_{1,n}^g D_{t_i+n}^g + \sum_d \sum_n \mathbf{a}_{2,n}^d D_{t_i+n}^j * W_t^d + \mathbf{e}_{t_i}$$

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  $d=1, \dots, 5$ ;  $n=-1$  to  $+2$ hrs for the intervention variable and  $n=0$  to  $+1$ hr 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)

$$V_{t_i}^s = \mathbf{a}_0 + \sum_k \sum_n \mathbf{a}_{1,n}^k D_{t_i+n}^k + \sum_n \mathbf{a}_{2,n} M_{t_i+n} + \mathbf{e}_{t_i}$$

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  $+1$ hr for the intervention variables and  $n=0$  to  $+1$ hr 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

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

$$V_{t_i}^s = \mathbf{a}_0 + \sum_k \sum_n \mathbf{a}_{l,n}^k D_{t_i+n}^k + \sum_n \mathbf{a}_{2,n} M_{t_i+n} + \mathbf{e}_{t_i}$$

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  $+1$ hr for the intervention variables and  $n=0$  to  $+1$ hr 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	Intervention Sample	Control Sample
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	Intervention Sample	Control Sample
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

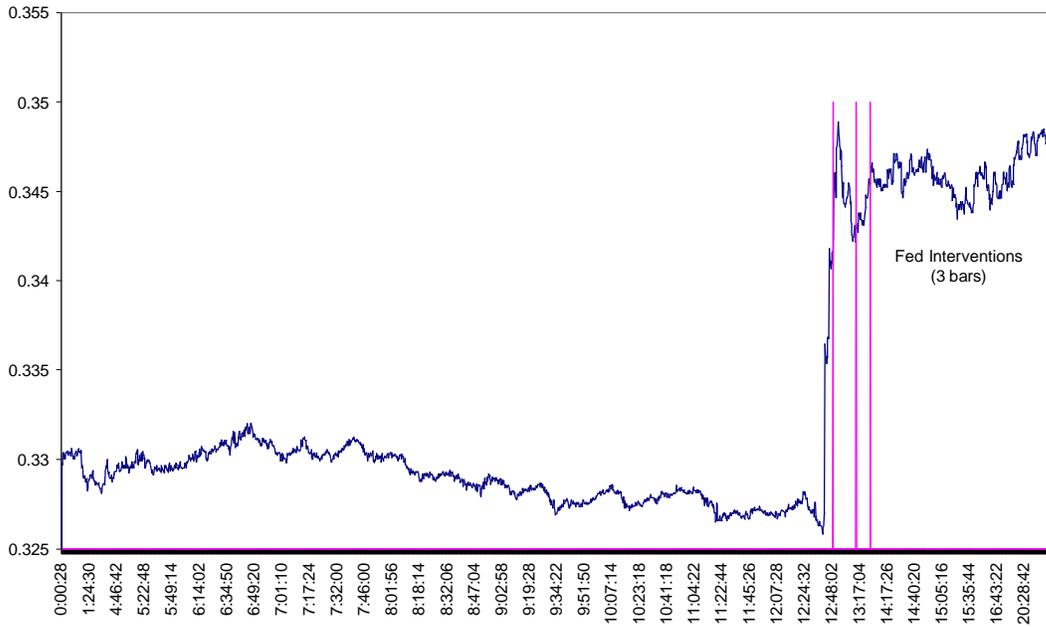
I Fed Intervention	USD-DEM	USD-JPY
Chemical Bank	0.7657	1.4175*
Morgan Guaranty	0.7	0.9438
Citibank	1.3546	1.108
critical values $F(38,2691) = 1.4094$ (5%) and $1.6202$ (1%)		

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%)		

