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Central bank intervention and exchange rate volatility

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Abstract

This paper explores the effects of foreign exchange intervention by central banks on the behavior of exchange rates. The G-3 central banks have undertaken an unprecedented number of both coordinated and unilateral intervention operations in the last 10 years. Existing empirical evidence on the effectiveness of intervention is mixed: studies using data from the 1970s suggest that intervention operations that do not affect the monetary base have, at most, a short-lived influence on exchange rates, but more recent studies indicate that the intervention operations that followed the Plaza Agreement influenced both the level and variance of exchange rates. This paper examines the effects of US, German and Japanese monetary and intervention policies on dollar-mark and dollar-yen exchange rate volatility over the 1977–1994 period. The results indicate that intervention operations generally increase exchange rate volatility. This is particularly true of secret interventions, which are those undertaken by central banks without notification of the public. Overt interventions in the mid-1980s appear to have reduced exchange rate volatility, but in other periods, and for the 1977–1994 period as a whole, central bank intervention is associated with greater exchange rate volatility.

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> "The past has shown us that whenever the finance ministers from the Big Five get together there's a lot of rhetoric and little action. Any time there's talk of intervention and outside forces in the market, it creates volatility and uncertainty. But in the long term it doesn't have any lasting impact... (*The Wall Street Journal*, 9/23/85)."

Foreign exchange intervention operations are a controversial policy option for central banks. In one view, exemplified by the *Wall Street Journal* quote, intervention policy is not only ineffective in influencing the level of the exchange rate, but also dangerous, because it can increase the volatility of the rate. Others argue that intervention operations can influence the level of the exchange rate, and can also 'calm disorderly markets', thereby decreasing volatility. Yet others argue that intervention operations are inconsequential, since they neither affect the level nor the volatility of exchange rates. This paper explores the validity of these three disparate views by examining the effects of US, German and Japanese intervention operations on foreign exchange rate volatility over the period 1977 through 1994.[1]

During the period in which countries adhered to the Bretton Woods exchange rate system, intervention operations were required whenever rates exceeded their parity bands. After the breakdown of the system in 1973, intervention policy was left to the discretion of individual countries. It was not until 1977 that the IMF Executive Board provided its member countries three guiding principles for intervention policy: (1) countries should not manipulate exchange rates in order to prevent balance of payments adjustment or to gain unfair competitive advantage over others; (2) countries should intervene to counter disorderly market conditions; and (3) countries should take into account the exchange rate interests of others.[2] These principles implicitly assume that intervention policy can effectively influence exchange rates, and explicitly state that countries should use intervention policy to decrease foreign exchange rate volatility.

After actively engaging in foreign exchange intervention in the 1970s, the United States abandoned intervention policy altogether during the period 1981 through 1984. In early 1985, after the dollar had appreciated by over 40% against the mark, and the US trade deficit was nearing $100 billion, the Federal Reserve System (Fed) in the United States joined with the Deutsche Bundesbank and the Bank of Japan (BOJ) to intervene against the dollar. In the autumn of 1985 the United States and the rest of the G-5 engaged in an unprecedented number of large and coordinated intervention operations as part of the Plaza Agreement.[3] The G-5

[1] Previous studies of the effects of intervention on the level of exchange rates include: Jurgenson (1983); Henderson and Sampson (1983); Loopesko (1984); Humpage (1989); Obstfeld (1990); Dominguez (1990a,b, 1992); Black (1992); Catte et al. (1992); Eijffinger and Gruijters (1992); Dominguez and Frankel (1993a,b,c); Baillie and Osterberg (1997a) and see the references in the Edison (1993) survey. Previous studies of the effect of intervention on the volatility of exchange rates include: Baillie and Humpage (1992); Dominguez (1993, 1997); Almekinders and Eijffinger (1994); Almekinders (1995); and Bonser-Neal and Tanner (1996).

[2] IMF executive Board Decision no. 5392-(77/63), adopted April 1977.

[3] The G-5 countries include: France, Germany, Japan, the United Kingdom, and the United States.

continued to intervene episodically throughout the rest of the 1980s and early 1990s.

The scale of central bank intervention operations was large in the post-1985 period relative to previous history, but small relative to the overall size of the foreign exchange market. The most recent Bank for International Settlements (BIS) foreign exchange market survey suggests that the average daily volume of foreign exchange trading is now over one trillion dollars. By comparison, the average Fed intervention operation during the late 1980s involved $200 million.[4] The BOJ and the Bundesbank have maintained a more consistent presence in the foreign exchange markets than has the Fed. The BOJ and the Bundesbank intervened steadily during the period before 1985 when the Fed was absent from the market. Germany was reported to have been the major initial force in starting the dollar on its decline in early 1985 through both its own intervention operations and its pressure on the US and Japan to join in coordinated operations. The BOJ seems to have been especially active in the foreign exchange market during periods in which the yen was appreciating against the dollar.

Do intervention operations influence the volatility of exchange rates? Section 1 begins with a discussion of how central bank intervention policy can influence exchange rates. Section 2 describes two alternative approaches to measuring exchange rate volatility. Estimates of the influence of intervention on exchange rate volatility, as well as the influence of volatility on intervention, are presented in Sec. 3. Overall, the econometric results indicate that official G-3 exchange rate policy often significantly influenced exchange rate volatility over the past 18 years. Secret interventions are found to always increase volatility, while reported interventions have different effects on volatility depending on the central bank involved in the operation, the currency and the sample period. Section 4 presents conclusions.

1. Can central bank intervention influence exchange rates?

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 most countries, intervention operations are implemented by the monetary authority, although the decision to intervene can often also be made by authorities in the finance ministry, or treasury department, depending on the country. In practice, central banks define intervention more narrowly as any official

[4] The average unilateral sale of dollars by the Fed over the period 1985 through 1994 involved $190 million, and the average unilateral purchase of dollars involved $217 million. If all operations involving less than $100 million are excluded from the time series, the average dollar purchase was $312 million and the average dollar sale was $234 million. There were 4 days in 1994 when Fed dollar purchases exceeded $1 billion dollars, (the largest of these occurred on November 2, 1994 when the Fed purchased $1600 million). The largest dollar sale occurred on May 18, 1989 when the Fed sold $1250 million.

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 simultaneously to achieve maximum visibility. 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.[5]

Historical data on daily official Fed purchases and sales in the foreign exchange market have recently been made available, with a 1-year lag, to researchers outside the central bank.[6] At this time no central bank systematically publishes contemporaneous intervention data. However, daily intervention operations are frequently reported in newspapers and over the wire services. So, although contemporaneous intervention data are unavailable from official sources, there exist numerous unofficial sources of the data.[7] Secret interventions (or interventions that central banks choose not to make public) are not differentiated in central banks' official data, but one can roughly infer which operations were secret by comparing the official historical data with published reports of intervention activity in the financial press. Although traders may sometimes know that central banks are intervening without such knowledge appearing in the financial press, this relatively conservative accounting for reported intervention reveals that the bulk of recent intervention is not secret. In the empirical tests described in the next section I distinguish 'secret' and 'reported' interventions to examine whether the distinction matters in the volatility regressions.

Regardless of whether interventions are made public, intervention operations may influence the domestic monetary base. Non-sterilized intervention operations involve a change in the domestic monetary base; they are analogous to open-market operations except that foreign, rather than domestic, assets are bought or sold. Sterilized operations involve an offsetting domestic asset transaction that restores the original size of the monetary base. The Federal Reserve Bank of New York is thought to fully and automatically sterilize its intervention operations on a daily basis. In practice, the foreign exchange trading room immediately reports its dollar

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[5] Dominguez and Frankel (1993c) provide a detailed description of this process.

[6] Daily Bundesbank intervention data have been made available to individual researchers; use of this data is typically subject to confidentiality agreements. My agreement with the Bundesbank involves presenting results using the German data in such a way so that individual daily operations are not revealed.

