Informational Efficiency, Expectation Heterogeneity and Signaling Effects of Foreign Exchange Interventions

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Abstract

This paper explores whether the efficacy of foreign exchange interventions hinges not only on the firmness of signals but also on expectation heterogeneity among traders. We empirically show that announced interventions significantly affect the level and reduce the volatility of the yen/dollar rate when traders' expectations of future exchange rate are relatively heterogeneous. We then explain the evidence by demonstrating a noisy rational expectations equilibrium model in which asymmetric information across agents leads to a misalignment of exchange rate from the fundamental value and, even though the monetary authority has no more accurate information than investors, intervention signals help to wipe out the "bubble" by enhancing the accuracy of informed traders' information on the future exchange rate. This model is consistent with our finding that intervention announcements are more effective in a high implied volatility period.

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1. Introduction

Recent research on foreign exchange interventions has focused on informational issues. This new trend reflects the fact that the existent literature has failed to find any robust evidence consistent with either portfolio balance channel or the signaling channel backed up by future monetary policy.[1] A number of studies suggest that interventions might occasionally affect the exchange rates and that the impact might be related to information asymmetries between monetary authorities and market participants (Baillie, Humpage and Osterberg, 2000). For example, monetary authorities may at times possess private information about future fundamentals and target values of foreign currencies. Accordingly, interventions might reveal such information and, depending on prevailing market sentiments, influence market expectations and affect exchange rates (Humpage, 2003).

Then, when are central bank interventions likely to influence exchange rates? Numerous studies on exchange rate behavior document that exchange rates are connected to fundamentals in the long run, but that they may deviate substantially from their fundamental value for significant periods (Meese and Rogoff, 1983; Engel, 2000). A growing strand of literature on market microstructure attributes the exchange rate misalignments to information asymmetry among traders (Frankel and Froot, 1986; Bacchetta and van Wincoop, 2006). They argue that information asymmetry across investors limits informed traders' risk-arbitrage and leads to excess volatility of exchange rates and their short-run misalignments from the fundamental values. In this case, one of the fundamental roles for monetary authorities is to recognize the "bubble" in the foreign exchange market and wipe it out in a timely manner by their interventions. In doing so, informative signals are crucial to enhance the accuracy of rational arbitragers' information on future exchange rates and to push the market rates back toward the fundamental values.

[1] The 'portfolio-balance channel' and the 'signaling channel' are two traditional channels through which sterilized interventions can affect exchange rates. The former comes from the fact that the sterilized interventions change the composition of portfolios and thus the risk premium. The small scale interventions relative to the large volume of transactions in the foreign exchange markets and the huge value of the stocks of international assets has led researchers to emphasize the signaling hypothesis (Mussa, 1981; Dominguez and Frankel, 1993c). However, Lewis (1995), Kaminsky and Lewis (1996) and Fatum and Hutchison (1999) find that U.S. interventions have not conveyed a clear signal about future monetary policy actions.

The recent literature actually suggests that the market reaction to a central bank intervention depends on the degree of heterogeneity across trader beliefs about the fundamentals as well as the intervention signals (Bhattacharya and Weller, 1997; Vitale, 1999). To my knowledge, Kenen (1987) is the first to raise the issue on the relationship between expectation heterogeneity across traders and the efficacy of foreign exchange interventions. Kenen (1987) notes that "[w]hen expectations are heterogeneous and especially when a bubble appears to be building, intervention may be quite effective." Hardly any studies have, however, tested the efficacy of official interventions when traders have heterogeneous expectation about future exchange rates.

With respect to practices of central bank interventions, a consensus has been reached among researchers that the impact of *reported* interventions is larger than that of *secret* interventions (Beine, Benassy-Quere and Lecourt, 2002; Dominguez, 1998). Most interventions were not officially announced over major news wires simultaneously with the trade (Dominguez and Frankel, 1993c), although there is a trend toward more announcements. To rigorously assess the signaling channel, reported interventions have to be separated between officially announced (cum reported) interventions and unannounced but reported interventions.[2] As described below, Japan's intervention policy on announcements changed frequently in accordance with who is in charge of foreign exchange interventions at the Ministry of Finance. In addition, the Japanese intervention strategy in terms of volume and frequency has not been consistent across the interveners. These uncommon features of the Japanese interventions allow us to investigate the effect of intervention policy regarding announcements and volume on exchange rates.

This paper empirically investigates which makes central bank interventions effective, intervention signals or market condition (in this case, trader heterogeneity), or both. We then present a market microstructure model to provide a consistent explanation to our findings. The key feature of our model is informational inefficiency; the equilibrium exchange rates are not fully revealing in that they do not reflect all the

[2] Beine and Bernal (2007) also distinguish between reported and secret interventions and investigate the determinants of secret interventions by the Bank of Japan. They find that the Bank of Japan tended to favor secret interventions when it was targeting its own level. Dominguez (2007) provide evidence that expectation of intervention, even when monetary authority does not intervene, can affect currency values.

available information in the market due to the existence of noise trades. Accordingly, informed traders' risk-arbitrage can be limited and public signals in interventions have informational values to move the exchange rates toward their fundamental values, even though the information signaled by the monetary authority is no more accurate than informed traders' own information.

The empirical results reveal that, even though we control for the volume effect, official announcements regarding interventions significantly affect the movements of exchange rates, supporting the signaling hypothesis. However, when this is divided into distinct phases, we find that announcements were quite effective only for the sub-sample period when former Vice Minister of Finance for International Affairs Eisuke Sakakibara, nicknamed "Mr. Yen" by the NY Times (Sep 16, 1995), was in charge. We then examine whether the effect of intervention signals is associated with market conditions. Indeed, announced interventions have a more significant influence on the level and reduce the volatility of exchange rates when implied volatility on the previous trading day is high. Given the high correlation between implied volatility and the dispersion of exchange rate expectations in the survey data, this suggests that the effectiveness of official interventions depends not only on the central bank signals but also on the heterogeneity of expectations among traders.

We then demonstrate a noisy rational expectations equilibrium model in which informed traders with asymmetric information and naive noise traders transact a foreign currency in the foreign exchange market. We show that less accurate information of informed traders on the fundamental value leads to a bigger bubble, higher heterogeneity of traders' expectation and higher implied volatility.

The monetary authority intervenes in the market if she recognizes the bubble with a certain subjective probability. The announcement of interventions provides traders with more accurate information on the fundamental values of exchange rates, which help informed traders arbitrage more effectively. Hence, even without actual operations, the monetary authority can move the exchange rate towards the fundamental value and reduce implied volatility. Furthermore, when traders have less accurate information, so does the monetary authority. It is shown that interventions do not take place unless the bubble expected by the monetary authority is quite large. Hence, interventions have large effects once they take place. This explains the phenomenon that Dr. Sakakibara conducted in high implied volatility periods and they had significant effects on exchange rates.

The remainder of the paper is organized as follows. Section 2 describes the intervention data and the sampling scheme. Section 3 explains the empirical methodology and Section 4 presents the estimation results. Section 5 demonstrates the theory to explain the evidence. Section 6 contains our conclusions.

2. Data

2.1. Japanese interventions classified by newswire reports

We classify interventions into three categories using news reports provided by Bloomberg and Reuters. 'Announced interventions' are those accompanied by official statements from government officials on the intervention day. The government officials may include the Minister of Finance, the Vice Minister of Finance for International Affairs, the Director General of the International Bureau and the Governor of the BOJ. They often confirm interventions by publicly stating that the BOJ intervened in the market. Then the statements are broadcast within few minutes by newswires along with the name of the official making the announcement. 'Unannounced but reported interventions' are reported by newswires but without any corresponding official statements. Newswire reports sometimes quote traders as saying, "[s]ome traders said that the BOJ intervened in the market at around 115 yen during the morning session" or "[t]he BOJ apparently bought dollars against yen." 'Secret interventions' are not reported by the newswires, but do actually take place.

Figure 1 displays monthly time-series evidence on the yen/dollar exchange rate and the size of Japanese interventions from May 13, 1991 to May 27, 2004. There are neither interventions for dollar sales above the rate of 125 yen/dollars nor dollar purchases below 125 yen/dollar.

The classification of interventions is shown in Figure 2. During the sample period, there are 343 intervention days for the yen/dollar rate (10.1% of the sample). Among the intervention days, 208 (60.6%) are correctly reported by newswires, while 135 (39.6%) are not reported but have actually taken place (secret interventions). 12.8% of the intervention days are announced by government officials (announced interventions) and 47.8% are not announced but are reported by newswires (unannounced interventions).

The disclosed intervention data indicates the daily size of interventions. Table 1 shows the relationships between intervention policy and intervention volume. The number of days for large-sized interventions (more than 500 billion yen a day) is 38 (11.1%). The breakdown is 14 days of announced interventions, 16 days of unannounced but reported interventions and eight days of secret interventions. On the other hand, the number of small-sized intervention days (less than 50 billion yen per day) is 133 (36.5%). They have six days of announced interventions, 73 days of unannounced but reported interventions and 54 days of secret interventions. In general, the share of announced interventions increases with their size.

2.2. Changes in intervention policy

The Japanese intervention policy changed in June 1995 when Eisuke Sakakibara took over as Director General of the International Finance Bureau. He made a deliberate decision to reduce the frequency and increase the size of interventions (Sakakibara, 2002). Accordingly, some studies on Japanese interventions divide their sample period into pre and post June 1995 (Ito, 2003). The intervention policy also changed after his resignation, especially in terms of making official announcements about interventions. Hence, we divide our sample period into four sub-periods according to who is the Vice Minister of Finance for International Affairs of the MOF at the time, as he has the most influence on Japanese intervention decisions.[3] The sub-sample periods are period 1 (6/15/1992 - 6/20/1995), period 2 (6/21/1995 - 7/7/1999), period 3 (7/8/1999 - 1/13/2003) and period 4 (1/14/2003 - 5/27/2004). Intervention techniques are quite different depending on the person who actually decides on the intervention.

Table 2 shows the average size and intervention types for the 4 sub-periods. Period 1 is characterized by frequent, small interventions. In this period, frequency is the

[3] The MOF determines the volume and timing of interventions and the BOJ, which receives the order from the MOF, executes the intervention in the foreign exchange market. The decision makers for intervention are limited to the Minister of Finance, the Vice Minister and Deputy Vice Minister of Finance for International Affairs, the Director General of the International Bureau and the Director of the foreign Exchange Market Division. (Sakakibara, 2002)

highest among 4 sub-periods (averaging an intervention every 4.77 days) and the average size of an intervention was 47 billion yen, which is the smallest among four sub-periods. There are 18 days of coordinated interventions with the Federal Reserve Bank of NY in period 1. During period 1, only 6.1% of interventions are announced, while more than 70% are unannounced but reported interventions.

In period 2, when Dr. Sakakibara was in charge of interventions, he reduced the intervention frequency (averaging 39.83 days between interventions), while increasing the average size of interventions (510 billion yen per day). The ratio of both 'officially announced' and 'unannounced but reported' interventions was high (91.6%). In addition, half of the announced interventions in period 2 were accompanied by Federal Reserve Bank of NY interventions.

In period 3 the trend of infrequent but large interventions continued. There were only 25 intervention days (averaging 36.72 days per intervention) and the average size of an intervention was approximately 530 billion yen, which is the largest among the four sub-periods. It is remarkable that all of the interventions in period 3 were announced.

In period 4 the intervention policy changed dramatically, from being infrequent and large to frequent and medium-sized. The frequency of interventions in period 4 increased to an average of an intervention every 2.78 business days. Another big change was the very high ratio of secret interventions, which made up 74.4% of all interventions in this period. After Mr. Mizoguchi was appointed as Vice Minister of Finance for International Affairs, government officials declined to make comments or give any interviews. Instead of announcing interventions as they occurred, the MOF started to reveal the monthly volume of interventions at the end of each month and the size of the interventions every three months. In response to the change in the intervention strategy, newswire reports turned to vague statements such as "market participants are keeping watch for a possible intervention" and "[t]he BOJ seemed to be active in the market."

3. Empirical methodology

The usually considered primary objectives of exchange rate interventions are directing trends in exchange rate movements and calming disorderly markets.[4] These motivations suggest that central banks aim to influence not only exchange rate values, but also exchange rate volatility. There are broadly two types of exchange rate volatility that one might address with interventions: GARCH volatility and expected volatility as implied by option prices on exchange rate futures. We choose the latter because the effect of interventions on market expectations seems more compatible with the signaling hypothesis.[5] Furthermore, the use of a GARCH model to estimate the effect of interventions on exchange rate volatility has been recently questioned. Since shocks to exchange rate volatility are highly persistent ("volatility clustering"), incorporating intervention variables into the GARCH specification is equivalent to assuming that the effects of interventions are also persistent. If the effects are transitory, this framework is not valid (Watanabe and Harada, 2005). In addition, having only a small number of classified interventions makes it difficult to estimate the volatility equation of the GARCH model especially when we include the interaction term between the intervention dummy and the expectation heterogeneity variable.

To analyze the effect of interventions on exchange rates, we assume that the daily rate of return of the yen/dollar exchange rate without interventions is built around the standard Martingale model with time dependent conditional heteroskedasticity. Following Bollerslev (1986) and Baillie and Bollerslev (1989), the conditional variance is modeled as a linear GARCH (1,1) process and the conditional density is Gaussian. We would judge that an intervention is effective in controlling the exchange rate if it significantly affects daily returns in the appropriate direction.

