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The Information Improving Channel of Exchange Rate Intervention: How Do Official Announcements Work?

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Abstract

This paper studies the relationship between official announcements and the effectiveness of foreign exchange interventions in a noisy rational expectations equilibrium model. We show that when heterogeneously informed traders have inaccurate information, an exchange rate is likely to be misaligned from its fundamental value in the presence of noise trades. Then the central bank uses the disclosure of public information to improve the accuracy of private agents' information and encourage risk-arbitrage thereby enhancing the informativeness of the exchange rate. This effect holds, even when the central bank does not possess superior information to traders, as long as public information is not perfectly correlated with the information of traders. We provide evidence that announced interventions are more effective in periods of high implied volatility, consistent with the theoretical prediction that the implied volatility of the exchange rate is positively correlated with the information inaccuracy of traders and the degree of an exchange rate misalignment.

JEL classification: F31, G15

Keywords: Exchange rate; Interventions; Announcements; Implied volatility; Information

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1. Introduction

There is a rapidly growing literature on the role of communication for monetary authorities managing market expectations in foreign exchange markets.¹ This new trend reflects the fact that major central banks such as the Fed and the ECB have become reluctant to intervene and have shifted toward the use of communication policy in the management of their exchange rates. The Bank of Japan still continues to intervene in the market, albeit with a lower frequency than before, but also puts serious effort into communication and transparency concerning its exchange rate policy.² Despite this shift towards communication policy, a consensus has not been reached among researchers on how official announcements as well as actual interventions influence exchange rate movements.

The portfolio-balance channel and the signaling channel are two traditional channels through which sterilized interventions can affect exchange rates. In the portfolio-balance channel, interventions change the composition of portfolios and thus the risk premium due to imperfect substitutability of the underlying assets (Dominguez and Frankel, 1993). The small scale of interventions relative to the large volume of transactions in foreign exchange markets and the huge value of stocks of international assets has led researchers to emphasize the signaling hypothesis, by which actual and announced interventions may be perceived by markets as indicating future monetary policy or developments of other policy measures (Mussa, 1981). Lewis (1995), Kaminsky and Lewis (1996) and Fatum and Hutchison (1999) find, however, that U.S. interventions have not conveyed a clear signal about future monetary policy.

The following theoretical models therefore explore the intervention channels under which central banks do not possess superior private information to market participants or influence the fundamental value of the exchange rate.³ Among these, the coordination channel was first advocated by Sarno and Taylor (2001) and formulated by Reitz and Taylor (2008). If the strong and persistent misalignments of exchange rates are caused by non-fundamental influences, such that a return to equilibrium is hampered by a coordination failure among fundamental-based traders, then official intervention may act as a coordinating signal, encouraging speculators to

¹ Examples include Beine and Bernal (2007), Beine et al. (2009a, 2009b), Dominguez and Panthaki (2007), Fratzscher (2006, 2008, 2009), Gnabo and Teiletche (2009), Gnabo et al. (2009), and Jansen and De Haan (2005, 2007).

² The criticism over currency manipulation is one reason that Japan hesitates to make frequent interventions. After a six-year moratorium, the Bank of Japan has recently intervened in currency markets three times: on Sep 15, 2010, March 18, 2011 and August 4, 2011.

³ Bhattacharya and Weller (1997), Vitale (1999), and Ferre and Manzano (2009) consider the secrecy puzzle with models in which the central bank knows perfectly the fundamental value of the exchange rate or infers it from the market rate.

re-enter the market and at the same time returning the exchange rate to a level consistent with economic fundamentals.

Closely related to the coordination channel is the information sharing channel proposed by Popper and Montgomery (2001). Under this channel, even if the central bank has no information about fundamentals, it can affect the exchange rate by aggregating and disseminating some traders' information about transitory exchange rate disturbances because the sharing of information makes the exchange rate less noisy and allows all market participants to extract a better signal of fundamentals from the exchange rate.

A drawback of the coordination channel is that it does not model how the central bank acquires information about the fundamental value of the exchange rate, which is relevant in deciding the time and magnitude of interventions. On the other hand, the information sharing channel assumes that the central bank frequently gathers information about market conditions from bank dealers, which enables it to infer the fundamental value. However, the assumption that the central bank can distinguish between price-informed dealers and uninformed dealers is too strong as it is extremely difficult to discern dealer type in reality.

In this paper, we provide an alternative channel to the above two theories, which highlights that the (even inaccurate) information endowed to and signaled by the central bank enables traders to improve their information accuracy. This information improving channel is introduced by incorporating intervention operations into the noisy rational expectations equilibrium models of Hellwig (1980) and Diamond and Verrecchia (1981). When informed traders have inaccurate information about fundamental values, an exchange rate is likely to be misaligned from its fundamental value and exhibit high implied volatility in the presence of noise trades. In this circumstance, we assume that the central bank intervenes in the market by disclosing its own signal about the fundamental value or, equivalently, announcing the target level of the future exchange rate. The announcement of the central bank improves the accuracy of traders' information and therefore helps them to engage in risk-arbitrage effectively. As a result, the exchange rate moves towards the fundamental value and becomes less noisy.

It should be stressed that this channel functions even when the central bank does not possess superior information to private agents. In the model, the equilibrium exchange rate does not fully reveal all the information available in the market due to the existence of noise trades. In other words, the market is informationally inefficient. Although informed traders' risk-arbitrage is profitable at the expense of noise traders, the arbitrage is limited because the informed traders are risk averse. We show that the more accurate information the informed traders have, the more

effectively they engage in risk-arbitrage and the more informational efficient the market becomes. Accordingly, the public signal from the central bank has informational value that affects the exchange rate, as long as traders' private signals are not perfectly correlated with the public signal.

Our model has several noteworthy features. First, unlike the coordination channel or the information sharing channel, our channel is not driven by the homogenization of traders' forecasts of the future exchange rate, but by an increase in the accuracy of their information about the fundamental value.^{4,5} Even in our model, both the accuracy improvement of traders' information and the homogenization of their forecasts can be achieved simultaneously by central bank announcements. However, the latter is not a necessary condition for diminishing exchange rate misalignments. To address the difference between the mechanism in our model and the mechanisms in the coordination channel and the information sharing channel, we show that the relationship between the accuracy improvement of traders' private information and the homogenization of their forecasts is nonlinear and that there is a case where worsening informed traders' private information could homogenize their forecasts. This is due to the fact that if the private information worsens, the informed traders are likely to rely more on their public signal (i.e., the exchange rate) and less on their private signal which includes an independent error term about the fundamental value across the traders. This will lead to the homogeneity of traders' forecasts.