[7] The Appendix to Dominguez and Frankel (1993c) provides a listing of all the news of G-3 intervention activity (as well as more general exchange rate policy announcements) by central banks reported in the *Wall Street Journal*, the *London Financial Times* and the *New York Times* over the period 1982 through 1990. In this paper, the reported intervention activity and exchange rate policy news series are updated to include newswire reports available in NEXIS, and each series has been extended back to 1977 and forward to 1994.

sales to the open market trading room, which then sells enough bonds to leave the daily US money supply unaffected. The Bundesbank also claims to sterilize their foreign exchange intervention operations routinely as a technical matter.[8] Nevertheless, the general perception is that both the Fed and the Bundesbank have at times allowed intervention operations to influence monetary aggregates — although the degree of monetary accommodation is limited to the extent that they both target their money supply growth.[9] The BOJ generally declines to provide information on its sterilization policy.

The standard monetary approach to exchange rate determination indicates that non-sterilized intervention will affect the level of the exchange rate in proportion to the change in the relative supplies of domestic and foreign money, just as any other form of monetary policy does. The effects of sterilized intervention are less direct and more controversial. In portfolio-balance models of exchange rate determination investors diversify their holdings among domestic and foreign assets based both on expected returns and on the variance in returns. According to the theory, as long as foreign and domestic assets are considered outside assets and are imperfect substitutes for each other in investor's portfolios, an intervention that changes the relative outstanding supply of domestic assets will require a change in expected relative returns.[10] This is likely to result in a change in the exchange rate.

The second channel through which sterilized intervention can affect the level of exchange rates is known as the signalling channel.[11] Intervention operations affect exchange rates through the signalling channel when they are used by central banks as a means of conveying (or signalling), to the market, inside information — information known to central banks but not the market — about future fundamentals.[12] If market participants believe the central bank's intervention signals, then even though today's fundamentals do not change when interventions occur, expectations of future fundamentals will change. When the market revises its expectations of future fundamentals, it also revises its expectations of the future spot exchange rate, which brings about a change in the current rate.[13] The magnitude of

[8]See Neumann and von Hagen (1992) for a detailed discussion of German sterilization policy.

[9]Germany and the US began to use monetary targets in 1975 and 1979, respectively.

[10]Branson and Henderson (1985) and Henderson (1984) provide a survey and analysis of portfolio balance models.

[11]One of the first descriptions of the signalling channel can be found in Mussa (1981).

[12]Interventions may signal information regarding monetary policy, or, more generally, as Friedman 1953, p. 188) argued, intervention might usefully convey information whenever, 'government officials have access to information that cannot readily be made available, for security or similar reasons, to private speculators'. Kenen (1987, p. 198) suggests that intervention signals may effectively 'change the market's confidence in its own projections . . . when expectations are heterogenous and especially when a bubble appears to be building'. Eijffinger and Verhagen (1997) suggest that interventions may convey (ambiguous) signals about the central bank's short-term exchange rate target (which in itself may reflect the central bank's assessment of the possible future paths of fundamentals).

[13]If the information revealed involves own future policy intentions, then sterilized intervention should not be considered an additional independent policy tool for central banks. The intervention operation may alter the timing or magnitude of the impact of monetary or fiscal policy on the exchange rate, but its effectiveness is not independent of those policies (Obstfeld, 1990).

the signalling effect of a sterilized intervention operation may exceed that of a non-sterilized operation, depending on the nature of the information that the signal conveys.

It is standard to model exchange rates as forward looking processes that are expectationally efficient with respect to public information. The current spot rate can be represented as

$$s_t = (1 - \delta) \sum_{k=0}^{\infty} \delta^k E_t(z_{t+k}|\Omega_t), \tag{1}$$

where s_t is the current spot exchange rate (domestic currency per unit of foreign currency) in log form, δ is the discount factor,[14] z_t is a vector of exogenous driving variables, and Ω_t is the public information set at time t. If intervention operations, denoted I_t, provide relevant information to the market, then they will enlarge the market's information set ($\Omega_t < \Omega_t + I_t$) and influence the spot exchange rate. For example, if a central bank intervention in support of the domestic currency signals future contractionary domestic monetary policy, the domestic currency will appreciate relative to the foreign currency:

$$s_t = (1 - \delta) \sum_{k=0}^{\infty} \delta^k E_t(z_{t+k}|\Omega_t) > (1 - \delta) \sum_{k=0}^{\infty} \delta^k E_t(z_{t+k}|\Omega_t + I_t), \tag{2}$$

where, in this example, I_t represents an official purchase of domestic assets.[15]

Explicit in the model of exchange rate behavior described by (Eq. (1)) is the assumption that currency prices are efficient aggregators of information and market expectations are rational. So any hypothesis test based on (Eq. (1)) involves a joint hypothesis that the foreign exchange market is economically efficient. Implicit in the signalling model of intervention illustrated by (Eq. (2)) is the hypothesis that intervention signals are fully credible and unambiguous. In practice, there is evidence against both of these assumptions: the foreign exchange market may not be fully efficient, and intervention signals may not always be credible or unambiguous.

As a consequence of the inherent joint nature of any hypothesis test involving the influence of intervention on the level or variance of exchange rates, at least eight possible scenarios need to be considered. These scenarios depend upon the nature and ambiguity of the intervention signal, and the efficiency of the foreign exchange market.

[14] In the monetary approach, $\delta = \beta/1 + \beta$, where β is the interest semi-elasticity of money demand.

[15] There is some empirical evidence to support the hypothesis that intervention serves to signal information regarding future monetary policy. Dominguez (1992, 1997), Ghosh (1992), Kaminsky and Lewis (1996) and Lewis (1995) test whether intervention helps forecast future monetary policy. These studies find evidence that knowledge of intervention policy does improve predictions of future monetary policy, although they also find that subsequent monetary policy changes are frequently in the opposite direction to what was signalled.

1.1. The expected influence of an intervention operation on the level and variance of the price of domestic currency

1.1.1. Intervention signal of commitment to change relevant fundamentals to appreciate the domestic currency

$\Delta s_t \mid I_t$ $\text{var}[\Delta s_t \mid I_t]$		Exchange market efficiency	
		s_t efficient	s_t inefficient
Nature of intervention signal	I_t credible and unambiguous	$\Delta s_t \mid I_t < 0$ $\text{var}[\Delta s_t \mid I_t] = 0$	$\Delta s_t \mid I_t < 0$ or $= 0$ $\text{var}[\Delta s_t \mid I_t] > 0$
	I_t not credible or ambiguous	$\Delta s_t \mid I_t > 0$ or $= 0$ $\text{var}[\Delta s_t \mid I_t] > 0$	$\Delta s_t \mid I_t > 0$ or $= 0$ $\text{var}[\Delta s_t \mid I_t] > 0$

1.1.2. Intervention signal of commitment to change relevant fundamentals to reduce exchange rate volatility

$\Delta s_t \mid I_t$ $\text{var}[\Delta s_t \mid I_t]$		Exchange market efficiency	
		s_t efficient	s_t inefficient
Nature of intervention signal	I_t credible and unambiguous	$\Delta s_t \mid I_t = 0$ $\text{var}[\Delta s_t \mid I_t] < 0$	$\Delta s_t \mid I_t > 0$ or < 0 $\text{var}[\Delta s_t \mid I_t] > 0$
	I_t not credible or ambiguous	$\Delta s_t \mid I_t > 0$ or < 0 $\text{var}[\Delta s_t \mid I_t] > 0$	$\Delta s_t \mid I_t > 0$ or < 0 $\text{var}[\Delta s_t \mid I_t] > 0$

If intervention signals are fully credible, unambiguous, and foreign exchange markets are efficient, they should either have no influence on the variance of exchange rates, or they should reduce volatility. In the example described previously, where intervention signals a future monetary contraction, the intervention should result in a one time appreciation in the domestic currency with no effect on the variance. Alternatively, if the information being signalled via intervention is that the central bank is committed to reducing volatility (potentially the Louvre Accord interventions), then we should expect interventions to be associated with no systematic effect on the level of the exchange rate and with lower exchange rate variances. On the other hand, if intervention signals are not fully credible,