We test the effect of interventions on the changes of exchange rates using equation (1).

[4] The other reasons for interventions include rebalancing central banks' reserve holdings and supporting fellow central banks in their exchange rate operations. Of the four listed reasons, only portfolio rebalancing does not involve a desired change in the level or volatility of exchange rates. Since monetary authorities rarely provide traders with information regarding their specific goals for particular intervention operations, we assume that relatively few interventions take place for the sole purpose of portfolio rebalancing.

[5] Another drawback of using implied volatility computed from currency option prices is that the results may be sensitive to assumptions about risk neutrality.

$$
\begin{aligned}
&r_t = a' X_t + \varepsilon_t \\
&\varepsilon_t \mid \Omega_{t-1} \sim N(0, h_t), \qquad (1)\\
&h_t = \alpha_0 + \alpha_1 \varepsilon_{t-1}^2 + \alpha_2 h_{t-1}, \quad \alpha_0 > 0, \alpha_1 \geq 0, \alpha_2 \geq 0
\end{aligned}
$$

where $r_t = 100 \ln(S_t / S_{t-1})$ is the logarithmic return of the spot exchange rate (expressed as a percentage) with S_t the being yen/dollar rate (NY close).[6] X_t denotes a vector of independent variables related to the Japanese and the U.S. interventions as well as macro variables which may affect exchange rates.

Following Bonser-Neal and Tanner (1996) and Dominguez (1998), the volatility equation is specified as follows:

$$iv_t = a' Y_t + b' Z_{t-1} + \varepsilon_t \qquad (2)$$

where $iv_t = 100 \ln(IV_t / IV_{t-1})$ is the logarithmic return of the implied volatility (expressed as a percentage) with IV_t the implied volatility estimate derived from at-the-money option prices (one- and three-month) on the spot yen/dollar rates from the Tokyo market (5 PM). Because market participants cannot know the Fed's intervention (with certainty) at 5 PM (Tokyo time) on the same day, the variables related to the Fed's intervention are lagged by one day. These form Z_{t-1}. The variables concerning the Japanese interventions and macro variables are included in Y_t. It should be noted that all variables in the volatility equation are taken to be the absolute values of those in the level equation.

Existing empirical research testing the signaling hypothesis using news reports typically splits interventions into reported interventions and secret interventions and analyzes the significance of the coefficients for the volume of each type of intervention (Dominguez, 1998; Beine, Benassy-Quere and Lecourt, 2002). The alternative way of analyzing the difference in the effectiveness of intervention strategies is to use intercept

[6] As explained by Ito (2003), the disclosed Japanese intervention volume is the result of interventions in the Tokyo, Europe, and U.S. markets, either carried out directly by the BOJ or by other central banks on behalf of the BOJ. Given the disclosure constraint of daily aggregation, the best proxy for exchange rate changes due to interventions on a particular day can be measured by the change in the NY closing rate across consecutive days.

dummies representing intervention strategies as independent variables independent of intervention volume.

Although market traders do not know the exact intervention volumes on intervention days, they can guess the approximate sizes based on market rumors and trading activity, especially when large-scale interventions are carried out. As intervention volume increases, these can function as signals from central banks to the market. This contradicts the view of shifting slopes because the difference between announced and unannounced interventions lessens as intervention volume increases. Although using intercept dummies seems preferable to shifting slopes, we would leave the choice of model specification to empirical tests. Accordingly, we estimate the model incorporating both slope and intercept dummies and test which specification is more appropriate.

Three dummies are considered in the estimation equations for announced interventions, unannounced but reported interventions and secret interventions for Japan and the U.S. (There were no secret interventions by the U.S.) Dummies take a value of +1 if such an intervention strategy is carried out for dollar purchases (yen sales), -1 for yen purchases (dollar sales) and zero otherwise. The intervention volume variable is also signed with + (dollar purchases) and – (yen purchases). If dollar purchase interventions by the U.S. and Japanese monetary authorities tend to cause the dollar to appreciate and the yen to depreciate, the coefficients would be expected to be positive.

When shifting slopes, one multiplies the intervention dummies and volumes with signs in accordance to purchases and sales of foreign currencies and uses these as the independent variables. As suggested by Dominguez (1998), we also include the interest rate differential between the Japanese and U.S. overnight money market rates in the level equation in order to account for relative contemporaneous monetary policies in both countries.[7]

For the volatility equation, a holiday dummy is included which takes a value of 1 if the previous day is a holiday and 0 otherwise, following Dominguez (1998). Since variables related to interventions are all taken as absolute values, we would expect

[7] The overnight market rates are the Federal Funds rate for the U.S. and the call rate for Japan.

negative signs for the coefficients if interventions were effective in reducing expected volatility.

The problem of simultaneity has been frequently raised in the empirical research on interventions. If official intervention and exchange rate changes are simultaneously determined, interventions are not exogenous to current market conditions and may yield inconsistent and biased estimates. Ideally, the equations of interventions and exchange rates would be estimated simultaneously, but the notorious difficulty in explaining daily intervention volume means that it is highly unlikely to find a good instrument for the intervention volume. In this regards, Goodhart and Hesse (1989) and Almekinders (1995) suggest that it takes at least two days for central banks to begin intervening in the foreign exchange market in response to excessively volatile spot exchange rates and deviations from target levels because of institutional features of monetary authority decision making processes. We assume that interventions are exogenous to spot exchange rate behavior on intervention days.

4. Estimation results

4.1. Is signaling effective?

We first examine whether officially announced interventions have a larger effect on exchange rates than secret interventions.

Table 3 presents the results of the estimations on the full sample period, one of which incorporates intercept dummies and differentiated slopes for announced, unannounced but reported, and secret interventions by the U.S. and Japanese monetary authorities. The Wald tests below show that the coefficients of slopes for the classified interventions are not significantly different from each other, while the intercept dummies are significantly different. This suggests that the intercept dummy model is preferable, as suggested in the previous section.

On the right hand side of the estimation results for the full sample period, the coefficient of the Japanese announced interventions dummy is significantly positive, while the coefficients of the Japanese unannounced but reported interventions dummy and the secret interventions dummy are significantly negative. The negative sign on the coefficient of unannounced interventions does not necessarily imply that interventions without official announcements cannot influence exchange rates. Taking into account the volume effect, such strategies can be effective although their efficacy is significantly less than that of announced interventions.

During the sample period, whenever the U.S. authorities intervened, the Japanese authorities intervened on the same day. There were no unilateral U.S. interventions, while there were many by the Japanese authorities. Hence, the U.S. intervention dummy captures the impact of coordinated interventions between the U.S. and Japan. On the other hand, the Japanese intervention dummies represent the Japanese unilateral intervention effect because we take into account the effect of coordinated interventions.

Both announced and unannounced but reported U.S. interventions are significantly effective, conditional on the volume of the intervention. On the other hand, the intervention volume does not affect exchange rates if we control for the intervention dummies. For the U.S. monetary authorities, it is whether the intervention is announced and/or reported that has a significant influence on exchange rates, not the size of the intervention.

The regression results for 4 sub-sample periods are presented in Table 4. The interesting result is that the coefficient of the dummy for secret interventions is significant and negative in period 1, while that of the dummy for announcement is significantly positive in period 2. This sharp contrast suggests that Dr. Sakakibara's policy change in favor of official announcements might lead to more successful interventions. The evidence that the signaling effect is effective only in period 2 and not in other sub-sample periods is consistent with previous studies showing that signaling effects have ambiguous empirical support.

The main result from Table 4 is that announcement effects are significant only in period 2. Official announcements alone do not necessarily guarantee the success of an intervention. A natural question arises: why did Dr. Sakakibara's announcements succeed in period 2?

4.2. Does heterogeneity matter for the efficacy of announcements?

We next investigate whether the announcement of interventions has a stronger influence when traders have heterogeneous expectations of exchange rates. In order to test this hypothesis, it is necessary to find a variable representing the expectation heterogeneity of future exchange rates among traders. However, survey data on exchange rate forecasts are not available on a daily basis. Thus we need to find a proxy for the dispersion of exchange rate expectations across traders.

Recent research on market microstructure presents theories for explaining volatility and trading volume in connection with the concentration of information in the market (Admati and Pfleiderer, 1988). Using survey data, there is an increasing amount of evidence supporting these theories. Frankel and Froot (1990) and Chionis and MacDonald (1997) find that expectation heterogeneity leads to an increase in trading volume and exchange rate volatility in the foreign exchange market. Furthermore, Ajinkya and Gift (1985) find that contemporaneous dispersion in financial analysts' forecasts has a strong explanatory power for the implied volatility computed from option prices, conditional on the information contained in the historical time series of returns. Following these studies, we use implied volatility and trading volume to test whether they are good proxies for expectation heterogeneity among traders.

To measure traders' expectation heterogeneity, we use survey data collected by the Japan Center for International Finance (JCIF) in Tokyo, Japan.[8] Since May 1985, the JCIF has been conducting telephone surveys twice a month, on the second and last Wednesdays. Point forecasts of the yen/dollar exchange rate for the one-, three- and six-month horizons are obtained from foreign exchange experts in forty-four companies.[9] The JCIF calculates the average, the standard deviation, the maximum and the minimum for the responses. Of these, we use the standard deviation and the coefficient of variation (the standard deviation divided by the sample mean forecasts) as measures of forecast dispersion.

We use the trading volume of all active brokered interdealer yen/dollar spot exchange trades on the Tokyo foreign exchange market, as collected by the Nikkei. This is the only available source of daily spot currency market trading volume data over our sample period. Daily trading volume has a moderate upward-trend over the sample period.

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[8] For the details of the data, see Ito (1990).

[9] These companies are 15 banks and brokers, four securities companies, six trading companies, nine export-oriented companies, five life insurance companies and five import-oriented companies.

In addition, the share of brokered interdealer trades may have increased since an electronic broking system was introduced in 1993, although there is no discontinuity in the data around the time of its introduction. To address these issues, we create the following volume variable, following Chaboud and LeBaron (1999). The variable is the ratio of today's trading volume to a sum of the previous 30, 50 and 100 trading volumes.

$$\textit{Trading volume variable}_t = vol_t \Big/ \sum\nolimits_{s=1}^{i} vol_{t-s}, \quad i = 30,50,100$$

The exchange rate forecast survey data is provided on a bimonthly basis, while implied volatility and trading volume data are provided on a daily basis. We then collect bimonthly data for implied volatility and trading volumes corresponding to exchange rate forecasts. The correlation coefficients are presented in Table 7. The standard deviation of forecasts is highly correlated with implied volatility (0.6.0.7), while the correlation between the heterogeneity of expectations and the trading volume variable is low (0.1.0.2). This result is robust if we use the standard deviation of heterogeneity measures divided by the sample mean (the coefficient of variation). Therefore, we make use of implied volatility as a proxy for the heterogeneity of exchange rate expectations among traders (Figure 3, 4 and 5).

Tables 6 and 7 report the results of whether the effects of official interventions on the level and the volatility of exchange rates depend on expectation heterogeneity. The independent variables include the interaction terms between the intervention dummies and implied volatility (one- and three-month). To prevent a simultaneity problem, the interaction terms consist of the one period lagged values of implied volatility. Since implied volatility is highly persistent, the one period lag is a proxy for the implied volatility just before an intervention.

In the first column of Table 6 (results for the whole sample period), the result of the estimation with one-month implied volatility is displayed. The coefficient of the interaction term between the Japanese announcement dummy and the lagged implied volatility is positive and significant, while that of the Japanese announced dummy is significantly negative. This suggests that the announcement effects have a non-linear relationship with exchange rate changes, which depends on implied volatility. Based on these coefficients, we can state that official announcements influence exchange rates if the lagged implied volatility is greater than 11.347%. Furthermore, the significantly positive coefficient of the interaction term between the Japanese intervention volume and the lagged implied volatility shows that large-scale interventions are effective when the lagged implied volatility is sufficiently high (more than 11%). By contrast, keeping interventions secret (both the unannounced but reported interventions and the secret interventions) has no significant impact on the exchange rates themselves. The results in the period 2 shows that lagged implied volatility of more than 10.187% is required for announced interventions to be effective. When implied volatility on the last trading day is sufficiently high, the effect of official announcements on exchange rate is significant. This result is robust even when we use the three-month implied volatility presented at the bottom of Table 6.

Table 7 shows the effect of interventions on the volatility of exchange rates. Like Table 6, there is a non-linear relationship between interventions and official announcements which depends on the implied volatility. The result for the whole sample period suggests that when the lagged implied volatility is more than 13.986%, official announcements can reduce volatility because the interaction term has a negative coefficient. However, the coefficient of the interaction term between intervention volume and the lagged implied volatility is significantly positive, mitigating the effect on volatility. We then consider both volume effect and announcement effect simultaneously. For example, suppose the intervention volume is 200 billion yen (the average for the whole sample period). We find that a lagged implied volatility of more than 15.119% is needed for an announced intervention to reduce the volatility of exchange rates. This indicates that lagged implied volatility, serving as a proxy for expectation heterogeneity, is an important factor in the efficacy of interventions on both the level and volatility of exchange rates.