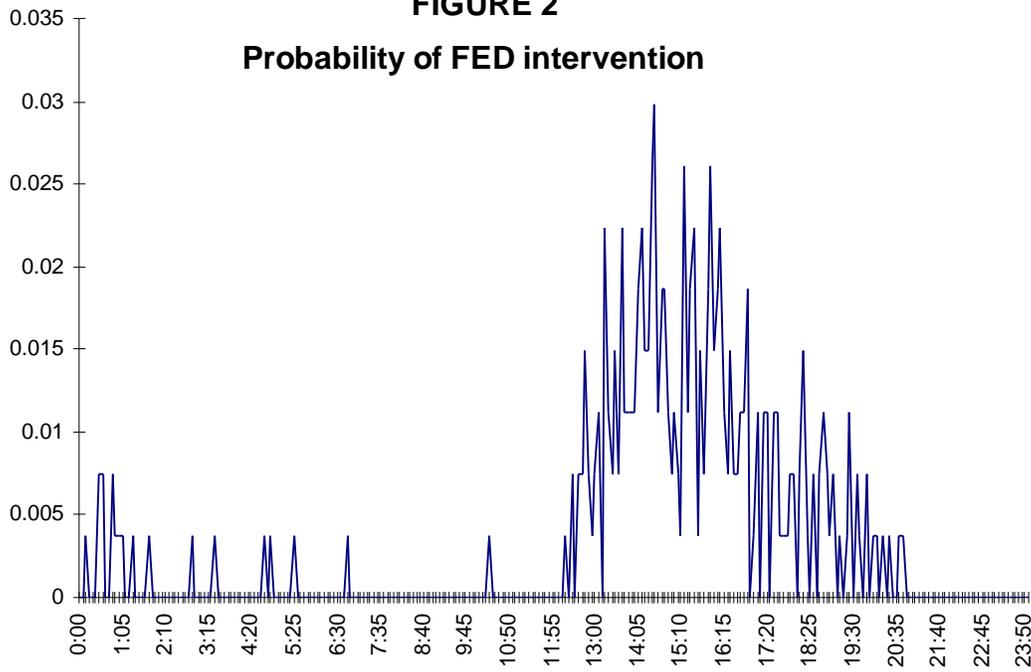
III. Bundesbank Intervention		
Chemical Bank	0.9354	0.931
Morgan Guaranty	1.4264*	0.8585
Deutsche Bank	0.9084	1.0059
Dresdner Bank	1.0111	1.2307
critical values $F(38,1209) = 1.4149$ (5%) and $1.6268$ (1%)		

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.

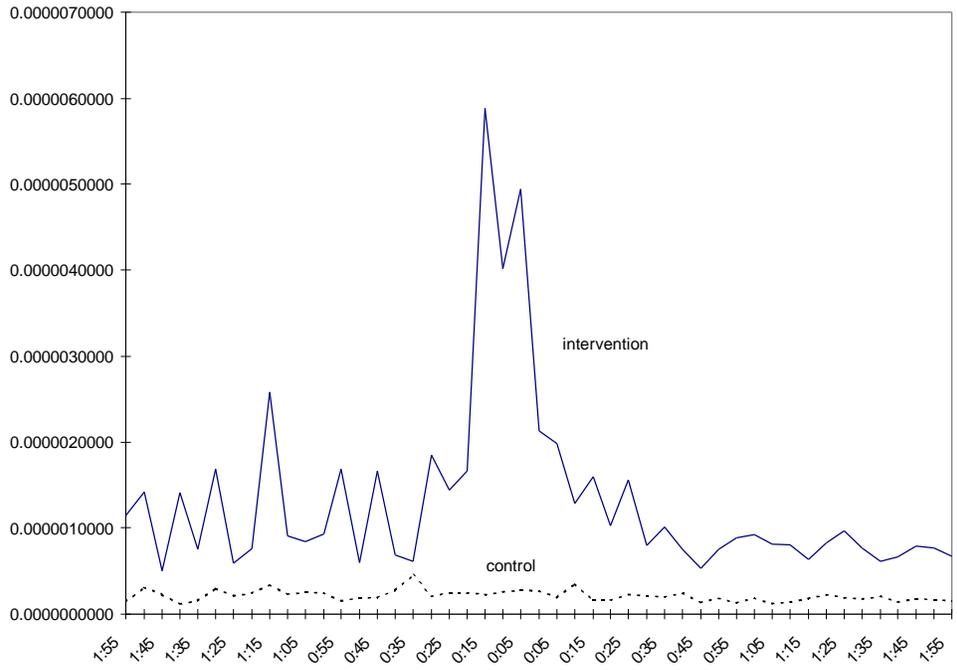
**FIGURE 1**  
**\$/dm (in natural logs) on May 31, 1995**



**FIGURE 2**  
**Probability of FED intervention**



**FIGURE 3**  
**FED intervention on DM data - variance comparison on 5-min returns**



**FIGURE 4**  
**FED intervention on JPY data - variance comparison of 5-min returns**