Second, this model shows that the degree of information *in*accuracy of informed traders about the fundamental value of the exchange rate, which is the key variable in the model, is positively linked to the implied volatility of the exchange rate. This implies that the information improving channel is more effective in an environment of high implied volatility or, in other words, large market uncertainty because this is when information inaccuracy causes the exchange rate to be significantly misaligned. Fratzscher (2008) provides consistent evidence that announced interventions are more likely to be successful if exchange rate volatility is high, i.e. above its median value, in the previous two weeks. Our theoretical prediction that implied volatility can be

⁴ Specifically, Reitz and Taylor (2008) propose a mechanism under which announced and actual interventions influence informed traders' confidence in fundamental analysis and coordinate their risk-arbitrage behavior. On the other hand, Popper and Montgomery (2001) assume that the central bank can transmit information to the market about average customer orders originating from a group of traders who have no information about the future exchange rate. In both channels, official interventions make traders' forecasts about the future exchange rate less heterogeneous.

⁵ Reitz et al. (2010) and Beine et al. (2007) provide empirical evidence on the impact of interventions on exchange rate forecast heterogeneity.

used as a proxy for traders' information *inaccuracy* allows us to easily detect an exchange rate misalignment and provides us with a tractable measure for deciding the timing of FX interventions. We present evidence that official announcements are more effective when accompanied interventions take place in high implied volatility periods.

We exploit changes in Japanese intervention policy to empirically test the theoretical predictions of our model. Japanese intervention policy changes frequently with regard to announcements in accordance with who is in charge of foreign exchange interventions at the Ministry of Finance. In addition, Japanese intervention strategy in terms of volume and frequency has not been consistent across the interveners. These uncommon features of Japanese interventions allow us to investigate the effect of official announcements, controlling for volume effects.

Our paper highlights the importance of market conditions for effective interventions. Although many studies investigate the effects of intervention strategies such as announced and secret interventions (Dominguez, 1998, 2003a; Beine et al., 2007, 2009a), few studies examine whether their effectiveness depends on market conditions (Fratzcher, 2006; Dominguez, 2003b). This paper provides empirical results that announcements have a more significant influence on the level and reduce the implied volatility of the exchange rate when the implied volatility on the previous trading day is high. This is consistent with the information improving channel we propose in this study.

The remainder of the paper is organized as follows. Section 2 demonstrates the theoretical model of actual and announced interventions in foreign exchange markets. Section 3 describes the intervention data and the sampling scheme. Section 4 explains the empirical methodology and Section 5 presents the estimation results. Section 6 contains our conclusions.

2. Theory

In this section, we present a noisy rational expectations equilibrium model with central bank's intervention operations. First, we study how the information accuracy of traders relates to the distribution of exchange rate misalignments, the implied volatility, and heterogeneity in investors' forecasts. We then specify the central bank's intervention decision rules to examine the effect of official announcements on the effectiveness of interventions through improvements in the information accuracy of traders.

2.1. Assumptions

Consider a pure exchange economy with three trading periods and two assets, one riskless domestic currency (with a constant price equal to one) and one risky foreign currency. The future value of the foreign currency is denoted y in terms of domestic currency, where y is normally distributed with mean \bar{y} and variance σ_y^2 , and it is revealed in period 3. In period 1 all traders choose net demand for the foreign currency and its price, denoted p , is determined in the market. The traders who trade in period 1 receive their payoff of y per unit in period 3 when y becomes public. We call p and y as the exchange rate of the foreign currency in periods 1 and 3, respectively. In period 2 the central bank decides whether to intervene in the foreign exchange market.

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

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

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

Apart from trades by informed traders, there are noise trades reflecting the demand and supply for the foreign currency from 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 . The random variables, $y, x, \varepsilon_1, \varepsilon_2, \dots, \varepsilon_n$, 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 gains, $(y - p) z_i$, 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:

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

Informed traders know that the demands of other informed traders affect the equilibrium price of the foreign currency and make rational inferences about 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 theorem⁶ which assures that the distribution of y conditional on (s_i, p) is normal. Under this CARA-Gaussian setting, we can easily derive investor i 's demand function for the foreign currency:

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

2.2. Equilibrium exchange rate function

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

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

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 a closed form solution of the model, its complicated form does not provide for a study of equilibrium properties. In addition, the model with finite traders contains a theoretical contradiction. Hellwig (1980) describes it as "schizophrenic," which means that traders behave as price takers 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

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

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

Proof: See the Appendix.

This proposition means that, by the strong law of large numbers, 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 results from a comparative statics analysis in the next section:

⁶ For a general version of the projection theorem, see Brunnermeier (2001, p.12).

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

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

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

An important property of this model is informational inefficiency; the equilibrium exchange rate does not reflect all the available information in the market because of noise trades x . Following this 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 a perfect estimate of the future value. In contrast, if there is no noise trade as in the model of Grossman (1976), 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 a bubble in the exchange rate as $p - y$, the misalignment of the current exchange rate from its fundamental value. We can measure the informativeness of the exchange rate by the variance of the bubble; the degree of informativeness increases as $\text{var}[p - y]$ decreases.

We show in a later section that, due to informational inefficiency, additional information provided by the central bank 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 informed traders to make more precise estimates of y (the smaller conditional variance of y) and therefore to have a larger position as indicated by equation (4). As a result of informed traders' active trades, the exchange rate shifts toward the fundamental value y .

2.3. Comparative statics with respect to signal accuracy

In this section, we analyze how traders' information accuracy has an influence on the distribution of the bubble, implied volatility and the heterogeneity of forecasts in the foreign exchange market before the central bank intervenes in the market. We show that less accurate information reduces the informativeness of the exchange rate and increases implied volatility, while the effect on the heterogeneity of traders' forecasts is ambiguous.

A. Distribution of the bubble

We first study the effect of σ_ε^2 on the distribution of the bubble. Since p is a linear function of normal random variables and y is also normal, $p - y$ is normally distributed. The price function (6) implies that the mean is zero, and the variance is

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

Then we can show that

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

Proof: See the Appendix.

The positive sign implies that when traders have more accurate signal (smaller σ_ε^2), the exchange rate p in period 1 distributes closer to the fundamental value y . The reason is that when the private signal is accurate, informed traders' risk-arbitrage becomes more effective. Such risk-arbitrage leads the exchange rate to distribute closer to its fundamental value and enhance the informativeness of the exchange rate. Conversely, when private information is less accurate, the exchange rate is likely to be disturbed more by noise trades and thus is noisier in period 1.

Although the parameter σ_ε^2 is unobservable, the following market variables are supposed to be used as proxies for it: implied volatility and the heterogeneity of traders' forecasts. We investigate the relationship between σ_ε^2 and these two variables 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. This volatility is, by definition, subjectively expected by investors in the market, and thus unobservable. If the market works as the theory assumes, however, we can infer volatility from the observed call price in the market by using the inverse function of the call option price function.

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

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

This expression is consistent with intuition. When private signals are less accurate, the public signal (in this case, p) is also less accurate, and the conditional variance of y is therefore larger. The strictly positive sign for (11) allows us to regard implied volatility as a proxy for σ_ε^2 .

C. Heterogeneity of forecasts

As traders have dispersed private information, their conditional expectations for y on their information are also dispersed. One may presume that less accurate information leads to heterogeneity of forecasts among traders. This is correct if we define trader i 's forecasts as equal to their private information s_i . However, the trader's forecasts should be defined as the expectation based on both their private information and all available information including public information. If the heterogeneity of traders' forecasts is defined this way, it is not always a good proxy for σ_ε^2 .