5. Theory

In the model, we incorporate the monetary authority's intervention operations into Hellwig's (1980) noisy rational expectations equilibrium model with dispersed private information. Focusing on traders' information accuracy as the key parameter to explain the effect of interventions by the monetary authority, we demonstrate that less accurate information leads to a larger "bubble" - the deviation of an exchange rate from its fundamental value-, higher implied volatility, more heterogeneous expectations among traders and larger impacts of official interventions.

First, we study the effect of information accuracy on the distribution of bubbles of an exchange rate, on the implied volatility, and on the heterogeneity of investors' opinions. We then specify the monetary authority's intervention decision rules and examine the relationship between the information accuracy and the effects of interventions.

5.1. Assumptions

Consider a three-period model (periods 1, 2, and 3). There are a risk-free home currency, which has a constant price of 1, and a foreign currency, whose future value in home currency, denoted y, is normally distributed with mean $\bar{y}$ and variance σ_y^2. Its future value y becomes public in period 3. In period 1, traders choose net demand for the foreign currency. Price of the foreign currency in home currency in period 1, denoted p, is determined in the market. Traders trade in period 1 at price p per unit of foreign currency, and receive payoff of y per unit in period 3. We also call p and y as the exchange rate of the foreign currency of period 1 and 3, respectively. In period 2, the monetary authority can make intervention to the foreign exchange market.

We deal with official interventions as if they were unexpected events for informed traders. This assumption is for simplicity. If we relax this assumption and allow the dynamic interaction between the monetary authority and traders, the model becomes too complicated to analyze. However, we do not regard that this assumption is critical for the result. Note that interventions support the risk-arbitrage of informed traders, instead of ruining it. Basically, informed traders buy under-priced foreign currency and sell over-priced one because they know the exchange rate turns to be the true value of the currency in period 3. If traders follow such an investment style, they can get the advance cash flow in period 2 thanks to the intervention by the monetary authority, who attempts to push the exchange rate toward the true value based on its information in period 2. Thus, we believe that the traders' behavior is not so much affected even if interventions were expected. We discuss the effect of interventions in detail in section 5.4.

We assume that there are n identical informed traders indexed by $i = 1, ..., n$. Trader i receives signal

(1) $\quad s_i = y + \varepsilon_i$

in period 1 about the future value of the foreign currency. The error terms, $\varepsilon_1, \varepsilon_2, ..., \varepsilon_n$ are drawn independently from an identical normal distribution with mean 0 and variance σ_ε^2. All traders receive its signal before trade begins. These informed traders have CARA utility with common coefficient of risk aversion $a > 0$ and maximize expected utility which is a function of wealth in home currency.

Apart from trades by informed traders, there are noise trades reflecting the demand and supply for the foreign currency by foreign traders, travelers, and naive arbitragers with biased belief. We denote the per-capita net demand of noise trades as x, which is assumed to be independently normally distributed with mean 0 and variance σ_x^2.

Random variables, $y, x, \varepsilon_1, \varepsilon_2, ..., \varepsilon_n$, are independent and the informed traders know their distributions.

Under the assumption of CARA utility, it is known that the optimal demand does not depend on traders' initial wealth. Hence we focus on capital gain, $(y - p)\, z_i$, where z_i is the quantity of the foreign currency that trader i purchases in period 1. Trader i's maximization problem is simplified as follows.

(2) $\quad \max_{z_i} E\left[-\exp[-a(y-p)z_i] \middle| s_i, p\right]$

Informed traders know that the demands of the other informed traders affect the equilibrium price of the foreign currency, and the traders rationally make inferences about the underlying information from the price. To learn from the price, these traders must conjecture a form for the price function, and in equilibrium this conjecture must be correct. Suppose that the traders conjecture the following affine price function.

(3) $\quad p = \beta_0 + \beta_s \frac{1}{n}\sum_{i=1}^{n} s_i + \beta_x x$

where β_0, β_s, and β_x are coefficients to be determined. Under this conjecture, we can apply the projection theorem[10] which assures that the distributions of y conditional on (s_i, p) is

[10] For general version of projection theorem, see Brunnermeier (2001) p.12.

normal. Under this CARA-Gaussian setting, we can easily derive investor *i*'s demand function for the foreign currency.

(4) $$z_i = \frac{E[y \mid s_i, p] - p}{a\,\mathrm{var}[y \mid s_i, p]} \equiv D(s_i, p).$$

5.2. Equilibrium exchange rate function

In equilibrium, the total net demand for the foreign currency must equal zero.

(5) $$\sum_{i=1}^{n} D(s_i, p) + n \cdot x = 0$$

We find the equilibrium by solving equation (5) for p and then verifying that p is of the form conjectured in (3). Our assumption of homogeneous traders allows us to obtain a closed form solution. Though we have the closed form solution of the model, it is too complicated to study the property. In addition, the model with finite traders contains a theoretical contradiction. Hellwig (1980) described it "schizophrenic," which means that traders behave as a price taker although each trader can affect the equilibrium price when traders are finite. To solve this contradiction, we follow Hellwig and study the limit case with infinite traders. In our setting, his result becomes as follows.

PROPOSITION 1: As n goes infinity, the equilibrium price converges almost surely to

(6) $$p = \bar{y} + \beta_s^*(y - \bar{y}) + \beta_x^* x$$

where $\beta_s^* = \dfrac{\sigma_y^2(a^2\sigma_\varepsilon^2\sigma_x^2 + 1)}{\sigma_y^2(a^2\sigma_\varepsilon^2\sigma_x^2 + 1) + a^2\sigma_\varepsilon^4\sigma_x^2}$, $\beta_x^* = \dfrac{a\sigma_\varepsilon^2\sigma_y^2(a^2\sigma_\varepsilon^2\sigma_x^2 + 1)}{\sigma_y^2(a^2\sigma_\varepsilon^2\sigma_x^2 + 1) + a^2\sigma_\varepsilon^4\sigma_x^2}$.

Proof: See the Appendix.

The proposition means that, by the strong law of large number, the error terms of private signals are canceled out and do not affect the equilibrium price. From now on, we study the property of this limit case equilibrium as a description of the foreign exchange market. We use the mean and variance conditional on (s_i, p) in the equilibrium in order to derive the results of comparative statics analysis in the next section.

(7) $$E[y \mid s_i, p] = \bar{y} + \alpha_s \cdot (s_i - \bar{y}) + \alpha_p \cdot (p - \bar{y}),$$

where $\alpha_s = \dfrac{a^2\sigma_x^2\sigma_y^2\sigma_\varepsilon^2}{\sigma_y^2 + a^2\sigma_x^2(\sigma_y^2 + \sigma_\varepsilon^2)\sigma_\varepsilon^2}$ and $\alpha_p = \dfrac{1}{a^2\sigma_x^2\sigma_\varepsilon^2 + 1}$,

(8) $$\mathrm{var}[y \mid s_i, p] = \frac{a^2\sigma_x^2\sigma_y^2\sigma_\varepsilon^4}{\sigma_y^2 + a^2\sigma_x^2(\sigma_y^2+\sigma_\varepsilon^2)\sigma_\varepsilon^2}.$$

The most important property of the Hellwig model is informational inefficiency; the equilibrium exchange rate does not reflect all the available information in the market because of noise trades x. Following the convention, let us define the fundamental value of the foreign currency as its value estimated from all information available in the market. Noise trades make it impossible for informed traders to infer the fundamental value from the exchange rate. Note that the fundamental value is equivalent to the future value y in the limit case with infinite traders because the infinite private signals and the strong law of large numbers enable us to obtain the perfect estimate of the future value. In contrast, if there is no noise trade as in the model of Grossman (1976), the informed traders can infer the fundamental value from the current exchange rate; we can verify from proposition 1 that, when $\sigma_x^2=0$, the equilibrium exchange rate is equal to the fundamental value y. Based on this understanding, in the rest of the paper, we define the bubble in the exchange rate as $p-y$, the difference between the current exchange rate and the fundamental value. We will show later that, because of this informational inefficiency, additional information provided by the monetary authority can affect the equilibrium exchange rate. Although additional information does not change the fundamental value of the foreign currency in the limit case, it enables traders to make more accurate estimation about y, leading smaller conditional variance of y, which allows the traders to have larger position as indicated by equation (4). As a result of traders' active trades, the exchange rate shifts toward the fundamental value y.

5.3. Comparative statics with respect to signal accuracy

In this section, we analyze the effect of signal accuracy on the foreign exchange market before the monetary authority's intervention takes place. We show that less accurate information leads bigger bubble and higher implied volatility. It is shown that the effect on the heterogeneity of investor's opinion is ambiguous.

A. Distribution of exchange rate

In our model, bubble in exchange rate is defined by $p - y$, the difference of the current exchange rate and the fundamental value. First of all, we study the effect of σ_ε^2 on the distribution of bubble. Since p is a linear function of normal random variables and y is also normal, $p - y$ has normal distribution. Price function (6) implies that the mean is zero, and the variance is

$$\text{(9)} \qquad \mathrm{var}[p - y] = (1 - \beta_s^*)^2 \sigma_y^2 + \beta_x^{*2} \sigma_x^2 .$$

Then we can show

$$\text{(10)} \qquad \frac{d}{d\sigma_\varepsilon^2} \mathrm{var}[p - y] > 0 .$$

Proof: See the Appendix.

The inequality implies that when traders have more accurate signal, which has smaller σ_ε^2, we have smaller bubble in exchange rate; exchange rate p in period 1 distributes closer to its fundamental value y. This occurs because, when private signal is accurate, informed traders' risk-arbitrage gets more effective. Without risk-arbitrage by informed traders, exchange rate in period 1 is disturbed by noise trade x, and contains serious bubble. Though informed traders' arbitrage is limited in our model, it contributes to make the bubble small. For example, suppose a trader observes a signal which says the current exchange rate p is lower than the expected future exchange rate y. Then he will have long position in the foreign currency. When his private signal is more accurate, he will have larger position. Such risk-arbitrage will push the exchange rate up. As a result, exchange rate distributes closer to its future value and the bubble is squeezed out when private signal is accurate. Conversely, when private information is less accurate, we expect bigger bubble in exchange rate in period 1.

The problem in testing inequality (10) is that parameter σ_ε^2 is unobservable. Intuitively, however, two observable statistics are supposed to be used as proxies for it. One is implied volatility, and another is heterogeneity of traders' opinion. We investigate this intuition analytically.

B. Implied volatility

Implied volatility is a concept developed in the study of option pricing. Under some assumptions, the equilibrium price for a call option is a monotone function of the volatility of underlying asset returns. The volatility is the one that subjectively expected by the investors in the market, and thus unobservable. If the market works as the theory assumes, however, we can infer the unobservable subjective volatility from the observed call price in the market by using the inverse function of the call option price function. This is the implied volatility.

In our model, it is corresponding to the conditional variance of y on each trader's information, $\mathrm{var}[y \mid s_i, p]$. The effect of σ_ε^2 on the implied volatility is given by the following inequality.

(11) $$\frac{\partial}{\partial \sigma_\varepsilon^2} \mathrm{var}[y \mid s_i, p] = \frac{a^2 \sigma_\varepsilon^2 \sigma_x^2 \sigma_y^4}{\left[\sigma_y^2 + a^2 \sigma_\varepsilon^2 \sigma_x^2 (\sigma_y^2 + \sigma_\varepsilon^2)\right]^2} (2 + a^2 \sigma_\varepsilon^2 \sigma_x^2) > 0 \quad \text{for all } i.$$

The inequality is consistent with intuition. When private signals are less accurate, then the public signal is also less accurate, therefore, the conditional variance of y is larger. The strict inequality (11) allows us to regard implied volatility as the first proxy for σ_ε^2.

C. Heterogeneity of traders' opinion

Because traders have dispersed private information, their conditional expectations for y on their information are also dispersed. Intuition tells us that less accurate information means heterogeneous opinion. This is true if we define trader i's opinion equals its private information, s_i. This would not be proper definition. When we say opinion about the exchange rate, it means our expectation based not only on our private information, but on our all available information including public information. In our model, it corresponds to $E[y|s_i, p]$. If the heterogeneity of traders' opinion is defined to be the dispersion of traders' conditional expectations of y, our intuition is not always true as shown below, which means that the heterogeneity of traders' opinion is not always a good proxy for information accuracy.

Suppose we take sample M traders, heterogeneity, denoted H, is given by the following statistics.

$$(12) \qquad H(s_1,\ldots,s_M,p)=\frac{1}{M}\sum_{i=1}^{M}\left(E[y\mid s_i,p]-\frac{1}{M}\sum_{j=1}^{M}E[y\mid s_j,p]\right)^2$$

Putting (7) into (12), we have

$$(13) \qquad H(s_1,\ldots,s_M,p)=\frac{\alpha_s^2}{M}\sum_{i=1}^{M}\left(\varepsilon_i-\frac{1}{M}\sum_{j=1}^{M}\varepsilon_j\right)^2.$$

When M is sufficiently large, this statistics distributes near the mean

$$(14) \qquad E[H(s_1,\ldots,s_M,p)]=\frac{(M-1)}{M}\alpha_s^2\sigma_\varepsilon^2.$$

As suggested above, $E[H]$ is not a increasing function of σ_ε^2. The following proposition gives the condition that we can regard the heterogeneity as a proxy of signal accuracy.