[16]Alternatively, in the Eijffinger and Verhagen (1997) theoretical framework, ambiguity may increase a central bank's influence on the level of the spot rate. In their model, interventions are used by central banks to signal information regarding exchange rate preferences (e.g. short-term exchange rate targets). Once market participants learn about these preferences, the central bank loses its informational advantage (and its ability to influence market expectations). As a consequence, it will be in a central bank's best interest to hide some of its information, or send noisy signals. In the model, regardless of the efficacy of these ambiguous interventions, they always lead to increases in the volatility of the spot rate.

ambiguous, or if the exchange market is inefficient, then intervention may have the opposite of the desired effect on the level of exchange rates,[16] and a likely positive influence on volatility.[17]

The scenarios previously detailed suggest that the influence of intervention (even if credible and unambiguous) on the level of exchange rates is in many cases indeterminate. Information on the exact nature of the intervention signal is essential to distinguish the expected effect of the signal on exchange rate levels. On the other hand, the influence of intervention on the variability of exchange rates is relatively straightforward, and it is for this reason that I focus on this empirical relationship. The only scenario under which we should expect intervention to reduce exchange rate variance is the case where intervention signals a commitment to reduce volatility and intervention is credible and unambiguous. (Central bank interventions in a credible target-zone model provide a theoretical example of this case.) Alternatively, if intervention is found to increase volatility, this could reflect evidence of any one of the other seven scenarios described.

2. Measuring exchange rate volatility

A plot of daily dollar-mark or dollar-yen exchange rate movements over the past 18 years reveals two types of volatility. On the one hand, long gradual swings in the data are apparent. For example, the dollar-mark rate averaged 0.49 in the late 1970s, fell to 0.32 in 1984, rose to 0.60 in 1988 and oscillated between 0.53 and 0.73 into the mid 1990s. At the same time, intra-day, daily and weekly movements in the dollar-mark exchange rate have also at times fluctuated widely. For example, on the day after the Plaza agreement the dollar-mark rate fell by four percentage points. The question of whether intervention policy influences exchange rate volatility obviously depends importantly on the definition of volatility. Because intervention decisions are made on a daily basis, and central banks rarely intervene continuously for long periods of time, it is difficult to econometrically examine the influence of intervention policy on the long swings of the dollar against the mark or yen. As a consequence, this study examines the influence of intervention on daily and short-term exchange rate volatility.

Short-term exchange rate volatility can be estimated using time series econometric techniques, and it can be calculated from market-determined option prices. Both approaches to measuring short-term volatility have their merits. Time series estimates of the conditional variance of exchange rates provide an ex-post measure of daily or weekly volatility. Studies by Westerfield (1977) and Hsieh (1988) 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

[17] In the context of a learning model, Lewis (1989) shows that policy ambiguity is likely to cause the conditional variance of the exchange rate to be higher than the conditional variance when policy is unambiguous.

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.[18] They conclude that the disturbances in the exchange rate process are uncorrelated but not stochastically independent.[19] These studies indicate that the variance of daily exchange rate changes is forecastable using GARCH models.

The expected volatility measure implicit in exchange rate option prices provide an alternative, ex ante, measure of volatility. If the options are efficiently priced, then the volatility implied by the option price provides an unbiased estimate of the market's forecast of volatility. Further, because the implied volatilities are calculated from options that expire in the future, they measure longer-term exchange rate volatility. Unfortunately exchange rate options were not actively sold on exchanges until the mid-1980s and during periods of low volatility option markets can be extremely thin, severely limiting data. In this paper, both GARCH conditional variances and implied volatilities from foreign exchange options are used to examine the relationship between intervention and exchange rate volatility.[20]

Denoting the one period change in the exchange rate by Δs_t, an empirical model of exchange rate changes can be represented as

$$\Delta s_t = z_t \beta + \varepsilon_t, \tag{3}$$

where z_t includes news and intervention variables and ε_t is the disturbance term. The conditional mean of the disturbance in (Eq. (3)) is $E[\varepsilon_t|\Omega_{t-1}] = 0$, (where Ω_{t-1} now includes I_{t-1}) and conditional variance is $\text{var}[\varepsilon_t|\Omega_{t-1}] = \text{var}[\Delta s_t|\Omega_{t-1}]$. The GARCH(1,1) conditional variance is $\nu_t = \alpha_0 + \alpha_1 \nu_{t-1} + \alpha_2 \varepsilon_{t-1}^2$,[21] while the implied volatility, denoted IV_t, can be estimated from exchange rate option prices.[22]

In order to examine the influence of intervention on exchange rate volatility, it would be ideal to categorize intervention operations based on central bank objec-

[18] Engle (1982) is the first application of ARCH to price data. Bollerslev (1986) generalized autoregressive conditional heteroscedasticity model (GARCH) extends the ARCH class of models to allow the conditional variance of exchange rate prediction errors to depend on lagged conditional variances as well as past sample variances.

[19] Diebold and Nerlove (1989) suggest that the nature of incoming information in asset markets may explain the non-linear serial dependence in daily exchange rates. 'When signals are relatively clear (i.e. easily and unambiguously interpretable) then, conditional upon those signals, exchange rate volatility is likely to be low. When there is disagreement about the meaning of incoming information, or when clearly relevant and significant information is scarce, we would expect greater market volatility' (p. 19).

[20] Over the period 1977–1994, the average conditional variance (estimated from a basic GARCH(1,1) model) is 0.58 and 0.55 for the dollar-mark and dollar-yen rates, respectively; the maximum conditional variance occurred on November 2, 1978 for the mark (at 6.14) and September 24, 1985 for the yen (at 3.27). Over the period 1985–1993, the average implied volatility is 9.79 and 8.29 for the dollar-mark and dollar-yen rates, respectively; the maximum implied volatility occurred on October 11, 1988 for the mark (at 16.84) and March 3, 1993 for the yen (at 17.25).

[21] The unconditional mean of the disturbance term is $E[\varepsilon_t] = 0$ and the unconditional variance is $\text{var}[\varepsilon_t] = \text{var}[\Delta s_t] = \alpha_0/(1 - \alpha_1 - \alpha_2)$.

tives and the credibility of each signal. In practice, there is information regarding the secrecy (or potential ambiguity) of each intervention, as well as the public statements made by each central bank regarding general intervention objectives. One hypothesis that can be tested using the GARCH model or implied volatilities extracted from option prices is that secret interventions are inherently ambiguous signals and they are consequently likely to increase uncertainty and, in turn, volatility in the market. Another testable hypothesis is that reported interventions provide unambiguous signals of intervention policy, and therefore have no effect on volatility or possibly reduce exchange rate volatility (depending on the central bank's objectives). In particular, reported interventions should reduce exchange rate volatility during periods when central banks announce their objective to 'calm disorderly markets'.[23]

The GARCH(1,1) models of the dollar-mark and dollar-yen exchange rates that I estimate have the following general specification:

$$\Delta s_t = \beta_0 + \sum_{i=1}^{4} \beta_i D_{it} + \beta_5 H_t + \beta_6 I_t^{\text{Fed}} + \beta_7 I_t^{BB} + \beta_8 I_t^{\text{secret}} + \beta_9 I_t^{\text{BOJ}} + \beta_{10} N_t + \beta_{11} \Delta i_t + \beta_{12} \sqrt{\nu_t} + \varepsilon_t, \tag{4}$$

$$\varepsilon_t | \Omega_{t-1} \sim N(0, \nu_t, \kappa), \tag{5}$$

$$\nu_t = \alpha_0 + \alpha_1 \nu_{t-1} + \alpha_2 \varepsilon_{t-1}^2 + \phi_1 H_t + \psi_1 |I_t^{\text{Fed}}| + \psi_2 |I_t^{BB}| + \psi_3 |I_t^{\text{secret}}| + \psi_4 |I_t^{\text{BOJ}}| + \psi_5 |N_t| + \psi_6 \Delta i_t, \tag{6}$$

where Δs_t is the log change in the dollar-mark or dollar-yen spot exchange rate between period t and $t-1$, D_{it} are day of the week dummy variables (i.e. $D_{1t} = 1$ on Mondays), H_t is a holiday dummy variable that is equal to one on the day following the market being closed for any reason other than a weekend,[24] I_t^{Fed} is a variable capturing reported Fed intervention operations known at time t,[25] I_t^{BB} is a

[22] The options used in this study are American call options which allow the possibility of early exercise. The Newton-Raphson algorithm was used to search for the Barone-Adesi and Whaley (1987) estimate of implied volatility that was closest to the actual call price for each option. These implied volatilities for all options meeting certain criteria (at-the-money call options, with maturities between 7 and 100 days, and with strike prices within 2% of the spot price) were then averaged to obtain the daily implied volatility measure used in the paper.