Suppose we take a sample of M traders. The heterogeneity of forecasts, denoted H , is given by the following statistics:

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

Putting (7) into (12), we have

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

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

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

PROPOSITION 2

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

if and only if

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

Proof: See the Appendix.

This proposition assures that, as long as the error term is less volatile than the fundamental value of the exchange rate, the heterogeneity of forecasts is increasing with σ_ε^2 . However, this proposition 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 common prior beliefs in our model, traders' forecasts $\{E[y|s_i, p]\}_i$ stay closer to the common unconditional expectation $E[y]=\mu$ and thus the difference in forecasts is decreasing with σ_ε^2 . This nonlinear relationship between the heterogeneity of forecasts and the measure of information inaccuracy is important for differentiating the mechanism of official interventions in our model from those of the coordination channel and the information sharing channel.

2.4. Intervention by the central bank

To complete our theoretical argument, we allow the central bank to intervene in the foreign exchange market if necessary in period 2. For simplicity, we deal with official interventions as if they are unexpected events for informed traders. If we relax this assumption and allow for dynamic interaction between the central bank and traders, the model becomes too complicated to analyze. However, we do not regard this assumption as critical for our results. 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 foreign currency because they know the exchange rate turns out to be the true value of the currency in period 3. If traders follow such an investment style, they can get an advanced cash flow in period 2 thanks to the intervention by the central bank, which attempts to push the exchange rate toward the true value based on its information in period 2. Thus, we believe that traders' behavior is not affected significantly by interventions, even if they are expected.

We assume that the central bank also receives imperfect information through the following signal:

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

The error term ε_B has an independent normal distribution with mean 0 and variance $\theta\sigma_\varepsilon^2$, where θ is a strictly positive constant and represents the accuracy level of the central bank's information relative to informed traders. For example, θ smaller than 1 implies the central bank has more accurate information than traders. Note that when σ_ε^2 is large, both informed traders and the central bank 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 central bank. We also assume that the distributions of random variables (y, x, ε) and the constant term θ are common knowledge among traders and the central bank and that the rational central bank knows the objective function of informed traders.

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

INTERVENTION RULE⁷: For a given probability π in $(0, 1)$, if $P[y > p | s_B, p] > \pi$, or if $P[y < p | s_B, p] > \pi$, then the central bank intervenes in the foreign exchange market to move the current exchange rate toward $E[y | s_B, p]$. π is set to a high value close to 1 in order to avoid a government failure.

This rule implies that the central bank intervenes in the foreign exchange market to move the exchange rate toward the fundamental value when it judges statistically that there is a bubble. Statistically speaking, interventions take place when a null hypothesis of no bubble is rejected with significance level $1 - \pi$. Parameter π represents how prudent the central bank is. Because the central bank has imperfect information, and thus the intervention can make the bubble bigger based on information with a serious error. This is why the prudent parameter π should be set sufficiently high.

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

$$(18) \quad |E[y | s_B, p] - p| > Z_\pi \sqrt{\text{var}[y | s_B, p]}.$$

Z_π is the solution for $\Phi(Z) = \pi$, 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 central bank. The right hand side is constant. That is, the central bank intervenes when the expected bubble is larger than a critical value. The expected bubble can be decomposed in the following manner:

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

This decomposition indicates that the expected bubble is comprised of the true bubble $y - p$, and the central bank's estimation error mainly due to ε_B . Needless to say, the aim of the intervention is to clear the true bubble. Although it is impossible for the central bank to discriminate between the true bubble and the estimation error, the central bank can clear the subjectively recognized bubble.

⁷ The spirit of this decision rule is analogous to the statistical decision-making of manufacturers when testing whether their products satisfy quality requirements. See Shewhart (1931)'s quality control chart.

Under this model setting, the central bank has two intervention measures: actual intervention and official announcement. To examine the effect of interventions, we need to specify traders' information and their reaction to interventions. We assume that interventions are unexpected events and therefore traders only realize that an intervention has occurred and update their posterior beliefs when the central bank makes an announcement. Actual interventions without any announcement are assumed to be unobservable like noise trades, and thus traders cannot update their posterior beliefs. We also assume that, when the central bank announces, informed traders know the distribution of the central bank's signal. That is, they know that the central bank also has imperfect information and that the error term is independent of their own private signals. Using this information they make rational inferences about y based on the announcement, and modify their demand function for the foreign currency in Period 2.

A. Actual interventions

The central bank can move the exchange rate toward the subjective fundamental value, $E[y|s_B, p]$, by trading the foreign currency in a manner that cancels the noise trade x . Note that the demand curve for the foreign currency is downward sloping when the market is informationally inefficient. Therefore, any trade can affect the exchange rate along the demand curve.⁸ The required trade for this purpose is $(E[y|s_B, p] - p) / \beta_x^*$. If the interventions are too costly due to low foreign reserves or a high borrowing cost, the exchange rate will not reach the target.

B. Official announcements

Under informational inefficiency, the central bank can affect the exchange rate by providing additional information to informed traders, which stimulates their risk-arbitrage. To see the pure effect of official announcements, suppose that the central bank announce s_B publicly but does not engage in any market operations. Note that, as long as the informed traders know that the central bank is also rational, announcing a signal s_B and the central bank'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 official announcement of s_B , which can be represented as

⁸ We assume that traders would not recognize interventions without official announcements. This means that traders suppose the change in the exchange rate is caused by a change in the noise trade, not by an intervention, and modify their demand for the foreign currency along the demand function (4).

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

The modified exchange rate is affected by the central bank's information error, ε_B . As this function is too complicated to derive a closed form solution for coefficients γ 's we analyze it numerically and obtain the following results.

First, the post-announcement implied volatility decreases to $\text{var}[y | s_i, s_B, p]$, which is always strictly lower than pre-announcement implied volatility $\text{var}[y | s_i, p]$ for any finite θ .⁹ The additional information through announced interventions makes traders' information more accurate as the error term ε_B is independent of private investors' information error ε_i .

Second, on average, the announcement successfully diminishes the “true bubble” with the help of active risk-arbitrage. As the demand function (4) demonstrates, lower implied volatility allows traders to bet larger positions based on their information. In other words, official announcements make risk-arbitrage by informed traders more active and effective than before. Figure 1 shows the effect of an announcement on the variance of the bubble (the reciprocal of the informativeness of the exchange rate). The graph is drawn for a set of parameters. The announcement has a larger effect for smaller θ when the central bank has more accurate information than informed traders. When θ is quite large, the announcement has little effect. Since informed traders are rational and know θ , an unreliable announcement is simply ignored and does not harm the market. In the middle range, the effect depends on parameters. For reasonable parameters, a central bank with the same accuracy level as traders (i.e. $\theta = 1$) can diminish the variance of the bubble to roughly half of its initial size. Note that the above results represent an average effect. We cannot exclude the case where the announcement may unintentionally increase the bubble when the central bank receives an unusually bad signal ε_B . This happens with a low probability, however, as the central bank is too cautious to intervene in the market when the variance of the signal is large.