PROPOSITION 2

$$(15) \qquad \frac{d}{d\sigma_\varepsilon^2}E[H(s_1,\ldots,s_M,p)]>0$$

if and only if

$$(16) \qquad \sigma_\varepsilon^2<\frac{a^2\sigma_x^2\sigma_y^2+\sqrt{a^4\sigma_x^4\sigma_y^4+12a^2\sigma_x^2\sigma_y^2}}{2a^2\sigma_x^2}\in(\sigma_y^2,\infty).$$

Proof: See the Appendix.

This proposition assures that, as long as the error term is less volatile than the fundamental value of exchange rate, the heterogeneity of expectations is increasing with σ_ε^2. The condition seems reasonable based on our empirical finding. Our data shows that implied volatility is positively correlated with heterogeneity of traders' opinion. Since the implied volatility is increasing with σ_ε^2, it is plausible the heterogeneity of traders' opinion is also increasing with σ_ε^2.[11]

[11] The condition of proposition 2 does not hold when traders' private signals are too inaccurate to rely on. In this case, private signals do not influence their posterior beliefs significantly. Since all traders have the common prior beliefs in our model, traders' opinions $\{E[y|s_i, p]\}_i$ stay closer to the common unconditional expectations $E[y]=\mu$, and thus become homogenous.

5.4. Intervention by the monetary authority

To complete our theoretical argument, we introduce the monetary authority who intervenes in the foreign exchange if necessary in period 2. We assume that the monetary authority also has imperfect information and follows a simple statistical decision rule.

In period 2 the monetary authority receives a signal.

(17) $s_B = y + \varepsilon_B$.

The error term ε_B has an independent normal distribution with mean 0 and variance $\theta\sigma_\varepsilon^2$. θ is a strictly positive constant and represents relative accuracy level of the monetary authority's information compared to informed traders. For example, that θ smaller than 1 implies the monetary authority has more precise information than traders. Note that when σ_ε^2 is large, both informed traders and the monetary authority have less accurate information. In other words, we assume that when it is difficult for informed traders to predict the true future value of the foreign currency, it is also difficult for the monetary authority.

Using this private information and the exchange rate p observed in period 1, the monetary authority follows the following simple statistical decision rule.

INTERVENTION RULE: For a given probability ρ in (0, 1), e.g. $\rho = 0.95$, if $P[y > p|s_B, p] > \rho$, or if $P[y < p|s_B, p] > \rho$, then the monetary authority intervenes so as to move the current exchange rate toward $E[y|s_B, p]$.

The rule implies that the monetary authority intervenes in the foreign exchange market when judged statistically that there is a bubble. In words of statistics, intervention happens when null hypothesis of no bubble is rejected with significance level $1 - \rho$. Parameter ρ represents how prudent the monetary authority is.[12] Because the monetary authority has imperfect information, and thus the intervention can make the bubble bigger based on information with serious error. This is why the prudent parameter ρ should be set high enough. This is the story behind the intervention rule.

[12] The spirit of this decision rule is analogous to statistical decision by manufacturers in testing whether their products satisf y quality requirements.

The conditional distribution of $y-p$ based on the monetary authority's information (s_B, p) is normal with mean $E[y|s_B, p]-p$, and variance $\mathrm{var}[y|s_B, p]$. Therefore, the intervention condition is replaced by

(18) $\quad |E[y \mid s_B, p]-p| > Z_\rho \sqrt{\mathrm{var}[y \mid s_B, p]}$,

where the Z_ρ is the solution for $\Phi(Z)=\rho$, where Φ is the cumulative distribution function of the standard normal distribution. The left hand side of inequality (18) represents the bubble subjectively recognized by the monetary authority. The right hand side is constant. That is, the monetary authority intervenes when the expected bubble is larger than a critical value. The expected bubble can be decomposed in the following way;

(19) $\quad E[y \mid s_B, p]-p=(E[y \mid s_B, p]-y)+(y-p)$

This decomposition clearly shows that the expected bubble is caused by both the true babble $y-p$, and the monetary authority's estimation error mainly due to ε_B. Needless to say, the intervention is aimed for clearing the true bubble. Unfortunately, it is impossible for the monetary authority to discriminate true bubble or estimation error. What the monetary authority can do is to clear the subjectively recognized bubble.

A. Intervention policy

Under the model setting, the monetary authority has two different intervention measures: direct market operation and public announcement.

In studying the effect of interventions, we need to specify the traders' information and reaction to the intervention. As stated in section 5.1, we deal with the intervention as an unexpected event for traders. That is, traders make investment decision in Period 1 without concerning the intervention in Period 2. We also assume that, only when the monetary authority makes announcement on its intervention, traders realize the intervention and update their posterior belief based on the announcement. Direct market operation without any announcement is assumed to be unobservable like noise trade x, and thus traders cannot update their posterior belief. We assume that, when the monetary authority makes announcement, informed traders know the distribution of monetary authority's private signal. That is, they know the monetary authority also has imperfect information and the error term is independent of their own private signals. Using this information they make rational inference about y based on the announcement, and modify their demand function for the foreign currency.

(i) Direct market operation

The monetary authority can move the exchange rate toward the subjective fundamental value, $E[y|s_B, p]$, by trading the foreign currency so as to cancel the noise trade x. Note that the demand curve for the foreign currency is down-sloping when the market is informationally inefficient. Therefore, any trade can affect the exchange rate along the demand curve.[13] The required trade for the purpose is $(E[y|s_B,p]-p)/\beta_x^*$. If the monetary authority does not have enough liquid asset, the exchange rate would not reach the target.

(ii) Public announcement

Under informational inefficiency, the monetary authority can affect the exchange rate by providing additional information to the informed traders, which stimulates traders' risk arbitrage. To see the pure effect of a public announcement, suppose that the monetary authority announce s_B publicly but does not engage in any market operations. Note that, as long as the informed traders know that the monetary authority is also rational, announcing whether signal s_B or the monetary authority's target $E[y|s_B, p]$ are equivalent because the conditional expectation of y is a one-to-one function of s_B given the public signal p.

Let p' be the equilibrium exchange rate after the public announcement of s_B, which can be represented as

(20) $$p' = \bar{y} + \gamma_y(y-\bar{y}) + \gamma_B\varepsilon_B + \gamma_x x\,.$$

Unlike the original exchange rate, the modified exchange rate is affected by the monetary authority's information error, ε_B. Unfortunately, the function is too complicated to derive a closed form solution for coefficients γs. We study it numerically and obtain the following four results.

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[13] We assume that traders cannot recognize the intervention when without announcement. This means that traders suppose the change in the exchange rate is caused by the change in the noise trade, not by the intervention, and modify their demand for the foreign currency along demand function (4).

First, the post-announcement implied volatility decreases to var[y| s_i, s_B, p], which is always strictly lower than pre-announcement implied volatility var[y| s_i, p] for any finite q.[14] The additional information through interventions makes traders' information more precise because the error term e_B is independent of private investors' information error e_i.

Second, on average, the announcement is successful to diminish the true bubble with the help of active risk-arbitrage. As demand function (4) demonstrates, smaller implied volatility allows traders to bet larger position on their information. In other words, public announcement makes risk-arbitrage by informed traders more active and effective than before. Figure 6 shows the effect of announcement to the distribution of the bubble. The graph is drawn for the given parameters by the numerical analysis. The announcement has larger effect for the smaller q, which implies the government has more accurate information than the informed traders. When q is quite large, the announcement has little effect. As long as traders are rational, unreliable announcement is simply ignored and does not harm the market. In contrast, when q is quite small the announcement clear the bubble effectively. In the middle range, the effect depends on the parameters. For reasonable parameters, the monetary authority with the same accuracy level as the traders, implying q = 1, can diminish the bubble roughly to the half of the original size. Note that this is an average effect. It is rare, though, when the monetary authority observes unusually large error term e_B, the announcement can make the bubble bigger than before the announcement.

Third, on average, the announcement is successful to diminish the subjectively recognized bubble, $E[y|s_B, p] - p$, by the monetary authority as well. Because the target $E[y|s_B, p]$ and the post-announcement equilibrium exchange rate p' are both biased by error e_B, the announcement based on information with large error helps the monetary authority to clear the subjective bubble, even though the announcement might make the true bubble bigger as discussed above. We cannot exclude quite rare cases where the announcement makes the subjective bubble bigger, though, it is much less likely than it

[14] In equilibrium, p' is a linear combination of other signals, and does not contain additional information. Thus, var[y| s_i, s_B, p, p'] equals to var[y| s_i, s_B, p]. In addition, because s_B has an independent error term, we have var[y| s_i, s_B, p] < var[y| s_i, p].

makes the true bubble bigger. This fact would be important for the monetary authority especially when it faces liquidity constraint. As stated above, when the monetary authority solely uses the market operation as intervention measure, the required foreign currency the monetary authority have to trade is $(E[y|s_i,p] - p)/\beta_x^*$. Since the public announcement moves the exchange rate toward $E[y|s_B,p]$, the required trade will be smaller. In other words, by using public announcement effectively, the monetary authority can encourage informed traders to help its intervention. These results are consistent with our empirical findings as shown later.

Fourth, the investors' opinions are less heterogeneous. In other words, post-announcement investors opinions ($E[y|s_i,s_B,p]$) distribute closer each other than pre-announcement opinions ($E[y|s_i,p]$). This change is caused mainly by result (a). In addition, the additional information is common for all traders, and thus this also helps traders hold similar opinion.

(iii) Direct market operation plus public announcement

What if the monetary authority takes these two measures simultaneously, direct market operation and announcement of s_B,? The answer would critically depend on the credibility of the monetary authority's market operation. If traders believe that the monetary authority would manage to achieve the target by its market operation after the announcement, then it is rational for traders to buy (sell) the foreign currency as much as possible when the price is lower (higher) than the target price because such arbitrage is riskless given the belief. The riskless arbitrage would make the exchange rate reach the target before the monetary authority actually makes market operation. This can happen even if the monetary authority does not have enough liquid asset to achieve the target by itself, as long as traders believe it has. In contrast, if traders believe that the monetary authority does not have enough liquidity to achieve the target, then the exchange rate would move to p', but would not reach the target without the monetary authority's market operation. In fact, the situation is like a coordination game in which traders' belief is self-fulfilling. Credible monetary authorities can achieve the target without any market operation by winning the traders over to its side.

B. The comparative statics with respect to information accuracy

Finally, we examine the effect of information accuracy σ_ε^2 on the impact of intervention. Look at intervention condition (18) again. The critical value of intervention (RHS) depends on the accuracy of the monetary authority's information. Consistent with intuition, we have

$$(21) \qquad \frac{\partial}{\partial \sigma_\varepsilon^2} \operatorname{var}[y \mid s_B, p] = \frac{a^2 \theta \sigma_\varepsilon^2 \sigma_x^2 \sigma_y^4}{\left[\theta \sigma_y^2 + a^2 \sigma_\varepsilon^2 \sigma_x^2 (\sigma_y^2 + \theta \sigma_\varepsilon^2)\right]^2} (2\theta + a^2 \sigma_\varepsilon^2 \sigma_x^2) > 0 .$$

This means, when it is difficult to predict the future value, the monetary authority set the higher critical value of intervention; the monetary authority wait and see until the recognized bubble is quite large. Suppose the monetary authority recognized the bubble with probability more than π and managed to clear the recognized bubble by public announcement and/or direct market operations. Then, the model predicts that less accurate information produces large effects of interventions on the exchange rates. Note that this qualitative result is true for any positive value of θ.

5.5. Consistency with the empirical results

Our model provides a new explanation to the success of Mr. Yen for two important reasons. First, he used public announcement quite intensively. If market is informationally inefficient, public announcement makes traders' information more accurate and moves the exchange rate toward the fundamental value. In addition, the traders' belief that his intervention is quite effective helps him achieve the target. Second, we think it was difficult for him to predict the future value in his era; therefore, he was hesitant to intervene until the bubble looks evident for him. When he decided to intervene, the bubble to clear was large. Therefore, it is natural that the interventions are "effective."

6. Conclusion

This paper contributes to the existing literature on foreign exchange interventions in two ways. Fist, we empirically show that the efficacy of interventions depends not only on intervention signals by monetary authorities but also market condition. Especially, we find the evidence that announced interventions are more effective in the high implied volatility period. Given the high correlation between the implied volatility and the dispersion of foreign exchange forecasts, this evidence clearly shows that the monetary authority should time the market and intervene in the FX market when traders have heterogeneous opinions on future exchange rates.

Second, we present a clear theoretical underpinning of the link between intervention signals, expectation heterogeneity among traders and currency values. Especially, we provide a consistent explanation to our findings with a noisy rational expectations equilibrium model. In our model, the equilibrium exchange rates are not fully revealing in that they do not reflect all the available information in the market due to the existence of noise trades. Accordingly, informed traders' risk-arbitrage can be limited and public signals in interventions have informational values to move the exchange rates toward their fundamental values, even though the information signaled by the monetary authority is no more accurate than informed traders' own information.