[23] It is important to note that if central bank intervention does not signal future fundamentals, but instead is based on current movements of the exchange rate, then $E[\varepsilon_t|\Omega_{t-1}] \neq 0$; I_t will not be an appropriate right-hand-side variable in (Eq. (3)). Dominguez and Frankel (1993c) find that the intervention operations that took place in the mid-1980s cannot be well explained on the basis of past exchange rate movements. But this hypothesis will be explicitly tested in the next section of the paper.

[24] Hsieh (1988) finds evidence that both day-of-week and holiday dummy variables should be included as explanatory variables in daily exchange rate GARCH models.

[25] Fed, Bundesbank and BOJ intervention operations need not be lagged one period because the exchange rate data are New York market close data, so that Fed intervention for day t is predetermined. Germany and Japan are 6 and 14 h ahead, respectively, of New York so their day t interventions will also be predetermined.

variable capturing reported Bundesbank intervention operations known at time t, I_t^{secret} is a variable capturing 'secret' Fed and Bundesbank intervention operations at time t, I_t^{BOJ} is a $(-1,0,1)$ dummy variable capturing reported BOJ intervention operations known at time t,[26] N_t is a $(-1,0,1)$ dummy variable capturing exchange rate policy news (excluding intervention),[27] Δi_t is the spread between German or Japanese and US overnight interest rates, $|\,|$ is the absolute value operator and ε_t is the disturbance term. The conditional distribution of the disturbance term is standardized t with variance ν_t and degrees of freedom κ.[28] The t distribution approaches a normal distribution as the parameter κ approaches infinity. The last explanatory variable in the conditional mean equation allows for the possibility that changes in the conditional variance influence the conditional mean. The implied volatility model specification that I estimate is analogous to the conditional variance equation in the GARCH model, except that the lagged implied volatility replaces the lagged conditional variance, and the lagged sample variance is omitted.[29]

In addition to the intervention variables, the spread between the German or Japanese interbank interest rate and the US federal funds rate is included in both volatility models to control for relative contemporaneous monetary policies in the three countries.[30] In the GARCH conditional mean equation, the intervention variables are included so that positive values denote purchases of dollars and negative values denote official dollar sales. In the conditional variance equation, intervention variables are included in absolute value form. I consider three specifications of the GARCH conditional variance equation. The first is a basic GARCH(1,1) model excluding the additional exchange rate policy variables, the second measures Fed and Bundesbank reported and secret interventions in dollars, and the third measures all the intervention variables as $(-1,0,1)$ dummy variables. It may be that what influences volatility is the presence of central banks in the market, regardless of the magnitude of the actual intervention operation. The

[26] Official BOJ daily intervention data is not available to the public. The BOJ data used in the regressions were collected from the financial press. Negative ones are used to denote days in which the BOJ was reported to have intervened against the dollar, positive ones to denote days in which the BOJ was reported to have intervened in support of the dollar, and zeros to denote days in which the BOJ was not reported to have intervened in the foreign exchange market.

[27] Negative ones are used to denote days in which an official G-3 (the US, Germany and Japan) statement was made against the dollar, positive ones to denote days in which an official G-3 statement was made in support of the dollar, and zeros to denote days in which no such announcements were made. Examples of the content of these announcements are in the Appendix of Dominguez and Frankel (1993c).

[28] Bollerslev (1986), Hsieh (1989) and Baillie and Bollerslev (1989) find evidence that the GARCH(1,1) using a conditional Student t distribution, rather than the normal distribution, is the most appropriate model for daily exchange rate data.

[29] The implied volatilities are estimated from option prices collected between 10:00 h and noon EST on each trading day. Because market participants cannot know (with certainty) the Fed's Tuesday interventions on Tuesday morning (before noon), Fed interventions in these regressions are lagged one day. Bundesbank and BOJ intervention operations need not be lagged, because the financial markets in these countries will already be closed for the day by noon EST.

GARCH model specification that includes only dummy variables allows a test of this hypothesis.

The GARCH models are estimated using the maximum likelihood procedure described in Berndt et al. (1974). The log-likelihood function of the data is given by:

$$L_T(\theta) = T\left[\log\Gamma\left(\frac{\kappa+1}{2}\right) - \log\Gamma\left(\frac{\kappa}{2}\right) - \tfrac{1}{2}\log(\kappa-2)\right] - \tfrac{1}{2}\sum_{t=1}^{T}\left[\log\nu_t + (\kappa+1)\log\left(1+\varepsilon_t^2\nu_t^{-2}(\kappa-2)^{-1}\right)\right], \quad (7)$$

where Γ denotes the gamma function and $\theta = (\beta,\alpha,\phi,\psi)$. The standard errors in the implied volatility models are corrected for serial correlation and conditional heteroscedasticity following Hansen (1982).

The Fed and Bundesbank intervention data series used in the empirical tests measure consolidated daily official foreign exchange transactions in billions of dollars at current market values. The Fed data exclude so-called ‘passive’ intervention operations. Passive interventions are Fed purchases and sales of foreign currency with customers who would otherwise have dealt with market agents.[31] The Bundesbank data exclude non-discretionary interventions required by EMS rules.

The exchange rate data used in the empirical tests are New York market close spot dollar-mark and dollar-yen prices (bid side) compiled by the Federal Reserve Bank of New York.[32] Table 1 presents various descriptive statistics for the two exchange rates and G-3 intervention operations over the period 1977 to 1994. These statistics confirm that daily exchange rates are strongly heteroscedastic martingale processes.

The implied volatilities used in the empirical tests are derived from prices of American call option contracts on spot dollar-mark and dollar-yen exchange rates from the Philadelphia Stock Exchange’s transaction database. As described in the previous section, one of the drawbacks to implied volatilities is that data only begin in the mid-1980s and there are numerous periods in which no option data are available. In particular, for both the dollar-mark and dollar-yen rates, option data are missing from October 25, 1985 through November 27, 1985 and August 29, 1988 through September 30, 1988. These periods are, unfortunately, also periods in which G-3 intervention activity was particularly heavy. In the case of the dollar-yen rate, 35 days in 1991, 113 days in 1992, and 246 days in 1993 are also missing.[33]

[30] The German and Japanese interest rates are the call money (overnight) rates, and the US interest rate is the Federal Funds rate. The source for these series is the Federal Reserve Bank of New York.
[31] Adams and Henderson (1983) provide detailed discussion and definition of customer transactions.
[32] I am grateful to Linda Goldberg for providing the spot data.
[33] Over the period 1985 through 1993, 157 days are missing for the dollar-mark rate and 543 days are missing for the dollar-yen rate.