Third, the post-announcement forecasts of traders ($E[y | s_i, s_B, p]$) distribute closer to each other than pre-announcement forecasts ($E[y | s_i, p]$). Figure 2 presents the effect of an announcement on the heterogeneity of forecasts. As explained in Section 2.3 C, pre-announced heterogeneity has an inverse-U shaped relationship with information inaccuracy. Heterogeneity increases until σ_ε^2 reaches a threshold level (in this case, $\sigma_\varepsilon^2 = 7.1$) and decreases thereafter. When the central bank announces its public signal, traders' forecasts homogenize regardless of

⁹ In equilibrium, p' is a linear combination of s_B and p (See Appendix D). This implies that $\text{var}[y | s_i, s_B, p, p']$ equals $\text{var}[y | s_i, s_B, p]$. In addition, since s_B has an independent error term, we have $\text{var}[y | s_i, s_B, p] < \text{var}[y | s_i, p]$.

the value of θ because the public signal is common for all traders and they utilized the information to form their expectations. Obviously, the degree of homogenization caused by an announcement depends on θ . When it is quite small, the announcement has a large effect on the homogenization of forecasts.

C. Actual interventions and official announcements

What if the central bank implements actual interventions and official announcements simultaneously? The answer depends critically on the credibility of the central bank's market operation. If traders believe that the central bank can achieve the target of 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. This riskless arbitrage causes the exchange rate to reach the target before the central bank conducts the actual interventions. A situation that will occur even if the required interventions are too costly for the central bank to achieve by itself, as long as traders believe it has enough reserves. In contrast, if traders believe that the central bank does not have enough reserves, then the exchange rate moves to p' , but will not reach the target $E[y|s_B, p]$ without the central bank's actual interventions. In fact, this situation is like a coordination game in which traders' beliefs are self-fulfilling. Credible monetary authorities can achieve the target without actual interventions by winning the traders over to their side.

2.5. Hypotheses derived from the model

Our model provides several theoretical predictions on the foreign exchange market and the effectiveness of interventions. First, in the presence of noise trades, an exchange rate is likely to be more misaligned from its fundamental value and exhibit a higher implied volatility when informed traders have less accurate information. Second, under plausible assumptions, the degree of information inaccuracy about the fundamental value and the implied volatility of an exchange rate are positively correlated. Hence, implied volatility can be used as a policy tool to determine the timing and magnitude of interventions, as the impact of interventions is greater when implied volatility is higher. Third, official announcements can make the exchange rate less noisy (i.e. increase the informativeness) and reduce both implied volatility and the heterogeneity of forecasts because they contribute to the improvement of traders' information accuracy. This holds even when the central bank does not possess superior information to that of traders.

These predictions provide the following testable hypotheses: First, official announcements and actual interventions have a more significant impact on the level of the exchange rate when the implied volatility of the exchange rate is high. Second, if they are conducted in a timely manner, the implied volatility of the exchange rate and the heterogeneity of forecasts are reduced.

Reitz et al. (2010) provide empirical evidence that central bank interventions reduce forecast dispersion, which is consistent with the coordination channel and the information sharing channel as well as our theory. To highlight the aspects of our theory that differ from the previous two channels, we leave heterogeneity in forecasts and empirically test whether high implied volatility of the exchange rate is a pre-condition for effective interventions and announcements using Japanese and US intervention data.

3. Data and Japanese intervention policy changes

To address the announcement effect, we classify interventions into three categories using news reports provided by Bloomberg: announced interventions, unannounced but reported interventions, and secret interventions.¹⁰ ‘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 along with the name of the official making the announcement within a few minutes by newswires. ‘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.” On the other hand, ‘secret interventions’ are not reported by the newswires, but do actually take place.

It is well known that 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 volume of interventions (Sakakibara, 2002).¹¹ Accordingly, some studies on Japanese interventions divide their sample periods into pre and post June 1995 (Ito, 2003; Beine et al., 2009b). Intervention policy also changed after his

¹⁰ We double-checked the classification of interventions using Reuters.

¹¹ Dr. Sakakibara became famous in the market after being nicknamed “Mr. Yen” by the NY Times (Sep 16, 1995).

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.¹² 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. Figure 3 illustrates the movement of the yen/dollar rates and intervention volume during the full sample period.

Table 1 displays the average volume and intervention types for the whole sample period and the four sub-periods from May 13, 1991 to July 2, 2004. 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).

Period 1 is characterized by frequent, small interventions. In this period, frequency is the highest among the four sub-periods (averaging an intervention every 4.77 days) and the average volume of an intervention was 47 billion yen, which is the smallest among the 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 volume of an

¹² 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)

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 infrequent and large to frequent and medium-sized. The frequency of interventions in period 4 increased to an average of one 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 volume 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.”

4. Empirical methodology

In the empirical sections, we test our hypothesis that official announcements and actual interventions are more effective when the implied volatility of an exchange rate is higher. We would expect that the level of the exchange rate will move in the desired direction and the implied volatility of the exchange rate will be reduced if they are conducted in a timely manner. This hypothesis can be tested using the GARCH model and the OLS model using implied volatilities extracted from option prices. The former examines the impact of interventions on the level and the ex-post volatility of an exchange rate, while the latter on the ex-ante volatility representing investors’ expected future volatility. Following Beine et al. (2009a) and Dominguez (1998), the GARCH (1, 1) model of the yen-dollar exchange rate has the following specification:

$$(21) \quad \begin{aligned} r_t &= a_0 + a' X_t + \varepsilon_t, & \varepsilon_t | \Omega_{t-1} &\sim N(0, h_t), \\ h_t &= \alpha_0 + \alpha_1 \varepsilon_{t-1}^2 + \alpha_2 h_{t-1} + b' | X_t |, & \alpha_0 > 0, 0 \leq \alpha_1, \alpha_2 \leq 1, \alpha_1 + \alpha_2 < 1 \end{aligned}$$

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 as the yen/dollar rate (NY close). X_t denotes a vector of independent variables related to the Japanese and U.S. interventions as well as macro variables that may affect exchange rates.

Three dummies are considered in the estimation equations for announced interventions, unannounced but reported interventions and secret interventions for Japan and the U.S. These

dummies are independent of intervention volume by both countries,¹³ and 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 are expected to be positive. 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.¹⁴ We include a holiday dummy in the volatility equation which takes a value of 1 if the previous day is a holiday and 0 otherwise. All variables in the volatility equation are taken to be the absolute values of those in the mean equation.

Following Bonser-Neal and Tanner (1996) and Dominguez (1998), the effects of official announcements and actual interventions on the implied volatility of the exchange rate are tested using the following specification:

$$(22) \quad iv_t = a'Y_t + b'Z_{t-1} + \varepsilon_t$$

where $iv_t = 100 \ln(IV_t / IV_{t-1})$ is the logarithmic return of 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 NY market (10 AM EST). The variables concerning the Japanese interventions and macro variables are included in Y_t . On the other hand, following Dominguez (1998), the variables related to the Fed's intervention are lagged by one day, which are included in Z_{t-1} , because market participants do not know (with certainty) the Fed's Tuesday interventions on Tuesday morning. Since variables related to interventions are all taken as absolute values, we expect negative signs for the coefficients if interventions are effective in reducing implied volatility.