Appendix

Proof for PROPOS ITION 1
First, we derive a rational expectations equilibrium in the case with finite traders. Then, we show the converge of the equilibrium price function converges to (6).

By applying projection theorem, the distribution of y conditional on (s_i, p) is normal with mean

$$\text{(A1)}\qquad E[y|s_i,p] = \bar{y} + \alpha_s(n)(s_i - Es_i) + \alpha_p(n)(p - Ep)$$
$$= \bar{y} + \begin{pmatrix}\operatorname{cov}(y,s_i) & \operatorname{cov}(y,p)\end{pmatrix}\begin{pmatrix}\operatorname{var} s_i & \operatorname{cov}(s_i,p)\\ \operatorname{cov}(s_i,p) & \operatorname{var} p\end{pmatrix}^{-1}\begin{pmatrix}s_i - Es_i\\ p - Ep\end{pmatrix}$$

and variance

$$\text{(A2)}\qquad \operatorname{var}[y|s_i,p] = \sigma_y^2 - \begin{pmatrix}\operatorname{cov}(y,s_i) & \operatorname{cov}(y,p)\end{pmatrix}\begin{pmatrix}\operatorname{var} s_i & \operatorname{cov}(s_i,p)\\ \operatorname{cov}(s_i,p) & \operatorname{var} p\end{pmatrix}^{-1}\begin{pmatrix}\operatorname{cov}(y,s_i)\\ \operatorname{cov}(y,p)\end{pmatrix}$$

where variance and covariance on p are derived from the conjectural exchange rate function. (For general version of projection theorem, see Brunnermeier p.12. It is proved from the definition of multidimensiona l normal distribution.) The conditional variance is constant and common for all traders, so from now on we omit indicator i for the conditional variance .

By definition, $Es_i = \bar{y}$. Putting the demand function into the market clearing conditi on, and taking the unconditional expectation of it, we h ave $Ep = \bar{y}$. The market clearing condition can be solved for p as follows.

$$\text{(A3)}\qquad p = \bar{y} + \frac{\alpha_s(n)}{1-\alpha_p(n)}\frac{1}{n}\sum_{i=1}^{n}(s_i - \bar{y}) + \frac{a\operatorname{var}[y\,|\,s,p]}{1-\alpha_p(n)}x$$

Thus, the rational expectations equilibrium is driven from the following simul taneous equations.

$$\text{(A4)}\qquad \beta_0 = \bar{y}\left(1 - \frac{\alpha_s(n)}{1-\alpha_p(n)}\right),$$

$$\text{(A5)}\qquad \beta_s = \frac{\alpha_s(n)}{1-\alpha_p(n)},$$

$$\text{(A6)}\qquad \beta_x = \frac{a\operatorname{var}[y\,|\,s,p]}{1-\alpha_p(n)}.$$

We can solve the clos ed form solution for the simultaneous equations by taking the ratio of β_s and β_x. Careful calculation leads the following eq uation.

(A7)

$$\frac{\beta_s}{\beta_x} = \frac{\alpha_s(n)}{a\operatorname{var}[y\,|\,s,p]} =$$

$$\frac{\beta_x^2\sigma_x^2}{a\sigma_\varepsilon^2[\beta_s^2\frac{1}{n}(1-\frac{1}{n})\sigma_\varepsilon^2+\beta_x^2\sigma_x^2]}=\frac{n^2\sigma_x^2}{a\sigma_\varepsilon^2[(\beta_s/\beta_x)^2(n-1)\sigma_\varepsilon^2+n^2\sigma_x^2]}$$

Consider this as a cubic equation of $k \equiv \beta_s/\beta_x$. By applying famous Cardano formula for cubic equation, we can find the unique solution as an explicit function of exogenous parameters.

(A8) $$k=\sqrt[3]{\frac{-\omega_1+\sqrt{\omega_1^2+\frac{4\omega_2^3}{27}}}{2}}+\sqrt[3]{\frac{-\omega_1-\sqrt{\omega_1^2+\frac{4\omega_2^3}{27}}}{2}}\in(0,1/a\sigma_\varepsilon^2)$$

where $\omega_1 \equiv -\frac{n^2\sigma_x^2}{a(n-1)\sigma_\varepsilon^4}, \omega_2 \equiv \frac{n^2\sigma_x^2}{(n-1)\sigma_\varepsilon^2}$.

Using k, the equilibrium coefficients are solved explicitly .

$\beta_0=\bar{y}(1-k\beta_x)$, $\beta_s=k\beta_x$, and $\beta_x=\frac{1}{k}\frac{\sigma_y^2\sigma_x^2+k^2(1-\frac{1}{n})\sigma_\varepsilon^2\sigma_y^2}{\sigma_y^2\sigma_x^2+k^2(1-\frac{1}{n})\sigma_\varepsilon^2\sigma_y^2+k^2\frac{1}{n}(1-\frac{1}{n})\sigma_\varepsilon^4+\sigma_\varepsilon^2\sigma_x^2}$.

Now we show the convergence of this equilibrium exchange rate function to (6). Since $\{\varepsilon_i\}$ are i.i.d. random variable with mean zero, we can apply the strong law of large number , and obtain

(A9) $$\lim_{n\to\infty}\frac{1}{n}\sum_{i=1}^{n}s_i=y \qquad \text{almost surely.}$$

Thus, the equilibrium function converges to

(A10) $$p=\bar{y}+\beta_s^*(y-\bar{y})+\beta_x^*x$$

where the coefficients are the limit of β_s and β_x. Taking the both sides of (A7), we have $\lim_{n\to\infty}k=1/a\sigma_\varepsilon^2$, which leads

(A11)

$$\beta_s^*\equiv\lim_{n\to\infty}\beta_s=\frac{\sigma_y^2(a^2\sigma_\varepsilon^2\sigma_x^2+1)}{\sigma_y^2(a^2\sigma_\varepsilon^2\sigma_x^2+1)+a^2\sigma_\varepsilon^4\sigma_x^2},\quad \beta_x^*\equiv\lim_{n\to\infty}\beta_x=\frac{a\sigma_\varepsilon^2\sigma_y^2(a^2\sigma_\varepsilon^2\sigma_x^2+1)}{\sigma_y^2(a^2\sigma_\varepsilon^2\sigma_x^2+1)+a^2\sigma_\varepsilon^4\sigma_x^2}.$$

This completes the proof for PROPOSITION 1 .

QED

Proof for inequality (10)

Putting the equilibrium function, the variance is given as a function of underlying parameters.

$$\text{(A12)}\qquad \operatorname{var}[p-y]=(1-\beta_s^*)^2\sigma_y^2+\beta_x^{*2}\sigma_x^2=\frac{[a^2\sigma_\varepsilon^4\sigma_x^2]^2\sigma_y^2+[a\sigma_\varepsilon^2\sigma_y^2(a^2\sigma_\varepsilon^2\sigma_x^2+1)]^2\sigma_x^2}{[\sigma_y^2(a^2\sigma_\varepsilon^2\sigma_x^2+1)+a^2\sigma_\varepsilon^4\sigma_x^2]^2}$$

Thus, the derivative of the variance w.r.t. σ_ε^2 is

$$\text{(A13)}\qquad \frac{d}{d\sigma_\varepsilon^2}\operatorname{var}[p-y]=\frac{a^2\sigma_x^2\sigma_y^2}{D_1^3}\Bigg[\left(\frac{d}{d\sigma_\varepsilon^2}\{a^2\sigma_\varepsilon^8\sigma_x^2+\sigma_\varepsilon^4\sigma_y^2(a^2\sigma_\varepsilon^2\sigma_x^2+1)^2\}\right)D_1 -2\{a^2\sigma_\varepsilon^8\sigma_x^2+\sigma_\varepsilon^4\sigma_y^2(a^2\sigma_\varepsilon^2\sigma_x^2+1)^2\}\left(\frac{d}{d\sigma_\varepsilon^2}D_1\right)\Bigg]$$

where $D_1\equiv\sigma_y^2(a^2\sigma_\varepsilon^2\sigma_x^2+1)+a^2\sigma_\varepsilon^4\sigma_x^2$. The derivatives in the square bracket are

$$\text{(A14)}\ \frac{d}{d\sigma_\varepsilon^2}\{a^2\sigma_\varepsilon^8\sigma_x^2+\sigma_\varepsilon^4\sigma_y^2(a^2\sigma_\varepsilon^2\sigma_x^2+1)^2\}=4a^2\sigma_x^2(a^2\sigma_x^2\sigma_y^2+1)\sigma_\varepsilon^6+6a^2\sigma_x^2\sigma_y^2\sigma_\varepsilon^4+2\sigma_y^2\sigma_\varepsilon^2,$$

$$\text{(A15)}\qquad \frac{d}{d\sigma_\varepsilon^2}D_1=2a^2\sigma_x^2\sigma_\varepsilon^2+a^2\sigma_x^2\sigma_y^2.$$

Thus, we have $d\operatorname{var}[p-y]/d\sigma_\varepsilon^2$

$$=\frac{a^2\sigma_x^2\sigma_y^2}{D_1^3}\left[4a^4\sigma_x^4\sigma_y^2(a^2\sigma_x^2\sigma_y^2+2)\sigma_\varepsilon^8+4a^2\sigma_x^2\sigma_y^2(2a^2\sigma_x^2\sigma_y^2+1)\sigma_\varepsilon^6+6a^2\sigma_x^2\sigma_y^4\sigma_\varepsilon^4+2\sigma_y^4\sigma_\varepsilon^2\right]>0$$

QED

Proof for PROPOSITION 2
Equation (13) implies

$$\text{(A16)}\qquad \operatorname{sgn}\left(\frac{d}{d\sigma_\varepsilon^2}E[H(s_1,\ldots,s_M,p)]\right)=\operatorname{sgn}\left(\frac{d}{d\sigma_\varepsilon}\alpha_s\sigma_\varepsilon\right).$$

The coefficient α_s s given in (7). We have

$$\text{(A17)}\qquad \frac{d}{d\sigma_\varepsilon}\alpha_s\sigma_\varepsilon=\frac{a^2\sigma_x^2\sigma_y^2\sigma_\varepsilon^2}{[\sigma_y^2+a^2\sigma_x^2(\sigma_y^2+\sigma_\varepsilon^2)\sigma_\varepsilon^2]^2}(3\sigma_y^2+a^2\sigma_x^2\sigma_y^2\sigma_\varepsilon^2-a^2\sigma_x^2\sigma_\varepsilon^4).$$

The sign of the derivative is determined by the sign of the round bracket of (A17), which is a concave quadratic function with one positive and one negative intersections with horizontal axis. Note $\sigma_\varepsilon^2>0$, then we can conclude that derivative (A17) is positive as long as σ_ε^2 is less than the positive intersection. The condition is

(A19) $$\sigma_{\varepsilon}^{2} < \frac{a^2\sigma_x^2\sigma_y^2 + \sqrt{a^4\sigma_x^4\sigma_y^4 + 12a^2\sigma_x^2\sigma_y^2}}{2a^2\sigma_x^2}.$$

The boundary is strictly larger than σ_y^2. This completes the proof for PROPOSITION 2.

QED

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Table 1. Intervention policy and volume (5/13/1991-5/27/2004)

Intervention volume 100 million yen	No. of days	Announced interventions	Unannounced but reported interventions	Secret interventions
1 499	133	6	73	54
	100.0%	4.5%	54.9%	40.6%
500 999	64	4	40	20
	100.0%	6.2%	62.5%	31.3%
1000 1999	48	7	14	27
	100.0%	14.6%	29.2%	56.2%
2000 4999	60	13	21	26
	100.0%	21.7%	35.0%	43.3%
5000 26201	38	14	16	8
	100.0%	36.8%	42.1%	21.1%
Total	343	44	164	135
	100.0%	12.8%	47.8%	39.4%

Source: the Ministry of Finance of Japan, Bloomberg and Reuters.

Table 2. Intervention policy in Japan and the US

Period	JP Interventions				US Interventions			
	No. of days	Announced interventions	Unannounced but reported interventions	Secret interventions	No. of days	Announced interventions	Unannounced but reported interventions	Secret interventions
Full sample period 3119days								
5/13/1991-5/27/2004	343	44	164	135	22	11	11	0
		12.8%	47.8%	39.4%		50.0%	50.0%	0.0%
Average volume of interventions per day (JPY 100 million/USD 1million)	1991	4225	1735	1573	358	398	318	0
Period 1 787days								
5/13/1991-6/20/1995	165	10	118	37	18	7	11	0
		6.1%	71.5%	22.4%		38.9%	61.1%	0.0%
Average volume of interventions per day (JPY 100 million/USD 1million)	470	642	514	281	328	344	318	0
Period 2 956days								
6/21/1995-7/7/1999	24	8	14	2	4	4	0	0
		33.3%	58.3%	8.3%		100.0%	0.0%	0.0%
Average volume of interventions per day (JPY 100 million/USD 1million)	5105	4598	6025	683	492	492	0	0
Period 3 918days								
7/8/1999-1/13/2003	25	25	0	0	0	0	0	0
		100.0%	0.0%	0.0%				
Average volume of interventions per day (JPY 100 million/USD 1million)	5282	5282	0	0	0	0	0	0
Period 4 358days								
1/14/2003-5/27/2004	129	1	32	96	0	0	0	0
		0.8%	24.8%	74.4%				
Average volume of interventions per day (JPY 100 million/USD 1million)	2719	10667	4359	2090	0	0	0	0

Source: The Ministry of Finance of Japan, Quarterly Review of Federal Reserve Bank of NY, Bloomberg and Reuters.
Note. The US interventions during the sample period were all coordinated with the Japan.