The subsamples used in the empirical tests throughout the paper were chosen on the basis of pre-announced intervention regime changes. The first subsample includes the period January 1985 through mid-February 1987. During this period, which includes the Plaza Agreement,[34] the dollar fell by over 50% against the mark. In the early part of this subsample the G-5 central banks explicitly stated that their goal was to depreciate the dollar. But by 1986 both the Bundesbank and the BOJ indicated — both verbally and through their intervention operations — that the dollar had fallen far enough, while the US continued to 'talk' the dollar down, but abstained from further interventions against the dollar. Nevertheless, throughout the period the central banks' stated intention was to affect the level rather than the variance of exchange rates. The second subsample covers the Post-Louvre Accord period, February 1987 through December 1994. The G-7 (excepting Italy) produced the Louvre Accord in late February 1987 which stated

Table 1
Daily exchange rate and intervention statistics

I. Daily exchange rate statistics (1977–1994)				
	Variable: S_t		Variable: $\Delta(\ln S_t)$	
	\$/DM	\$/Yen × 100	\$/DM	\$/Yen
Mean	0.511	0.599	0.009	0.238
Variance	0.009	0.035	0.529	0.471
Skewness[a]	−0.268**	0.479**	−0.015	0.363**
Kurtosis	−0.962**	−1.024**	4.364**	4.404**
$Q_{\Delta s}(20)$[b]			26.799	42.259**
$Q_{\Delta s2}(20)$			294.987**	161.764**
II. Sample and partial autocorrelation coefficients (1977–1994)				
	Dollar-Mark		Dollar-Yen	
	r[c]	ρ[d]	r	ρ
Lag 1	0.99909	0.99909	0.99909	0.99909
Lag 2	0.99822	0.01493	0.99820	0.00459
Lag 3	0.99732	−0.01090	0.99730	−0.00256
Lag 4	0.99642	−0.00434	0.99640	−0.00205
III. Number of intervention days				
Sample period	Reported Fed	Reported BBank	Reported BOJ	Secret
1985–1987[e]	29	48	56	11
1987–1994[f]	209	132	295	105
1977–1994	274	236	656	1367

[34] The Plaza Agreement communique stated that 'in view of the present and prospective changes in fundamentals, some orderly appreciation of the main non-dollar currencies against the dollar is desirable. They [the Ministers and Governors] stand ready to cooperate more closely to encourage this when to do so would be helpful' (G5 Announcement, September 22, 1985).

[35] Two recent papers have examined whether dollar exchange rates in the post-Louvre Accord period behaved as if they were in a target zone (Klein and Lewis, 1993; Baillie and Humpage, 1992).

Table 1. (*Continued*)

IV. Average intervention magnitudes[g] (millions of dollars)

	Reported Fed	Reported BBank	Reported BOJ	Secret
1985–1987	135.4	126.0	NA	43.3
1987–1994	236.1	143.0	NA	91.3
1977–1994	221.3	141.6	NA	72.2

V. Conditional probability of reported intervention[h]

	Reported Fed	Reported BBank
1985–1987	0.94	0.83
1987–1994	0.79	0.70
1977–1994	0.26	0.21

Sources: Federal Reserve Bank of New York (spot data), Board of Governors of the Federal Reserve System (Fed intervention data), Deutsche Bundesbank (BBank intervention data) and NEXIS (reports of central bank interventions).
** Denotes significance at the 99% level.
[a] The skewness and kurtosis statistics are normalized so that a value of zero corresponds to the normal distribution.
[b] $Q_{\Delta s}(20)$ pertains to the Box-Pierce Q-statistic test for high-order serial correlation in Δs; 20 correlations are tested.
[c] r denotes the sample autocorrelation coefficient.
[d] ρ denotes the partial autocorrelation coefficient.
[e] The 1985–1987 subperiod begins 1/2/85 and ends 2/27/87.
[f] The 1987–1994 subperiod begins 3/2/87 and ends 12/30/94.
[g] Average intervention magnitudes include dollar purchases and the absolute value of dollar sales, and exclude days on which no intervention occurred.
[h] Conditional probabilities are calculated as the number of reported interventions divided by the total number of interventions in the subperiod.

that nominal exchange rates were 'broadly consistent with underlying economic fundamentals' and should be stabilized at their current levels (G-6 Communique, February 22, 1987).[35]

The statistics in Table 1 indicate that skewness and kurtosis are generally significant in the raw daily dollar-mark and dollar-yen data. Percentage changes in both the dollar-mark and dollar-yen spot data consistently exhibit a high degree of kurtosis. The Box-Pierce Q-statistic tests for high-order serial correlation generally indicate that the squared percentage change spot data exhibit substantially more autocorrelation than the unsquared data.[36] This is indicative of strong conditional heteroscedasticity. The first four sample autocorrelation and partial autocorrelation coefficients for the raw dollar-mark and dollar-yen exchange rates indicate homogeneous non-stationarity. The first lag of the sample partial autocorrelation is

[36] Under the null hypothesis of iid, the Q-statistic is asymptotically a chi-squared distribution with x degrees of freedom (Hsieh, 1989, p. 307).

Table 2
Daily exchange rate GARCH model: conditional variance equation sample: 1/85–2/87, 540 obs
$\nu_t = \alpha_0 + \alpha_1 \nu_{t-1} + \alpha_2 \varepsilon^2_{t-1} + \phi_1 H_t + \psi_1 |I_t^{\mathrm{Fed}}| + \psi_2 |I_t^{BB}| + \psi_3 |I_t^{\mathrm{secret}}| + \psi_4 |I_t^{\mathrm{BOJ}}| + \psi_5 |N_t| + \psi_6 \Delta i_{\mathrm{t}}$

	$/DM			$/Yen	
	Basic	Magni-[a] tudes	Dummy vars[b]	Basic	Magni- tudes
α_0	0.064	0.001	0.061	0.022	0.045
	(0.032)*	(0.005)	(0.025)*	(0.011)*	(0.023)
α_1	0.826	0.852	0.803	0.847	0.716
	(0.058)**	(0.028)**	(0.065)**	(0.041)**	(0.059)
α_2	0.098	0.086	0.111	0.136	0.152
	(0.039)**	(0.022)**	(0.041)**	(0.058)*	(0.044)
ϕ_1	0.245	0.331	0.311	0.220	0.165
	(0.171)	(0.116)**	(0.116)**	(0.155)	(0.072)
Ψ_1		−0.248	−0.168		−0.833
		(0.139)†	(0.035)**		(0.433)
Ψ_2		−0.167	−0.083		−0.187
		(0.038)**	(0.030)**		(0.089)
Ψ_3		5.734	0.251		1.778
		(1.371)**	(0.092)**		(0.664)
Ψ_4		−0.017	−0.007		0.112
		(0.030)	(0.006)		(0.063)
Ψ_5		−0.022	−0.014		−0.098
		(0.031)	(0.079)		(0.032)
Ψ_6		0.009	0.009		−0.016
		(0.001)**	(0.011)		(0.006)
κ[c]	7.936	6.424	7.961	3.145	3.407
	(2.44)**	(1.337)**	(2.327)**	(0.526)**	(0.518)
ln L[d]	−386.20	−369.21	−369.09	−216.19	−194.33

Table 2 (*Continued*)

	$/DM			$/Yen	
	Basic	Magni-[a] tudes	Dummy vars[b]	Basic	Magn tudes
ρ^{e}	15	16	38	18	44
$Q_z\,(20)^{f}$	26.13	26.39	28.09	16.05	13.34
$Q_z^{2}\,(20)^{g}$	15.29	17.22	11.59	5.38	4.75

Sources: Federal Reserve Bank of New York (daily spot data and overnight interest rates), Board of Governors of t intervention data), Deutsche Bundesbank (BBank intervention data) and NEXIS (reports of central bank interventions a Asymptotic standard errors are in parentheses, †denotes significance at the 90% level, *denotes significance at the 95% **denotes significance at the 99% level.

[a] In this column Fed, BBank and Secret intervention data are measured in billions of dollars.

[b] In this column Fed and BBank intervention data are included as (0,1) dummy variables on days that the respective cer intervened. Secret intervention is also included as a (0,1) dummy variable denoting days on which Fed and/or Bundesbar in the financial press.