¹³ Existing empirical research testing the signaling hypothesis using news reports typically splits interventions into reported and secret interventions and analyzes the significance of the coefficients for the volume of each type of intervention (Dominguez, 1998; Beine et al., 2002). This paper analyzes the efficiency of interventions using intercept dummies that represent reported and secret interventions, while controlling for 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. This contradicts the view of shifting slopes because the difference between announced and unannounced interventions lessens as intervention volume increases. We pre-test the model incorporating both slope and intercept dummies and find that using intercept dummies is preferable to shifting slopes.

¹⁴ The overnight market rates are the Federal Funds rate for the U.S. and the call rate for Japan.

A potential caveat of our regressions is that interventions may be endogenous. Kearns and Rigobon (2004) suggest an empirical methodology for taking this endogeneity into account by directly modeling the potential behavior and reaction of central banks. It is well known, however, that specifying the determinants of interventions is not an easy task. Most studies on the reaction functions of central bank interventions use either a binary choice approach or a nested logit model and do not fully specify intervention volume (Ito and Yabu, 2007; Beine et al., 2009b). There is a risk, therefore, of misspecification when specifying a parametric model of intervention behavior that corrects for the endogeneity bias. Moreover, as suggested by Fratzscher (2006), the literature, including Sarno and Taylor (2001), has shown that actual interventions tend to be of the leaning-against-the-wind type, i.e. they usually go against the previous exchange rate trend. Therefore, if endogeneity generates a bias, it will be a downward bias, and the true effect of interventions may be even larger.

5. Estimation results

5.1. Linear estimation of announcement effects

We first examine whether officially announced interventions have a larger effect on exchange rates than secret interventions and unannounced but reported interventions. Table 2 presents the results of the GARCH estimations for the full sample period as well as the four subsample periods distinguished by Vice Ministers of Finance for International Affairs of MOF. In the results of the mean equation for the full sample period, the coefficient of the Japanese announced interventions dummy is significantly positive, while those of the Japanese unannounced but reported interventions dummy and the secret interventions dummy are significantly negative, suggesting that announced interventions are not just effective but significantly more effective than non-announcement interventions. The negative signs of the non-announcement interventions do not necessarily imply that interventions without official announcements inversely affect the return of exchange rate. Taking into account the volume effect, such strategies can be effective although their efficiency is significantly less than that of announced interventions.

During the full sample period, whenever the U.S. authorities intervened, the Japanese authorities intervened on the same day. As there were no unilateral U.S. interventions, but were many unilateral Japanese interventions, the U.S. intervention dummies with and without official announcements capture the impacts 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. With regard to coordinated interventions, it is whether the intervention is announced and/or reported that has a significant influence on exchange rates, not the volume of the intervention.

Table 2 also presents the regression results for the four sub-sample periods. Interestingly, the coefficient of the dummy for secret interventions is significantly 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. However, the evidence that the intervention announcement is effective only in period 2 and not in other sub-sample periods may question previous studies which show that official announcements have unambiguous effects (Fratzscher, 2006; Beine et al., 2009a).

The results from the volatility equation are also striking. In the full sample, neither the Japanese intervention volume nor its announced intervention dummy is significant. Moreover, the unannounced but reported intervention dummy is significantly negative. Together with the results from the mean equation, this evidence suggests that Japanese interventions are quite effective in stabilizing the market as well as affecting the level of exchange rate in the desired direction. However, the four sub-sample regressions show that announced interventions are volatility enhancing in periods 2 and 3, while unannounced interventions contribute to lower volatility in periods 1 and 4. One may conclude that the difference in intervention policies may lead to the difference in outcome. Specifically, if the central bank aims to alter the previous exchange rate trend, i.e., the leaning-against-the-wind policy, announced interventions are appropriate although they are accompanied by an increase in volatility. On the other hand, if stabilizing exchange rate movements is the primary objective, the central bank should choose secret interventions even if they may have little effect on the exchange rate level.

A careful comparison between periods 2 and 3, however, allows us to find that this is not always true. Although Mr. Kuroda followed Dr. Sakakibara's announcement strategy, his interventions are not effective in period 3. This implies that official announcements alone do not necessarily guarantee the success of interventions.

5.2. Non-linear estimation of announcement effects

We then investigate whether the effectiveness of announcements hinges on market conditions just before the intervention takes place. Specifically, we test whether the announcements on interventions have a stronger impact when traders have inaccurate information and the exchange rate misalignment is therefore large. We use the implied volatility derived from at-the-money option prices (one- and three-month) on the spot yen/dollar rates as a proxy for the above two variables as they are positively related as shown in our model.

Tables 3 reports the results of the GARCH model in which we introduce the interaction repressor: the product of the intervention dummy and the implied volatility (one- and three-month) of the exchange rate. 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. The results of volatility equation are omitted for the sake of space because the interaction terms are not significant.

In the first column of Table 3 (results for the whole sample period), the result of the estimation with one-month and three-month implied volatility is displayed. The coefficient of the interaction term between the Japanese announcement dummy and the lagged implied volatility is significantly positive, while that of the Japanese announced dummy is significantly negative. This suggests that announcement effects have a non-linear relationship with exchange rate changes, which depend on the implied volatility of the previous business day. Based on these coefficients, we infer that official announcements influence exchange rates in the desired direction if the lagged implied volatility is greater than 11.38% for 1 month maturity and 11.32% for 3 month maturity, respectively. Furthermore, the significantly positive coefficient of the interaction term between the Japanese intervention volume and lagged implied volatility shows that large-scale interventions are effective when lagged implied volatility is sufficiently high (more than 3.78% for 1 month and 3.60% for 3 month, respectively). In 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 for period 2 show that lagged implied volatility of more than 10.43% for 1 month and 11.30% for 3 month, respectively, are 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.

Table 4 also shows a similar non-linearity effect for announcements on current implied volatility depending on lagged implied volatility. The result for the whole sample period suggests

that when lagged implied volatility is more than 13.99% for 1 month, official announcements can reduce current implied volatility because the interaction term has a negative coefficient and the announced intervention dummy is positively signed. However, the coefficient of the interaction term between intervention volume and lagged implied volatility is significantly positive, mitigating the effect on volatility. We then need to 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 15.24% is needed for an announced intervention to reduce the volatility of exchange rates. This indicates that lagged implied volatility, serving as a proxy for information inaccuracy and the degree of an exchange rate misalignment, is an important determinant of the efficiency of announcements and interventions on both the level and expected volatility of exchange rates. Figure 4 displays the movements of 1 month and 3 month implied volatilities and suggests that Mr. Yen conducted announced interventions when the implied volatility was high, especially in the summer of 1995 and in April and June of 1998.