Table 3. Signaling effects of interventions (full sample period)

Dependet variable: % change in exchange rate Method GARCH-ML	Full sample period 5/13/1991-5/27/2004					
Independent variables	Estimates		(Standard error)	Estimates		(Standard error)
Mean Equation						
Constant	-0.02841	*	(0.01686)	-0.02908	*	(0.01681)
Interest rate differential	-0.01029	**	(0.00444)	-0.01023	**	(0.00441)
(a) JP announced intervention dummy	0.20622	*	(0.11830)	0.16964	*	(0.10284)
(b) JP unannounced but reported intervention dummy	-0.27716	***	(0.05577)	-0.23575	***	(0.05291)
(c) JP secret intervention dummy	-0.08170		(0.07398)	-0.16268	***	(0.06227)
(d) US announced intervention dummy	0.27741		(0.32715)	0.88021	***	(0.23395)
(e) US unannounced but reported intervention dummy	1.21369	***	(0.16220)	0.82522	***	(0.12386)
JP intervention volume				0.00006	***	(0.00001)
US intervention volume				0.00028		(0.00036)
(f) JP intervention volume * JP announced intervention dummy	0.00006	**	(0.00003)			
(g) JP intervention volume * JP unannounced but reported intervention dummy	0.00008	***	(0.00001)			
(h) JP intervention volume * JP secret intervention dummy	0.00002		(0.00003)			
(i) US intervention volume * US announced intervention dummy	0.00186	***	(0.00052)			
(j) US intervention volume * US unannounced but reported intervention dummy	-0.00079		(0.00051)			
Varivance Equation						
Constant	0.00847	***	(0.00125)	0.00847	***	(0.00124)
ARCH(1)	0.04183	***	(0.00339)	0.04225	***	(0.00340)
GARCH(1)	0.94122	***	(0.00504)	0.94093	***	(0.00498)
Log likelihood	-3441.867			-3447.455		
Obs.	3404			3404		

Wald tests on the coefficients

	Statistic		P-value
JP intervention dummies H0: (a)=(b)=(c)	11.88	***	0.0026
US intervention dummies H0: (d)=(e)	6.72	***	0.0095
JP dummies with volume H0: (f)=(g)=(h)	3.49		0.1742
US dummies with volume H0: (i)=(j)	13.79	***	0.0002

Note. *, ** and *** denote statistical significance at the 10%, 5% and 1% levels, respectively.

Table 4. Signaling effects of interventions (4 sub-periods)

Dependent variable % change in exchange rate Method GARCH-ML	Period 1 5/13/1991-6/20/1995		Period 2 6/21/1995-7/7/1999		Period 3 7/8/1999-1/13/2003		Period 4 1/14/2003-5/27/2004	
Independent variables								
Mean Equation								
Constant	-0.02287	(0.02088)	-0.08063	(0.31185)	-0.03560	(0.05211)	-0.35502	(0.25780)
Interest rate differential	-0.00464	(0.01149)	-0.02597	(0.06303)	-0.00702	(0.01146)	-0.29332	(0.23486)
JP intervention volume	-0.00034 ***	(0.00010)	0.00008 **	(0.00004)	0.00007 **	(0.00003)	0.00005 ***	(0.00002)
US intervention volume	-0.00051	(0.00052)	0.00363	(0.00341)				
JP announced intervention dummy	0.71887	(2.20465)	0.98002 ***	(0.22459)	0.00146	(0.21008)	0.13401	(1410422.0)
JP unannounced but reported intervention dummy	-0.13588 *	(0.07932)	-0.21027	(0.24231)			-0.07833	(0.12260)
JP secret intervention dummy	-0.04024	(0.12817)	0.61182	(0.96955)			-0.12982 *	(0.07849)
US announced intervention dummy	-0.19043	(2.24582)	0.24045	(1.24923)				
US unannounced but reported intervention dummy	1.21644 ***	(0.16579)						
Variance Equation								
Constant	0.01458 ***	(0.00314)	0.00867 ***	(0.00269)	0.78552 ***	(0.03472)	0.06685 **	(0.02742)
ARCH(1)	0.04485 ***	(0.00625)	0.06651 ***	(0.00846)	0.01408	(0.00895)	0.14402 ***	(0.04131)
GARCH(1)	0.92437 ***	(0.00998)	0.92195 ***	(0.01052)	0.92162 ***	(0.06338)	0.63744 ***	(0.11435)
Log likelihood	-1062.058		-1161.028		-890.183		-283.995	
Obs.	1072		1056		918		358	

1. Standard errors are in parenthesis. *, ** and *** denote statistical significance at the 10%, 5% and 1% levels, respectively.
2. There were no US interventions in Period 3 and 4.
3. The scales are 100 million yen for JP interventions and million dollars for US interventions.

Table 5. Correlation Coefficients

	Implied volatility (1M)	Implied volatility (3M)	Trading volume variable (30days)	Trading volume variable (50days)	Trading volume variable (100days)
S.d. of forecasts (1M)	0.6687 ***		0.1552 ***	0.1607 ***	0.1712 ***
S.d. of forecasts (3M)		0.5813 ***	0.1545 **	0.1202 **	0.1418 **
Coefficient of variation (1M)	0.7045 ***		0.2040 ***	0.1694 ***	0.1604 ***
Coefficient of variation (3M)		0.6434 ***	0.1844 ***	0.1350 **	0.1358 **

1. The s.d. of forecasts is the standard deviation of foreign exchange forecasts and the coefficient of variation is the standard deviation devided by the sample mean of forecasts.

2. The trading volume variables are the % ratios of spot trading volumes on intervention days in the Tokyo market to the sum of trading volume from 30, 50, and 100 days prior to the intervention day to 1day, respectively.

3. The implied volatility is calculated from yen/dollar option price (at the money).

4. *, ** and *** denote statistical significance at the 10%, 5% and 1% levels, respectively.

Table 6. Impact on the level of exchange rates

Dependent variable % change in exchange rate	Full sample period		Period 1		Period 2		Period 3		Period 4	
Method GARCH-ML	5/13/1991-5/27/2004		5/13/1991-6/20/1995		6/21/1995-7/7/1999		7/8/1999-1/13/2003		1/14/2003-5/27/2004	
Independent variables										
Mean Equation										
Constant	-0.02631	(0.04994)	-0.25873 **	(0.12318)	-0.11425	(0.30864)	-0.04228	(0.10372)	-0.29945	(0.36541)
Interest rate differential	-0.00967 **	(0.00490)	0.00216	(0.01218)	-0.04234	(0.06250)	-0.00556	(0.01329)	-0.30890	(0.23609)
JP intervention volume	-0.00003	(0.00005)	0.00021	(0.00060)	-0.00025	(0.00034)	-0.00034	(0.00031)	-0.00007	(0.00023)
US intervention volume	-0.00011	(0.00036)	-0.00074	(0.00051)	-0.00082	(0.00476)				
JP announced intervention dummy	-1.57181 ***	(0.50811)	-2.97095	(1.92571)	-4.61717	(3.18750)	1.95604	(1.99689)		
JP unannounced but reported intervention dummy	-0.08796	(0.20888)	-0.14556	(0.36894)	-0.38956	(2.20585)			0.66116	(1.01010)
JP secret intervention dummy	-0.00271	(0.36922)	0.10749	(0.68229)	-8.52430	(1498.27)			0.35933	(0.70338)
US intervention dummy	0.95277 ***	(0.13555)	1.14824 ***	(0.16245)	2.05673	(1.83969)				
IV1M (-1)	0.00003	(0.00503)	0.02493 *	(0.01277)	-0.00374	(0.00639)	0.00115	(0.01039)	-0.00791	(0.02601)
JP intervention volume IV1M (-1)	0.00001 **	(0.00000)	-0.00005	(0.00004)	0.00003	(0.00003)	0.00003	(0.00002)	0.00001	(0.00002)
JP announced intervention dummy IV1M (-1)	0.13852 ***	(0.03957)	0.21583	(0.13807)	0.45325 *	(0.23692)	-0.15397	(0.15457)	-0.01403	(63804.6)
JP unannounced but reported intervention dummy IV1M (-1)	-0.01397	(0.01860)	-0.00108	(0.03034)	0.01095	(0.16304)			-0.07934	(0.11188)
JP secret intervention dummy IV1M (-1)	-0.01526	(0.03887)	-0.01818	(0.06406)	0.67754	(107.399)			-0.05289	(0.07559)
Variance Equation										
Constant	0.00852 ***	(0.00127)	0.01498 ***	(0.00322)	0.01041 ***	(0.00310)	0.78111 ***	(0.03530)	0.06853 **	(0.02890)
ARCH (1)	0.04241 ***	(0.00351)	0.04620 ***	(0.00696)	0.07447 ***	(0.00981)	0.01603 *	(0.00953)	0.13984 ***	(0.04316)
GARCH (1)	0.94056 ***	(0.00518)	0.92209 ***	(0.01042)	0.91115 ***	(0.01231)	0.91099 ***	(0.06622)	0.63400 ***	(0.12073)
Log likelihood	-3440.337		-1060.802		-1151.408		-889.090		-283.304	
Obs.	3404		1072		1056		918		358	
Independent variables										
Mean Equation										
Constant	-0.03923	(0.06079)	-0.50221 ***	(0.19141)	-0.09809	(0.31079)	-0.06723	(0.13341)	-0.32266	(0.46624)
Interest rate differential	-0.00894 *	(0.00518)	0.01305	(0.01335)	-0.04063	(0.06233)	-0.00269	(0.01525)	-0.31468	(0.23686)
JP intervention volume	-0.00004	(0.00006)	0.00002	(0.00078)	-0.00010	(0.00049)	-0.00033	(0.00033)	-0.00010	(0.00030)
US intervention volume	-0.00018	(0.00036)	-0.00069	(0.00048)	-0.00013	(0.01522)				
JP announced intervention dummy	-2.33257 ***	(0.59075)	-3.79772	(3.17507)	-7.21467 *	(4.10557)	1.32081	(2.21997)		
JP unannounced but reported intervention dummy	0.00580	(0.28845)	0.10305	(0.51123)	-2.31101	(3.34916)			1.15995	(1.44807)
JP secret intervention dummy	-0.01553	(0.42226)	0.42541	(0.97802)	-7.15537	(423.179)			0.62308	(0.99393)
US intervention dummy	0.94631 ***	(0.13360)	1.15783 ***	(0.15861)	1.42588	(4.85990)				
IV3M (-1)	0.00147	(0.00608)	0.04841 **	(0.01919)	-0.00424	(0.00729)	0.00442	(0.01439)	-0.00605	(0.04103)
JP intervention volume IV3M (-1)	0.00001 *	(0.00001)	-0.00003	(0.00006)	0.00001	(0.00004)	0.00003	(0.00003)	0.00002	(0.00003)
JP announced intervention dummy IV3M (-1)	0.20538 ***	(0.04695)	0.28650	(0.24277)	0.64898 **	(0.30666)	-0.10151	(0.17698)	-0.00497	(6240.25)
JP unannounced but reported intervention dummy IV3M (-1)	-0.02278	(0.02623)	-0.02304	(0.04354)	0.16009	(0.25207)			-0.13292	(0.16298)
JP secret intervention dummy IV3M (-1)	-0.01360	(0.04433)	-0.04840	(0.09143)	0.56456	(30.5099)			-0.08156	(0.10739)
Variance Equation										
Constant	0.00861 ***	(0.00127)	0.01508 ***	(0.00327)	0.01045 ***	(0.00310)	0.78313 ***	(0.03374)	0.06891 **	(0.02938)
ARCH (1)	0.04288 ***	(0.00349)	0.04601 ***	(0.00669)	0.07433 ***	(0.00979)	0.01470 *	(0.00872)	0.13952 ***	(0.04406)
GARCH (1)	0.93988 ***	(0.00516)	0.92190 ***	(0.01021)	0.91121 ***	(0.01231)	0.92136 ***	(0.06032)	0.63284 ***	(0.12286)
Log likelihood	-3463.860		-1059.322		-1151.355		-888.501		-283.249	
Obs.	3404		1072		1056		918		358	

1.Standard errors are in parenthesis. *,** and *** denote statistical significance at the 10%, 5% and 1% levels, respectively.

2.The implied volatilities are calculated from the 1month and 3month yen/dollar option prices (at the money).

3.There were no US interventions in Period 3 and 4.

4.Announced intervention dummy is dropped in Period 4 due to collinearity since Period 4 had only one announced intervention.

5.The scales are 100 million yen for JP interventions and million dollars for US interventions.