[c] κ is the degrees of freedom parameter in the Student-t distribution.

[d] $\ln L$ is the value of the log likelihood function.

[e] ρ is the number of convergence iterations.

[f] $Q_z(20)$ denotes the Box-Pierce Q-statistic (with 20 lags) for the standardized residuals ($z = \varepsilon_t(\nu_t)^{-1/2}$).

[g] $Q_{z^2}(20)$ denotes the Box-Pierce Q-statistic (with 20 lags) for the squared standardized residuals.

Table 3
Daily exchange rate GARCH model: conditional variance equation sample: 3/87–12/94, 1972 obs
$\nu_t = \alpha_0 + \alpha_1 \nu_{t-1} + \alpha_2 \varepsilon^2_{t-1} + \phi_1 H_t + \psi_1 |I_t^{\mathrm{Fed}}| + \psi_2 |I_t^{BB}| + \psi_3 |I_t^{\mathrm{secret}}| + \psi_4 |I_t^{\mathrm{BOJ}}| + \psi_5 |N_t| + \psi_6 \Delta i_t$

	$/DM			$/Yen	
	Basic	Magnitudes	Dummy vars	Basic	Magnitudes
α_0	0.033	0.034	0.033	0.021	0.011
	(0.009)**	(0.009)**	(0.009)**	(0.006)**	(0.005)
α_1	0.865	0.840	0.839	0.892	0.900
	(0.027)**	(0.032)**	(0.032)**	(0.023)**	(0.019)
α_2	0.057	0.042	0.047	0.065	0.053
	(0.014)**	(0.014)**	(0.015)**	(0.016)**	(0.013)
ϕ_1	0.214	0.246	0.246	0.057	0.107
	(0.074)**	(0.079)**	(0.078)**	(0.049)	(0.048)
Ψ_1		0.208	0.060		0.148
		(0.091)*	(0.024)*		(0.071)
Ψ_2		−0.007	−0.014		−0.066
		(0.157)	(0.012)		(0.108)
Ψ_3		0.417	0.027		0.250
		(0.240)†	(0.003)**		(0.021)
Ψ_4		−0.016	0.008		−0.005
		(0.017)	(0.020)		(0.014)
Ψ_5		0.066	0.066		0.059
		(0.024)**	(0.025)**		(0.021)
Ψ_6		0.003	0.003		0.001
		(0.001)**	(0.001)**		(0.001)
κ	6.681	6.318	6.283	4.321	4.240
	(1.128)*	(1.039)**	(1.033)**	(0.476)**	(0.461)
ln L	−937.96	−871.84	−872.40	−785.72	−741.00

Table 3 (*Continued*)

	$/DM			$/Yen	
	Basic	Magni-tudes	Dummy vars	Basic	Magni-tudes
ρ	14	18	18	11	22
Q_z (20)	15.47	20.01	20.27	26.29	23.33
Q_z^2 (20)	23.38	18.10	21.69	10.83	7.88

See notes for Table 2.

Table 4
Daily exchange rate GARCH model: conditional variance equation sample: 1/77–12/94, 4515 obs
$\nu_t = \alpha_0 + \alpha_1 \nu_{t-1} + \alpha_2 \varepsilon^2_{t-1} + \phi_1 H_t + \psi_1 |I_t^{\text{Fed}}| + \psi_2 |I_t^{BB}| + \psi_3 |I_t^{\text{secret}}| + \psi_4 |I_t^{\text{BOJ}}| + \psi_5 |N_t| + \psi_6 \Delta i_t$

	\$/DM			\$/Yen	
	Basic	Magni-tudes	Dummy vars	Basic	Magni-tudes
α_0	0.006	0.005	0.013	0.009	0.022
	(0.001)**	(0.002)**	(0.002)**	(0.002)**	(0.005)
α_1	0.893	0.872	0.885	0.904	0.841
	(0.009)**	(0.010)**	(0.009)**	(0.010)**	(0.019)
α_2	0.097	0.109	0.086	0.085	0.098
	(0.009)**	(0.011)**	(0.009)**	(0.011)**	(0.014)
ϕ_1	0.101	0.103	0.059	0.032	0.081
	(0.027)**	(0.026)**	(0.024)*	(0.023)	(0.034)
Ψ_1		0.092	0.015		0.144
		(0.049)†	(0.004)**		(0.075)
Ψ_2		0.065	−0.015		−0.172
		(0.111)	(0.004)**		(0.081)
Ψ_3		0.083	0.012		0.089
		(0.032)*	(0.004)**		(0.046)
Ψ_4		−0.005	0.005		0.029
		(0.005)	(0.004)		(0.012)
Ψ_5		0.037	0.018		0.013
		(0.013)*	(0.013)		(0.016)
Ψ_6		0.0009	0.0001		−0.000
		(0.0003)**	(0.0003)		(0.001)
κ	5.830	5.927	5.818	4.221	4.441
	(0.551)**	(0.576)**	(0.550)**	(0.297)**	(0.331)

Table 4 (*Continued*)

	\$/DM			\$/Yen	
	Basic	Magni-tudes	Dummy vars	Basic	Magn tudes
ln L	−1991.27	−1838.53	−1853.72	−1709.55	−168
ρ	15	49	18	14	5
Q_z (20)	31.53	25.97	25.45	38.40*	2
Q_z^2 (20)	15.81	15.68	13.21	14.14	1

See notes for Table 2.

Table 5
Daily exchange rate volatility model: implied volatility equation

$$\ln[\frac{IV_t}{IV_{t-1}}] = \alpha_0 + \alpha_1 IV_{t-1} + \beta_1 H_t + \gamma_1 |I_{t-1}^{\text{Fed}}| + \gamma_2 |I_t^{BB}| + \gamma_3 |I_{t-1}^{\text{secret}}| + \gamma_4 |I_t^{\text{BOJ}}| + \gamma_5 |N_{t-1}| + \gamma_6 \Delta i_{t-1}$$

	\$/DM			\$/Yen		
	1985–1987[a]	1987–1993[b]	1985–1993	1985–1987	1987–1993	1985–1993
α_0	6.320	9.386	5.386	5.995	8.917	7.024
	(6.490)	(3.343)**	(2.279)*	(6.383)	(7.396)	(4.935)
α_1	−0.341	−1.083	−0.600	−0.192	−1.214	−0.922
	(0.402)	(0.345)**	(0.219)**	(0.476)	(0.888)	(0.564)†
β_1	4.781	2.512	2.959	4.418	5.925	2.876
	(4.760)	(2.201)	(2.047)	(5.004)	(3.093)†	(2.639)
γ_1	−0.035	0.012	0.007	−0.042	0.021	0.015
	(0.008)**	(0.004)**	(0.004)†	(0.011)**	(0.004)**	(0.005)**
γ_2	−0.015	0.022	0.018	−0.017	0.002	0.005
	(0.006)*	(0.007)**	(0.005)**	(0.009)†	(0.009)	(0.007)
γ_3	0.158	0.019	0.001	0.284	0.020	0.024
	(0.074)*	(0.012)	(0.001)	(0.222)	(0.010)†	(0.012)†
γ_4	−0.429	0.722	0.300	0.351	3.840	3.076
	(0.285)	(0.799)	(0.500)	(0.212)	(1.290)**	(1.282)*
γ_5	1.163	0.875	1.001	2.246	3.413	2.778
	(1.970)	(1.261)	(1.065)	(1.756)	(1.509)*	(1.324)*
γ_6	−1.011	0.243	0.039	−2.627	0.354	0.292
	(1.244)	(0.134)†	(0.113)	(1.559)†	(0.300)	(0.291)
R^2	0.020	0.016	0.011	0.022	0.014	0.009
Obs	527	1702	2229	527	1471	1998

Sources: Federal Reserve Bank of New York (daily spot and overnight interest rate data), Board of Governors of the Federal Reserve System (Fed intervention data), Deutsche Bundesbank (BBank intervention data), NEXIS (reports of central bank intervention and exchange rate policy news), Philadelphia stock exchange transaction database (option data), Data Resources Incorporated (daily eurodollar, euromark and euroyen rates, various maturities).
Asymptotic standard errors are in parentheses, †denotes significance at the 90% level, *denotes significance at the 95% level, and **denotes significance at the 99% level. Fed, BBank and Secret intervention data are measured in millions of dollars. The dependent variable is multiplied by 1000.
[a] The 1985–1987 subperiod begins 1/2/85 and ends 2/27/87.
[b] The 1987–1993 subperiod begins 3/2/87 and ends 12/31/93.

approximately one, and subsequent lags are insignificantly different from zero. Standard Dickey-Fuller tests for unit roots fail to reject the hypothesis of a unit root in the daily spot data, while the Hasza and Fuller (1979) test for two unit roots is rejected.