6. Conclusion

This paper contributes to the existing literature on foreign exchange interventions. First, we present an alternative channel for exchange rate interventions under which announcements by the central bank can make the exchange rate more efficient through an improvement in traders' information about the exchange rate's fundamental value, even when the information disclosed by the central bank is inferior to that of traders. Second, this model provides the testable implication that announced interventions are more effective in periods of high implied volatility because the degree of information inaccuracy and the exchange rate misalignment is positively correlated with implied volatility. This prediction is borne out empirically in our findings based on Japanese and U.S. intervention data.

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Appendix

A. Proof of PROPOSITION 1

We first derive a rational expectations equilibrium with finite traders and show that the equilibrium price function converges to (6). By applying the projection theorem, we derive the distribution of y conditional on (s_i, p) which is normal with mean

$$(A1) \quad E[y|s_i, p] = \bar{y} + \alpha_s(n)(s_i - Es_i) + \alpha_p(n)(p - Ep)$$

$$= \bar{y} + (\text{cov}(y, s_i) \quad \text{cov}(y, p)) \begin{pmatrix} \text{var } s_i & \text{cov}(s_i, p) \\ \text{cov}(s_i, p) & \text{var } p \end{pmatrix}^{-1} \begin{pmatrix} s_i - Es_i \\ p - Ep \end{pmatrix},$$

and variance

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

where the variance and covariance with regards to p are derived from the conjectural exchange rate function. Since the conditional variance is constant and common for all traders, we omit indicator i for the conditional variance hereafter.

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

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

Thus, the rational expectations equilibrium is derived from the following simultaneous equations:

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

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

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

We can solve the closed form solution for the simultaneous equations by taking the ratio of β_s and β_x . A careful calculation obtains the following equation:

$$(A7) \quad \frac{\beta_s}{\beta_x} = \frac{\alpha_s(n)}{a \text{var}[y|s, p]} =$$

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

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

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

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

Using k , the equilibrium coefficients are solved explicitly.

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

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

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

Thus, the equilibrium function converges to

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

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

(A11)

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

QED

B. Proof of inequality (10)

From the equilibrium function, the variance is given as a function of underlying parameters:

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

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

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

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

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

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

$$\begin{aligned} & \text{Thus, we have } d\text{var}[p-y]/d\sigma_\varepsilon^2 \\ &= \frac{a^2\sigma_x^2\sigma_y^2}{D_1^3} [4a^4\sigma_x^4\sigma_y^2(a^2\sigma_x^2\sigma_y^2 + 2)\sigma_\varepsilon^8 + 4a^2\sigma_x^2\sigma_y^2(2a^2\sigma_x^2\sigma_y^2 + 1)\sigma_\varepsilon^6 + 6a^2\sigma_x^2\sigma_y^4\sigma_\varepsilon^4 + 2\sigma_y^4\sigma_\varepsilon^2] > 0 \end{aligned}$$

QED

C. Proof of PROPOSITION 2

Equation (13) implies

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

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

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

The sign of the derivative is determined by the sign of the term in parenthesis in (A17), which is a concave quadratic function with one positive and one negative intersections. 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

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

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

QED

D. Procedure for numerical exercises on Figure 1 and Figure 2

As we derived for the *pre-announcement* equilibrium price function in section 2.2, the post announcement price function is derived as a fixed point of the correspondence from an affine price function in the form of equation (20) to another price function satisfying the market clearing condition,

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

The rational traders use this price function and other information to derive the net demand function for the foreign currency. Investor i has four information signals s_i, s_B, p, p' , so the demand function is

$$z_i(s_i, s_B, p, p') = \frac{E[y | s_i, s_B, p, p'] - p'}{a \text{var}[y | s_i, s_B, p, p']}.$$

Before deriving conditional expectations, we should note the following fact.

Fact: Price function p' in (20) is a linear combination of s_B and price function p in (6), and

therefore either p or p' is redundant for rational investors.

Otherwise rational investors can solve three linear equations (6), (17), and (20) and pin down three unknown variables (y, ε_B, x), and therefore the price after the announcement p' must become y . Of course, the announcement of the imperfect signal, s_B , cannot clear the informational inefficiency perfectly. We have checked the redundancy for the numerically derived price functions although we use the fact without proof.

This fact allows us to ignore the pre-announcement price, p , to calculate the conditional expectations as given by

$$E[y | s_i, s_B, p, p'] = E[y | s_i, s_B, p'],$$

$$\text{var}[y | s_i, s_B, p, p'] = \text{var}[y | s_i, s_B, p'].$$

Still the conditional expectations have three signals as conditions. To simplify the calculations, we introduce the sufficient statistic of the first two signals, s_i and s_B . Let w_i be the sufficient statistic, then it is given as

$$w_i = \frac{\tau_s s_i + \tau_B s_B}{\tau_s + \tau_B} = y + \frac{\tau_s \varepsilon_i + \tau_B \varepsilon_B}{\tau_s + \tau_B},$$

where

$$\tau_s = \frac{1}{\text{var}(\varepsilon_i)} = \sigma_\varepsilon^{-2} \quad \text{and} \quad \tau_B = \frac{1}{\text{var}(\varepsilon_B)} = \theta^{-1} \sigma_\varepsilon^{-2}.$$

τ_s and τ_B are the precision of the signals, showing how reliable the signals are. Being the sufficient statistic implies the following equivalences:

$$E[y | s_i, s_B, p'] = E[y | w_i, p'],$$

$$\text{var}[y | w_i, p'] = \text{var}[y | w_i, p'].$$

That is, in order to derive the conditional expectations it is sufficient to know w_i , and the weighted averages of s_i and s_B . You do not need each value of s_i and s_B . It is worth noting that the weights of s_i and s_B are their precisions. A more precise signal has a greater impact on the conditional expectations.

Now conditional expectations have just two signals as conditions, and we can apply the projection theorem that we used in the proof of proposition 1. Thus, we have

$$\begin{aligned} E[y | s_i, s_B, p, p'] &= E[y | w_i, p'] \\ &= \bar{y} + \begin{pmatrix} \text{cov}(y, w_i) & \text{cov}(y, p') \end{pmatrix} \begin{pmatrix} \text{var } w_i & \text{cov}(w_i, p') \\ \text{cov}(w_i, p') & \text{var } p' \end{pmatrix}^{-1} \begin{pmatrix} w_i - Ew_i \\ p' - Ep' \end{pmatrix} \\ &= \bar{y} + \lambda_w (w_i - Ew_i) + \lambda_{p'} (p' - Ep') \end{aligned}$$

$$\text{var}[y | s_i, s_B, p, p'] = \text{var}[y | w_i, p']$$

$$= \sigma_y^2 - \begin{pmatrix} \text{cov}(y, w_i) & \text{cov}(y, p') \end{pmatrix} \begin{pmatrix} \text{var } w_i & \text{cov}(w_i, p') \\ \text{cov}(w_i, p') & \text{var } p' \end{pmatrix}^{-1} \begin{pmatrix} \text{cov}(y, w_i) \\ \text{cov}(y, p') \end{pmatrix}.$$

The expected values, variances, and co-variances are

$$Ew_i = Ep' = \bar{y},$$

$$\text{var } w_i = \sigma_y^2 + \frac{1}{\tau_s + \tau_B},$$

$$\text{var } p' = \gamma_y^2 \sigma_y^2 + \gamma_B^2 \sigma_B^2 + \gamma_x^2 \sigma_x^2,$$

$$\text{cov}(w_i, p') = \gamma_y \sigma_y^2 + \frac{\gamma_B}{\tau_i + \tau_B},$$

$$\text{cov}(y, w_i) = \sigma_y^2, \text{ and}$$

$$\text{cov}(y, p') = \gamma_y \sigma_y^2.$$

Putting these into the demand function, we get the demand function as a linear function of w_i and p' . Substituting the linear demand function into the market clearing condition and take the limit of n going to infinity, we have another price function in the form of equation (20).