Table 7. Impact on the implied volatility of exchange rates

Dependent variable % change in implied volatility (1Month) Method OLS (White (1980)'s robust standard error)	Whole sample period 5/13/1991-5/27/2004		Period 1 5/13/1991-6/20/1995		Period 2 6/21/1995-7/7/1999		Period 3 7/8/1999-1/13/2003		Period 4 1/14/2003-5/27/2004	
Independent variables										
Constant	1.60325 ***	(0.58613)	2.78583 ***	(0.88959)	1.50555	(1.02865)	3.41512 ***	(1.02003)	5.92218	(3.86109)
Holiday dummy	1.67066 ***	(0.22027)	2.10783 ***	(0.43275)	1.12039 ***	(0.40584)	1.59795 ***	(0.34845)	2.19670 ***	(0.68378)
IV1M (-1)	-0.19584 ***	(0.05391)	-0.35538 ***	(0.08861)	-0.15448 *	(0.08414)	-0.36101 ***	(0.09580)	-0.67275	(0.41184)
JP intervention volume	-0.00123 **	(0.00053)	0.02015 **	(0.00809)	-0.00107	(0.00236)	0.00184	(0.00202)	-0.00067	(0.00147)
US intervention volume (-1)	-0.00536	(0.00736)	-0.00844	(0.00710)	-0.02343	(0.02023)				
JP announced intervention dummy	18.29030 ***	(6.02462)	9.89727	(9.83324)	15.70027	(13.30194)	-1.28443	(12.54632)		
JP unannounced but reported intervention dummy	6.21695 **	(2.52241)	-2.56888	(4.57857)	12.69043	(14.05274)			-0.07677	(7.85854)
JP secret intervention dummy	1.80667	(2.13406)	-1.76348	(3.98475)	19.76964 ***	(2.57810)			4.10002	(5.91153)
US intervention dummy (-1)	7.71190 **	(3.85237)	5.92973 *	(3.47585)	24.37526 *	(13.17329)				
JP intervention volume * IV1M (-1)	0.00013 ***	(0.00005)	-0.00127 **	(0.00059)	0.00011	(0.00018)	-0.00006	(0.00016)	0.00008	(0.00015)
JP announced intervention dummy * IV1M (-1)	-1.30776 ***	(0.47959)	-0.71599	(0.82659)	-1.17238	(0.92174)	0.03450	(1.00898)	0.67676 **	(0.31147)
JP unannounced but reported intervention dummy * IV1M (-1)	-0.43812 **	(0.21486)	0.21149	(0.36682)	-0.82513	(1.11691)			0.02871	(0.79520)
JP secret intervention dummy * IV1M (-1)	-0.21101	(0.21002)	0.11263	(0.33427)	-1.19621 ***	(0.20020)			-0.53828	(0.63916)
R-squared	0.0607		0.0970		0.0569		0.0931		0.0987	
Durbin-Watson d statistic	2.0023		2.0692		1.9835		1.9633		1.6604	
Obs.	3404		1072		1056		918		358	
Dependet variable % change in implied volatility (3Month)										
Independent variables										
Constant	0.96651 **	(0.38843)	1.86833 ***	(0.70690)	0.95245	(0.68698)	2.36562 ***	(0.77683)	5.64470 *	(3.26212)
Holiday dummy	0.59117 ***	(0.13607)	0.97851 ***	(0.23696)	0.38082	(0.26173)	0.43107 *	(0.24474)	0.50561	(0.41553)
IV3M (-1)	-0.10624 ***	(0.03530)	-0.21742 ***	(0.07031)	-0.08867	(0.05476)	-0.22918 ***	(0.07196)	-0.61372 *	(0.35298)
JP intervention volume	-0.00079 **	(0.00037)	0.01297 *	(0.00670)	-0.00196	(0.00165)	0.00020	(0.00088)	-0.00048	(0.00146)
US intervention volume (-1)	-0.00335	(0.00360)	-0.00493	(0.00318)	-0.01578	(0.01446)				
JP announced intervention dummy	8.97668 **	(4.37981)	7.30466	(7.79161)	20.54609 *	(11.44985)	-3.27220	(8.17312)		
JP unannounced but reported intervention dummy	3.24442 *	(1.75997)	-2.37052	(3.43706)	15.04017	(9.86125)			-1.21566	(7.59332)
JP secret intervention dummy	1.13428	(1.72996)	-1.63846	(3.32618)	6.06547 ***	(1.78249)			2.21941	(4.87820)
US intervention dummy (-1)	4.01334 **	(1.99582)	2.83572 *	(1.51006)	15.16852	(9.86614)				
JP intervention volume * IV3M (-1)	0.00008 **	(0.00003)	-0.00089 *	(0.00053)	0.00016	(0.00012)	0.00003	(0.00007)	0.00005	(0.00016)
JP announced intervention dummy * IV3M (-1)	-0.62742 *	(0.36728)	-0.55516	(0.67645)	-1.54815 *	(0.81109)	0.31250	(0.64482)	0.54156 **	(0.23298)
JP unannounced but reported intervention dummy * IV3M (-1)	-0.22380	(0.15581)	0.20840	(0.28880)	-1.04263	(0.77519)			0.14566	(0.81607)
JP secret intervention dummy * IV3M (-1)	-0.12460	(0.17642)	0.10060	(0.30367)	-0.27575 **	(0.13578)			-0.27723	(0.53089)
R-squared	0.0329		0.0761		0.0360		0.0541		0.0512	
Durbin-Watson d statistic	2.0041		2.0415		1.9753		1.9956		1.8040	
Obs.	3404		1072		1056		918		358	

1. White (1980)'s heteroskedasticity-consistent standard errors are in parenthesis. *, ** and *** denote statistical significance at the 10%, 5% and 1% levels, respectively.

2. Holiday dummy takes 1 for the day one day after holidays and 0 for others.

3. There were no US interventions in Period 3 and 4.

4. The implied volatilities are calculated from the 1month and 3month yen/dollar option prices (at the money)

5. The scales are 100 million yen for JP interventions and million dollars for US interventions.

6. Announced intervention dummy is dropped in Period 4 due to collinearity since Period 4 had only one announced intervention.

Figure 1. (Japanese interventions and yen/dollar rate

(May 1991 – May 2004)

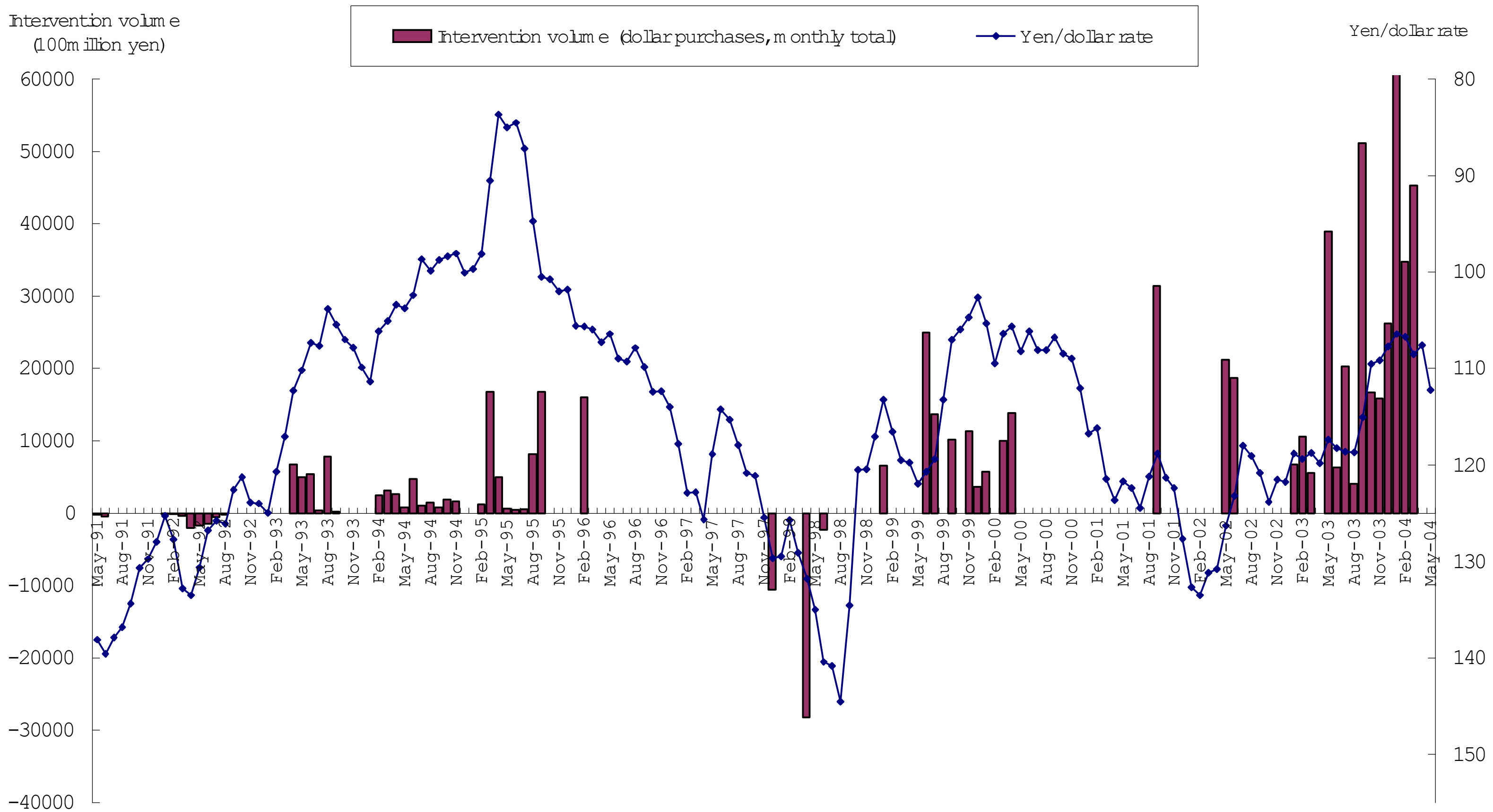

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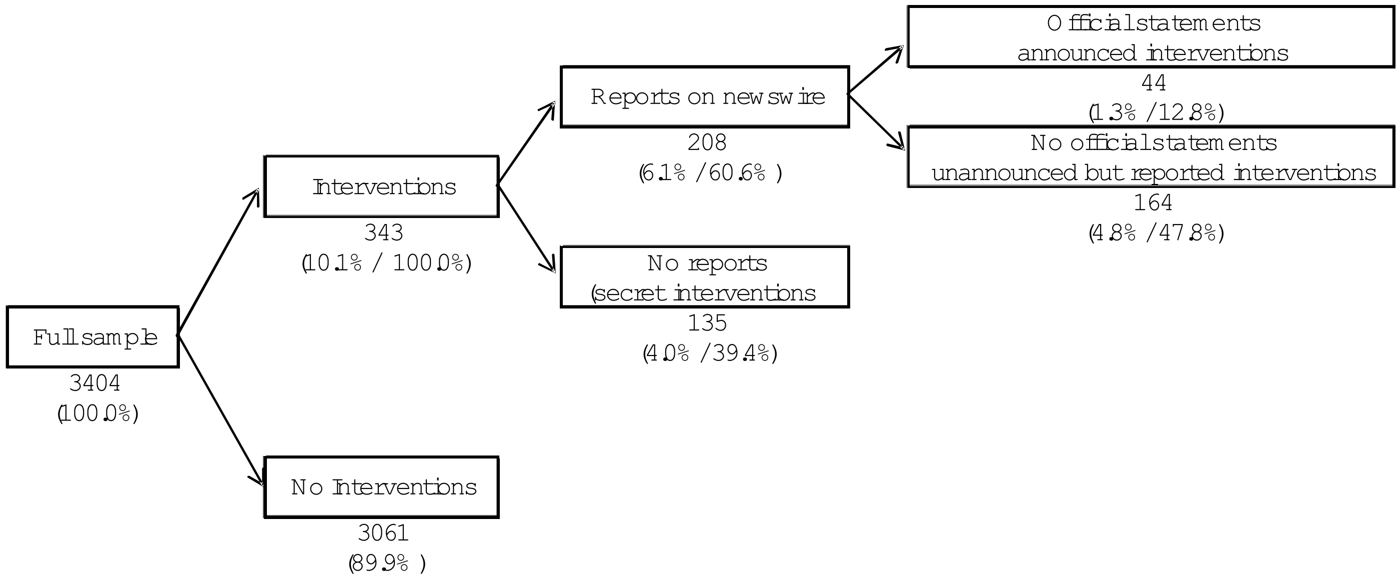
Figure 2. Japanese interventions 5/13/1991-5/27/2004



Source: the Ministry of Finance of Japan, Bloomberg and Reuters.