3. Estimation results

Tables 2–4 present estimates from the GARCH(1,1) exchange rate model over

Table 6

Daily intervention reaction function: probits $|I_t^j| = \alpha_0 + \alpha_1(S_{t-1} - \frac{1}{k}\sum_{n=1}^{k} s_{t-n}) + \alpha_2(\nu_{t-1} - \frac{1}{k}\sum_{n=1}^{k} \nu_{t-n})$

	$/DM			$/Yen	
	85–87[a]	87–94[b]	77–94	85–87	87–
I^j = reported Fed intervention					
α_0	−1.631	−1.249	−1.546	−1.621	−
	(0.091)**	(0.038)**	(0.295)**	(0.090)**	
α_1	18.845	−2.871	0.324	18.108	−
	(10.351)[†]	(5.416)	(4.202)	(12.946)	
α_2	−0.146	−0.207	−0.053	−0.126	−
	(0.426)	(0.429)	(0.222)	(0.422)	
LR(2)[c]	3.345	0.533	0.064	1.970	
ln L[d]	−111.36	−666.45	−1033.05	−112.07	−6
Obs[e]	541	1973	4512	541	19

Table 6 (*Continued*)

	\$/DM			\$/Yen		
	85–87[a]	87–94[b]	77–94	85–87	87–94	77–94
I^{j} = reported BBank intervention						
α_0	−1.356	−1.499	−1.623	−1.355	−1.500	−1.624
	(0.076)**	(0.043)**	(0.031)**	(0.076)**	(0.043)**	(0.031)**
α_1	10.881	−3.015	−4.649	10.895	4.535	4.741
	(8.909)	(6.067)	(6.470)	(11.533)	(6.318)	(4.733)
α_2	0.284	0.255	−0.163	0.453	−0.371	0.267
	(0.365)	(0.479)	(0.348)	(0.371)	(0.450)	(0.251)
LR(2)	2.363	0.522	0.732	2.620	1.177	2.199
ln L	−160.86	−484.21	−925.87	−160.73	−483.88	−924.97
Obs	541	1973	4512	541	1973	4512
I^{j} = reported BOJ intervention						
α_0	−1.273	−1.040	−1.057	−1.271	−1.040	−1.056
	(0.073)**	(0.034)**	(0.023)**	(0.073)**	(0.034)**	(0.022)**
α_1	23.614	−9.080	−4.159	27.964	2.083	−0.363
	(12.788)†	(4.905)†	(3.302)	(16.915)†	(5.018)	(3.457)
α_2	0.088	0.507	−0.245	0.704	−0.595	−0.253
	(0.551)	(0.386)	(0.187)	(0.627)	(0.331)†	(0.204)
LR(2)	3.411	3.427	3.269	3.036	3.392	1.563
ln L	−178.27	−830.63	−1869.15	−178.43	−830.63	−1870.01
Obs	541	1973	4512	541	1973	4512

Table 6 (*Continued*)

	$/DM			$/Yen	
	85–87[a]	87–94[b]	77–94	85–87	87–94
I^j = secret Fed and BBank intervention					
α_0	−2.049	−1.617	−0.519	−2.059	−1.616
	(0.124)**	(0.047)**	(0.019)**	(0.126)**	(0.046
α_1	3.935	−1.647	−4.458	−6.293	−8.277
	(15.002)	(6.817)	(2.899)	(19.233)	(7.116
α_2	−0.309	−0.622	−0.175	−0.643	−0.007
	(0.863)	(0.521)	(0.159)	(0.841)	(0.491
LR(2)	0.188	1.503	3.446	0.824	1.373
ln L	−53.64	−409.39	−2761.56	−53.35	−409.46
Obs	541	1973	4512	541	1973

Asymptotic standard errors are in parentheses, †denotes significance at the 90% level, *denotes significance at the 95% le the 99% level. $k = 10$ and ν is the GARCH(1,1) estimated conditional variance of s (from the basic $/DM and $/yen G 4). The reported intervention data are included as (0,1) dummy variables denoting days on which the Fed, BBank and B the finanicial press to have intervened. Secret interventions are also included as a (0,1) dummy variable denoting days o interventions were not reported in the
financial press.

[a] The 1985–1987 subperiod begins 1/2/85 and ends 2/27/87.

[b] The 1987–1994 subperiod begins 3/2/87 and ends 12/30/94.

[c] LR(2) is the likelihood ratio test for the inclusion of the two explanatory variables.

[d] ln L is the value of the log likelihood function.

[e] Obs is the number of observations used in the probit regression.

the two subperiods and the full sample using daily dollar-mark and dollar-yen data. Table 5 presents estimates of a similar regression specification using changes in implied volatilities from option prices as the dependent variable. Finally, Table 6 presents results of reverse causality tests of the influence of volatility on the intervention variables.

The first three explanatory variables included in the conditional variance equations are generally highly significant, indicating that the GARCH parameters $(\alpha_0,\alpha_1,\alpha_2)$ have explanatory power in the daily model. The magnitude of the coefficient on the lagged conditional variance, α_1, is about 0.8 and highly significant, indicating that the variance effect is highly persistent. Further, the distribution parameter κ is highly significant and relatively small, suggesting that the disturbances are not normally distributed.

A number of regression diagnostics are presented at the bottom of the tables: (ln L) denotes the value of the log-likelihood function, ρ denotes the number of iterations that were needed to reach model convergence, $Q_z(20)$ and $Q_{z^2}(20)$ denote the Box-Pierce Q-statistic (with 20 lags) for the standardized residuals $(z = \varepsilon_t(\nu_t)^{-1/2})$ and the squared standardized residuals, respectively. According to the distributional assumptions in the model, the standardized residuals should be normally distributed if the GARCH model accounts fully for the leptokurtic unconditional distribution. The standardized residuals from all the regression specifications over all subsamples have mean values that are insignificantly different from zero and variance values that are approximately equal to one. Further, the absolute size of both the Q-statistics and the coefficients of skewness and kurtosis in the standardized residuals is generally smaller than that of the unadjusted residuals, presented in Table 1, providing support for the GARCH models.

In all the volatility regression specifications the holiday dummy is positive and generally significant; the size of the coefficient suggests that exchange rate volatility increased by between 0.06 and 0.3, (depending on the dependent variable, the sample period and the exchange rate) when the market reopened after a holiday.

In the mid-1980 subperiod, for both the dollar-mark and dollar-yen equations, reported Fed and Bundesbank intervention are significant and negative, indicating that intervention reduced volatility. However, in the post-Louvre Accord subsample, and over the full sample period, reported Fed interventions generally increased volatility. Interestingly, in the GARCH models reported Bundesbank interventions generally reduced dollar-mark and dollar-yen volatility in both subperiods and the full sample period.[37] However, in one of the few inconsistencies between the GARCH estimates and the implied volatility estimates, Bundesbank interventions increased dollar-mark volatility in the post-Louvre and full sample periods in the implied volatility regressions.