The rational expectations equilibrium requires that the derived price function be equivalent to the original price function (20). Since the price function is specified by the confidents $(\gamma_y, \gamma_B, \gamma_x)$, we need to find the fixed point of the correspondence from the coefficients of equation (20) to the coefficients of the derived price function.

Since it is too difficult to derive the fixed point coefficients analytically, we use a simple numerical procedure. In the numerical procedure to find the fixed point, we have to give values of parameters. For given parameter values, we start from an arbitrary set of positive coefficients $(\gamma_{y0}, \gamma_{B0}, \gamma_{x0})$, and then derive the coefficients $(\gamma_{y1}, \gamma_{B1}, \gamma_{x1})$ of the market clearing price function. If $(\gamma_{y1}, \gamma_{B1}, \gamma_{x1})$ are incidentally equal to $(\gamma_{y0}, \gamma_{B0}, \gamma_{x0})$, this is the set of parameters we are looking for. If not, we feed back the derived coefficients $(\gamma_{y1}, \gamma_{B1}, \gamma_{x1})$ as an input of the correspondence, and derive new coefficients $(\gamma_{y2}, \gamma_{B2}, \gamma_{x2})$. If $(\gamma_{y2}, \gamma_{B2}, \gamma_{x2})$ are incidentally equal to $(\gamma_{y1}, \gamma_{B1}, \gamma_{x1})$, this is the set of parameters we are looking for. If not, we repeat the process until we reach to the fixed correspondence.

In Fig. 1, we fix four parameters as $\sigma_y^2 = 5$, $\sigma_\varepsilon^2 = 3$, $\sigma_x^2 = 5$, $a=1$ and take different values for θ . For each value of θ , we first derive the equilibrium price function. Then, using that function we calculate

$$\text{var}[p' - y] = (1 - \gamma_y^*)^2 \sigma_y^2 + \gamma_B^{*2} \theta \sigma_\varepsilon^2 + \gamma_x^{*2} \sigma_x^2$$

for each value of θ .

In Fig. 2, we fix three parameters as $\sigma_y^2 = 5$, $\sigma_x^2 = 5$, $a=1$, and give different values for θ and σ_ε^2 . For each pair of θ and σ_ε^2 , we first derive the equilibrium price function. Then, using that function we calculate

$$E[H(s_1, \dots, s_M, s_B, q)] = \frac{(M-1)}{M} \left(\frac{\lambda_w \cdot \tau_s}{\tau_s + \tau_B} \right)^2 \sigma_\varepsilon^2 \approx \left(\frac{\lambda_w \cdot \tau_s}{\tau_s + \tau_B} \right)^2 \sigma_\varepsilon^2$$

when M is large.

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Table 1. Intervention policy in Japan and the U.S.

| Period | JP Interventions | | | | US Interventions | | | |
|---|-------------------------|-------------------------|--|----------------------|-------------------------|-------------------------|--|----------------------|
| | Total intervention days | Announced interventions | Unannounced but reported interventions | Secret interventions | Total intervention days | Announced interventions | Unannounced but reported interventions | Secret interventions |
| <Full sample period : 3430 days> | | | | | | | | |
| 5/13/1991-7/2/2004 | 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 (unit: 100 million yen for JP int. and 1million dollars for US int.) | 1991 | 4225 | 1735 | 1573 | 358 | 398 | 318 | 0 |
| <Period 1 : 1072 days> | | | | | | | | |
| 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 (unit: 100 million yen for JP int. and 1million dollars for US int.) | 470 | 642 | 514 | 281 | 328 | 344 | 318 | 0 |
| <Period 2 : 1056 days> | | | | | | | | |
| 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 (unit: 100 million yen for JP int. and 1million dollars for US int.) | 5105 | 4598 | 6025 | 683 | 492 | 492 | 0 | 0 |
| <Period 3 : 918 days> | | | | | | | | |
| 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 (unit: 100 million yen for JP int. and 1million dollars for US int.) | 5282 | 5282 | 0 | 0 | 0 | 0 | 0 | 0 |
| <Period 4 : 384 days> | | | | | | | | |
| 1/14/2003-7/2/2004 | 129 | 1 | 32 | 96 | 0 | 0 | 0 | 0 |
| | | 0.8% | 24.8% | 74.4% | | | | |
| Average volume of interventions per day (unit: 100 million yen for JP int. and 1million dollars for US int.) | 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 2. GARCH estimation with intervention dummies

| | Full sample period | Period 1 (Pre- Sakakibara) | Period 2 (Sakakibara) | Period 3 (Kuroda) | Period 4 (Mizoguchi) |
|---|-----------------------|-------------------------------|--------------------------|-----------------------|-------------------------|
| Mean Equation | | | | | |
| Constant | -0.036 ** (0.016) | -0.036 * (0.021) | -0.201 (0.299) | -0.039 (0.049) | -0.332 (0.254) |
| Interest rate differential | -0.011 *** (0.004) | -0.012 (0.010) | -0.051 (0.061) | -0.009 (0.011) | -0.266 (0.231) |
| JP intervention volume | 0.059 *** (0.011) | -0.363 *** (0.080) | 0.084 * (0.045) | 0.057 (0.035) | 0.030 *** (0.011) |
| US intervention volume | 0.404 (0.566) | -1.081 ** (0.491) | 4.221 (5.784) | - - | - - |
| JP announced intervention dummy | 0.185 * (0.099) | 0.914 (0.584) | 0.803 ** (0.351) | 0.023 (0.237) | 0.174 (3.894) |
| JP unannounced but reported int. dummy | -0.201 *** (0.051) | -0.103 ** (0.042) | -0.246 (0.302) | - - | -0.015 (0.114) |
| JP secret intervention dummy | -0.149 ** (0.062) | -0.037 (0.115) | 0.382 (0.511) | - - | -0.094 (0.063) |
| US announced intervention dummy | 0.717 ** (0.340) | -0.249 (0.703) | 0.038 (2.102) | - - | - - |
| US unannounced but reported int. dummy | 0.751 *** (0.197) | 1.214 *** (0.166) | - - | - - | - - |
| Variance Equation | | | | | |
| Constant | 0.006 ** (0.003) | 0.258 *** (0.040) | 0.339 *** (0.034) | 0.435 ** (0.195) | 0.088 *** (0.031) |
| Arch(-1) | 0.032 *** (0.003) | 0.007 ** (0.003) | 0.059 *** (0.007) | 0.008 *** (0.003) | 0.181 *** (0.051) |
| Garch (-1) | 0.953 *** (0.005) | 0.983 *** (0.003) | 0.939 *** (0.007) | 0.912 *** (0.003) | 0.574 *** (0.100) |
| Holiday | 0.007 (0.009) | 0.003 *** (0.001) | 0.014 *** (0.004) | 0.001 (0.001) | 0.039 (0.035) |
| JP intervention volume | 0.001 (0.002) | 0.021 (0.014) | -0.031 ** (0.013) | -0.021 *** (0.006) | -0.011 *** (0.004) |
| US intervention volume | 0.346 * (0.198) | 0.373 *** (0.090) | -0.354 (1.230) | - - | - - |
| JP announced intervention dummy | -0.017 (0.016) | -0.130 (0.112) | 0.471 * (0.260) | 0.104 *** (0.031) | -0.045 (0.947) |
| JP unannounced but reported int. dummy | -0.034 *** (0.006) | -0.031 *** (0.007) | 0.056 (0.048) | - - | 0.088 (0.062) |
| JP secret intervention dummy | 0.004 (0.005) | 0.014 (0.012) | -0.110 *** (0.023) | - - | -0.049 ** (0.021) |
| US announced intervention dummy | 0.044 (0.084) | 0.137 (0.156) | 0.078 (0.558) | - - | - - |
| US unannounced but reported int. dummy | 0.286 *** (0.079) | -0.015 (0.038) | - - | - - | - - |
| Obs. | 3430 | 1072 | 1056 | 918 | 384 |
| Log Likelihood | -3453.09 | -1027.8 | -1146.3 | -896.061 | -305.017 |