Figure 3. Expectation heterogeneity

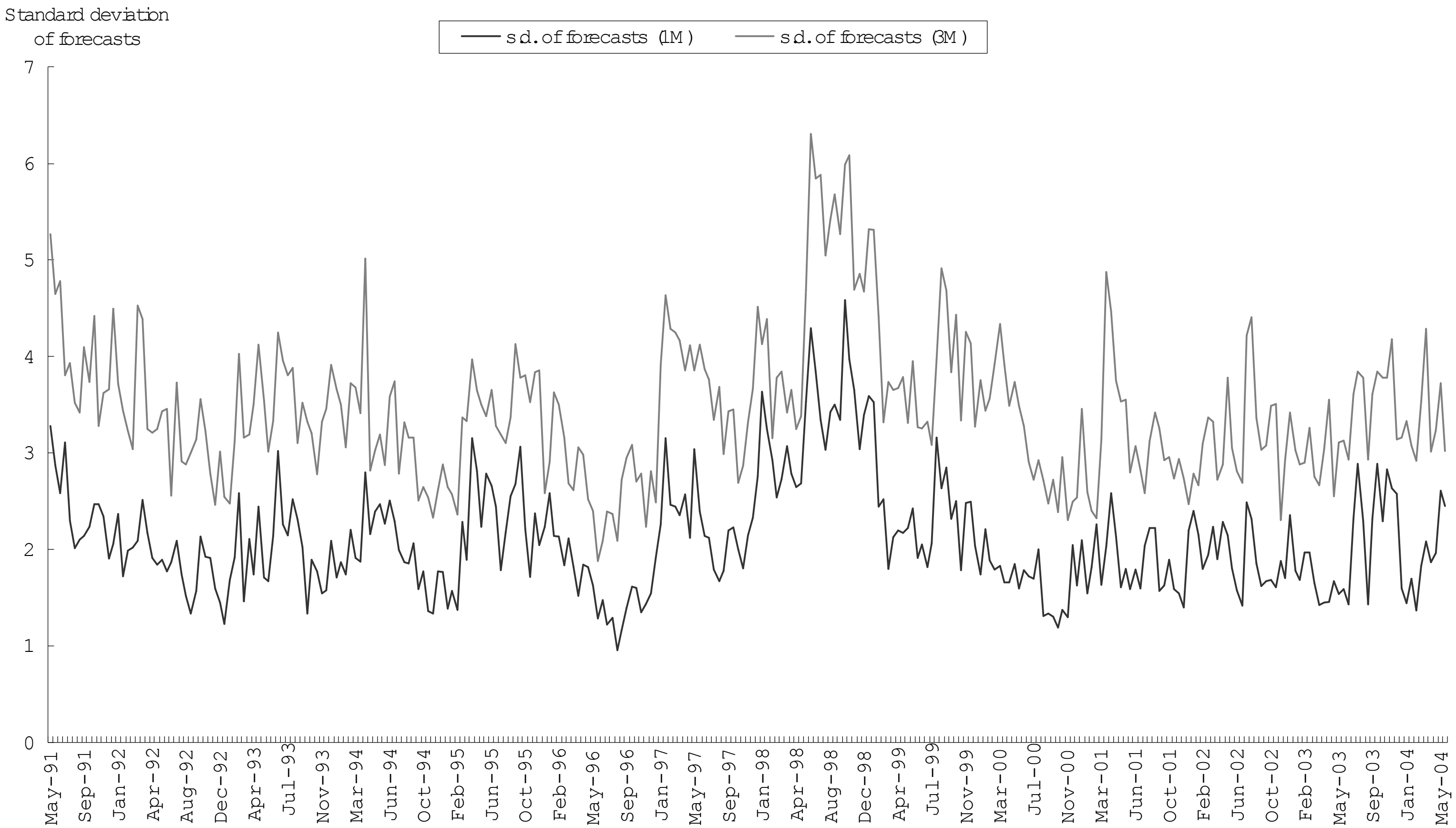


Figure 4. Implied volatility

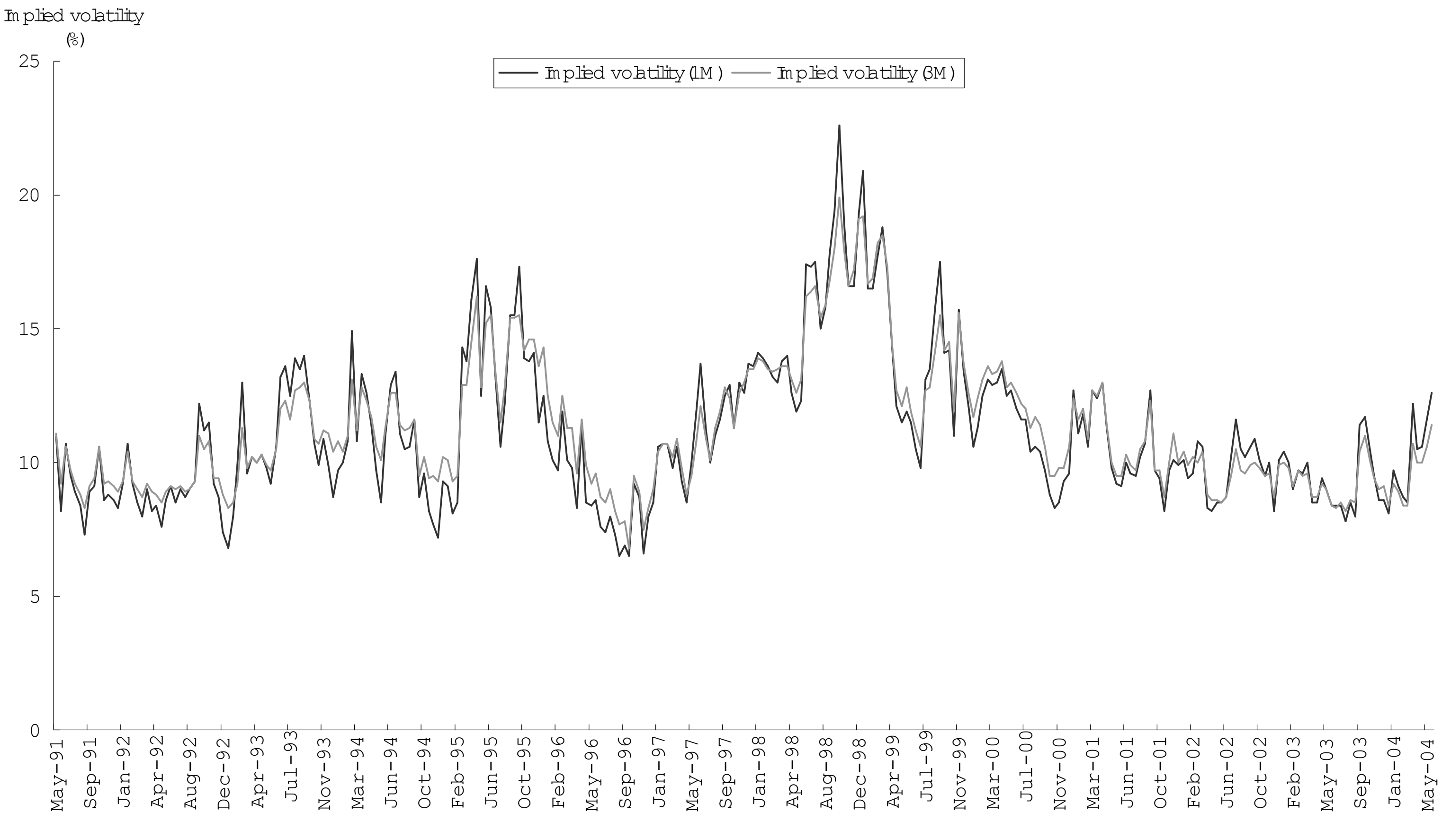
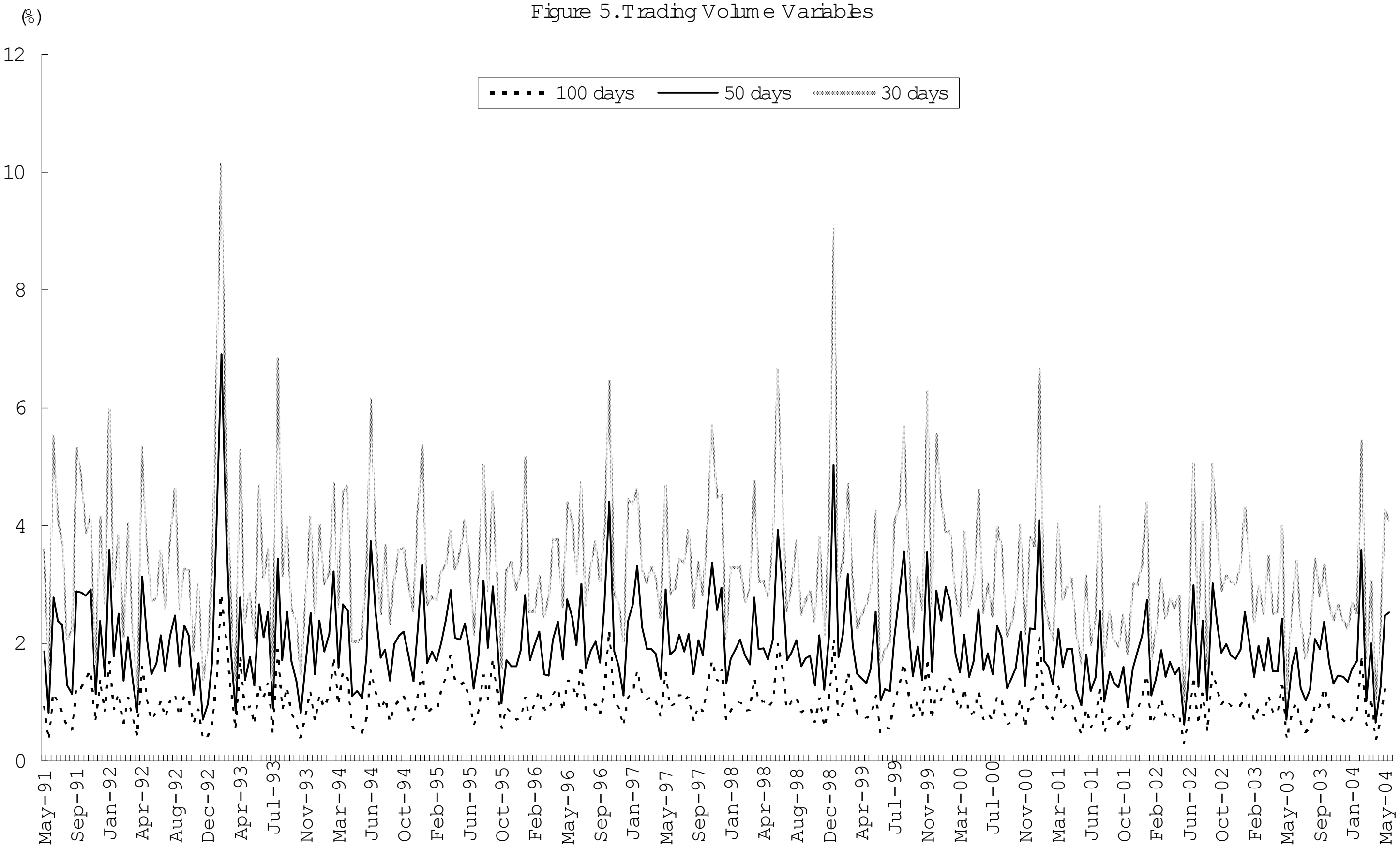


Figure 5.Trading Volume Variables



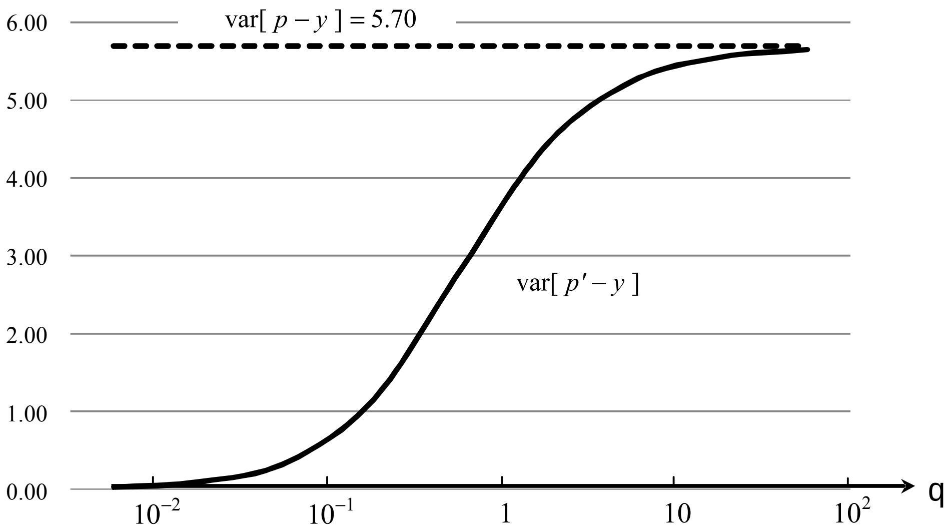


Figure 6. The effect of announcement on the distribution of bubble.
The graph is drawn for the following parameters. $\sigma_y^2 = 5$, $\sigma_\varepsilon^2 = 3$, $\sigma_x^2 = 5$, $a = 0.5$.

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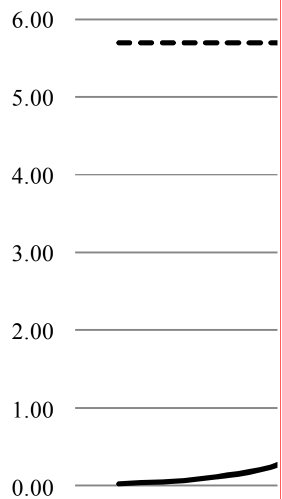

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Figure : The effect of announcement on the distribution of bubble.¶
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