[37] One possible explanation for the finding that reported Bundesbank interventions reduce dollar-yen volatility (suggested by Sylvester Eijffinger) is that these interventions provide information on the BBank's 'dollar target'. As a consequence of the BBank's high reputation in financial markets, signals regarding this 'target' (even though unrelated to dollar-yen fundamentals) constitute valuable information for speculators.

The average reported Fed and Bundesbank dollar purchase and sale over the full period is \$221.3 million and \$141.6 million, respectively, and the average sample variance of the daily percentage change in the dollar-mark and dollar-yen rates is 0.529 and 0.471, respectively. So, using the GARCH parameter estimates the average effect of publicly known Fed intervention is to increase daily dollar-mark volatility by approximately 0.04 and increase daily dollar-yen volatility by 0.07 over the full sample period.[38] (Using the implied volatility regression parameter estimates the average effect of publicly known Fed intervention is to increase dollar-mark and dollar-yen implied volatility by ~ 0.2. The average dollar-mark and dollar-yen implied volatility for the period 1985–1993 is 9.79 and 8.29, respectively. So, if the dollar-mark implied volatility were 9.7, a \$200 million intervention by the Fed would increase that number to 9.9.[39]) Over the mid-1980 subperiod, reported Fed intervention reduced exchange rate volatility by ~ 0.04 for the mark and 0.21 for the yen, respectively, for both currencies. Likewise, reported Bundesbank interventions in the mid-1980 subperiod reduced dollar-mark volatility by 0.02 and dollar-yen volatility by 0.04.

The effect of secret intervention on volatility is generally significant and positive in the regressions. The average daily (combined) secret Fed and Bundesbank dollar purchase and sale over this period is \$72 million, so the average effect of secret intervention is to increase daily volatility by ~ 0.01 for both currencies.

BOJ intervention rarely seems to have influenced dollar-mark volatility, but it was generally found to have a positive and significant influence on dollar-yen volatility. The dummy variable capturing exchange rate policy news also had a differential effect on the two currencies. Exchange rate policy news reduced yen volatility in the mid-1980s subperiod, it increased dollar-yen volatility in the post-Louvre subperiod, and it increased mark volatility in both the post-Louvre and full sample periods. Finally, the interest rate spread variable generally increased mark volatility over all the sample periods, while it had a negative impact on dollar-yen volatility in the mid-1980s subperiod.

Overall, reported central bank intervention increased exchange rate volatility over the full sample period and in the post-Louvre Accord period. Somewhat surprisingly, reported Fed and Bundesbank intervention were found to reduce exchange rate volatility over the period between the Plaza Agreement and the Louvre Accord, when the stated G-3 objective was to influence the level, and not the volatility, of the dollar.[40] One possible explanation for why the G-3 did not reduce volatility in the post-Louvre Accord period, when the stated objective was to stabilize rates, was that in as early as 1989 (2 years after the announcement of

[38] The average effect of publicly known Fed intervention on volatility is: $(\partial v/\partial I^{\mathrm{Fed}})(I^{\mathrm{Fed}}/v)$.

[39] In percentage terms the estimated effects of intervention on volatility are larger in the GARCH model than they are in the implied volatility regressions.

[40] An interpretation of the finding that interventions reduced volatility during the period between the Plaza and Louvre Agreements is that market participants believed that the Plaza Agreement had ushered in a new era of international policy coordination, which in turn, would lead to future G-3 exchange rate stability commitments.

the Accord), there was division among US policy-makers[41] regarding intervention decisions. The FOMC minutes in 1989 suggest that a number of the Fed Board members were uncomfortable with the heavy dollar selling intervention operations, because Fed monetary policy was relatively contractionary during this period. Governors Angell and Johnson, in particular, were concerned that the Fed was sending the market mixed signals.[42] Fed and Bundesbank intervention operations that were not reported by the financial press consistently increased volatility over all the periods for both currencies. The sign and significance of the intervention variables measured in magnitudes or dummy variable form were often quite similar. This result confirms that just the presence of a central bank in the foreign exchange market influences volatility.

The results from the various volatility equations indicate that intervention and exchange rate volatility are often correlated, but it may be that volatility causes intervention, rather than the other way around. This raises the issue of whether intervention is truly an exogenous signal, or whether past exchange rate changes influence the decision to intervene. In previous studies of central bank intervention reaction functions (for example, Neumann, 1984; Eijffinger and Gruijters, 1991; Dominguez and Frankel, 1993c; Almekinders and Eijffinger, 1994; Baillie and Osterberg, 1997b), researchers have often hypothesized that past changes in exchange rates and exchange rate volatility may influence a central bank's decision to intervene. Obviously, if past changes in the conditional variance or implied volatility of exchange rates enter into the central bank's objective function, then we cannot conclude from the previous results that intervention influences volatility.

Intervention only occurs on a small percentage of the days in our sample period, so that Probit analysis is used to test whether volatility in exchange rates Granger-caused intervention. The generated conditional variance, ν_t, of the dollar-mark and

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[41] In the United States, the Treasury department has official jurisdiction over foreign exchange intervention policy. In practice the Treasury Department and the Fed typically jointly decide when the United States should be in the market, but on occasion a decision may be made by Treasury over the objections of the Fed. Even though the Treasury can mandate intervention policy, it is the Federal Reserve Bank of New York that actually implements the policy.

[42] Kaminsky and Lewis (1996) also make this point.

[43] A number of different probit specifications were estimated in order to test for 'reverse causality'. Reverse-causality was not detected in any of these alternative specifications. The specification presented in Table 6 includes the deviation of the spot rate and the conditional variance from a 10-day moving average of each variable, respectively. Alternative specifications included: 5-day moving averages, and 1-day changes in the spot rate and the past conditional variance (not in deviation form). The estimates from these specifications are not included in the tables to save space, but are available from the author on request.

[44] Almekinders and Eijffinger (1994) find evidence that, when interventions were examined over four short subsamples (over the period 1987 through 1989) in which the Fed and Bundesbank were involved in prolonged operations to either purchase or sell dollars, increases in the conditional variance of the dollar-mark rate led the central banks to increase the volume of intervention. Baillie and Osterberg (1997b), on the other hand, find no evidence over the period 1985 through 1990 that changes in the conditional variance of the dollar-mark rate Granger-cause intervention, while they do find evidence of causality for the dollar-yen rate. Bonser-Neal and Tanner (1996) also find little evidence that changes in implied volatilities Granger-cause intervention over the period 1985 through 1991.

dollar-yen exchange rates from the basic GARCH model (excluding intervention and other macro and news variables) and changes in implied volatility were both used as explanatory variables in the probit with intervention (defined in the various ways) as the dependent variable.[43] The results of the analysis are reported in Table 6 and indicate that there is no evidence that exchange rate volatility (or level changes) Granger-caused intervention for either the dollar-mark or the dollar-yen rates.[44]

4. Conclusions

The results described in the previous section indicate that changes in monetary policy and intervention policy often influence exchange rate volatility. Reverse causality tests, moreover, suggest that it is not volatility that causes intervention.

One of the more surprising results in the paper is that intervention need not be publicly known in order to influence volatility. Secret interventions were generally found to increase volatility. This result provides evidence in support of the hypothesis that the more ambiguous are signals, the more likely they are to increase volatility.

The evidence presented in this paper indicates that intervention had effects on volatility that are situation-specific. The regression estimates suggest that secret central bank exchange rate policy did increase volatility, but secret interventions make up less than 23% of all intervention operations after 1985. The bulk of secret interventions took place during the period 1977 through 1984, suggesting that one of the factors distinguishing the interventions in the first half of the sample period from the post-1985 interventions is the propensity for central banks to make their intervention operations public. Reported central bank intervention over the full period generally led to an increase in daily and longer-term exchange rate volatility. However, the reported interventions in the mid-1980s led to reductions in volatility. These results suggest that while it is apparently possible for central banks to reduce short-term exchange rate volatility using intervention policy, in practice they have rarely done so.

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