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

Table 3. GARCH estimation with intervention dummies and implied volatility

| | Full sample period | Period 1 (Pre-Sakakibara) | Period 2 (Sakakibara) | Period 3 (Kuroda) | Period 4 (Mizoguchi) |
|--|-----------------------|---------------------------|-----------------------|-------------------|-----------------------|
| Mean Equation | | | | | |
| Constant | -0.025 (0.050) | -0.253 ** (0.122) | -0.190 (0.308) | -0.014 (0.110) | -0.321 (0.358) |
| Interest rate differential | -0.010 ** (0.005) | 0.001 (0.012) | -0.060 (0.061) | -0.008 (0.012) | -0.330 (0.234) |
| JP intervention volume | -0.034 (0.052) | 0.048 (0.576) | -0.116 (0.345) | -0.146 (0.346) | -0.083 (0.233) |
| US intervention volume | -0.112 (0.428) | -0.755 (0.523) | -1.036 (5.025) | - | - |
| JP announced intervention dummy | -1.570 *** (0.510) | -1.595 (2.911) | -5.185 ** (2.298) | 0.621 (2.196) | -0.185 (5.220) |
| JP unannounced but reported int. dummy | -0.089 (0.219) | -0.145 (0.359) | -1.263 (2.285) | - | 0.649 (1.023) |
| JP secret intervention dummy | -0.006 (0.369) | 0.134 (0.684) | -8.884 (148.348) | - | 0.372 (0.707) |
| US announced intervention dummy | 0.968 *** (0.263) | 0.067 (1.281) | 2.212 (1.782) | - | - |
| US unannounced but reported int. dummy | 0.946 *** (0.138) | 1.294 *** (0.161) | - | - | - |
| IV(-1, 1m) | 0.000 (0.005) | 0.024 * (0.013) | -0.004 (0.006) | -0.002 (0.011) | -0.009 (0.024) |
| JP int. volume × IV(-1, 1m) | 0.009 ** (0.005) | -0.032 (0.043) | 0.016 (0.027) | 0.016 (0.028) | 0.014 (0.025) |
| JP announced int. × IV(-1, 1m) | 0.138 *** (0.040) | 0.168 (0.208) | 0.497 *** (0.170) | -0.042 (0.176) | - |
| JP unannounced int. × IV(-1, 1m) | -0.014 (0.019) | -0.003 (0.029) | 0.081 (0.170) | - | -0.078 (0.113) |
| JP secret int. × IV(-1, 1m) | -0.015 (0.039) | -0.021 (0.064) | 0.708 (11.136) | - | -0.054 (0.076) |
| Obs. | 3429 | 1071 | 1056 | 918 | 384 |
| Log likelihood | -3467.9 | -1058.1 | -1149.57 | -897.937 | -312.375 |
| | Full sample period | Period 1 (Pre-Sakakibara) | Period 2 (Sakakibara) | Period 3 (Kuroda) | Period 4 (Mizoguchi) |
| Mean Equation | | | | | |
| Constant | -0.038 (0.061) | -0.487 ** (0.190) | -0.097 (0.318) | -0.036 (0.141) | -0.325 (0.443) |
| Interest rate differential | -0.010 * (0.005) | 0.011 (0.013) | -0.045 (0.062) | -0.006 (0.013) | -0.336 (0.235) |
| JP intervention volume | -0.036 (0.061) | -0.224 (0.751) | 0.226 (0.526) | -0.196 (0.350) | -0.114 (0.313) |
| US intervention volume | -0.178 (0.419) | -0.707 (0.497) | -0.070 (15.587) | - | - |
| JP announced intervention dummy | -2.355 *** (0.593) | -2.187 (3.716) | -7.808 ** (3.480) | 0.502 (2.318) | -0.069 (15925.990) |
| JP unannounced but reported int. dummy | -0.010 (0.296) | 0.126 (0.499) | -4.814 (3.938) | - | 1.141 (1.482) |
| JP secret intervention dummy | -0.015 (0.423) | 0.468 (0.979) | -7.550 (95.031) | - | 0.631 (1.006) |
| US announced intervention dummy | 0.893 *** (0.268) | 0.076 (1.299) | 1.521 (4.974) | - | - |
| US unannounced but reported int. dummy | 0.968 *** (0.137) | 1.302 *** (0.159) | - | - | - |
| IV(-1, 3m) | 0.001 (0.006) | 0.047 ** (0.019) | -0.005 (0.007) | 0.001 (0.015) | -0.009 (0.036) |
| JP int. volume × IV(-1, 3m) | 0.010 * (0.006) | -0.012 (0.059) | -0.011 (0.041) | 0.020 (0.029) | 0.017 (0.034) |
| JP announced int. × IV(-1, 3m) | 0.208 *** (0.048) | 0.217 (0.279) | 0.691 *** (0.260) | -0.032 (0.193) | - |
| JP unannounced int. × IV(-1, 3m) | -0.021 (0.027) | -0.027 (0.042) | 0.596 (7.046) | - | -0.130 (0.167) |
| JP secret int. × IV(-1, 3m) | -0.014 (0.044) | -0.053 (0.091) | 0.000 (0.000) | - | -0.082 (0.109) |
| Obs. | 3429 | 1071 | 1056 | 918 | 384 |
| Log likelihood | -3464.43 | -1056.79 | -1151.71 | -897.325 | -312.332 |

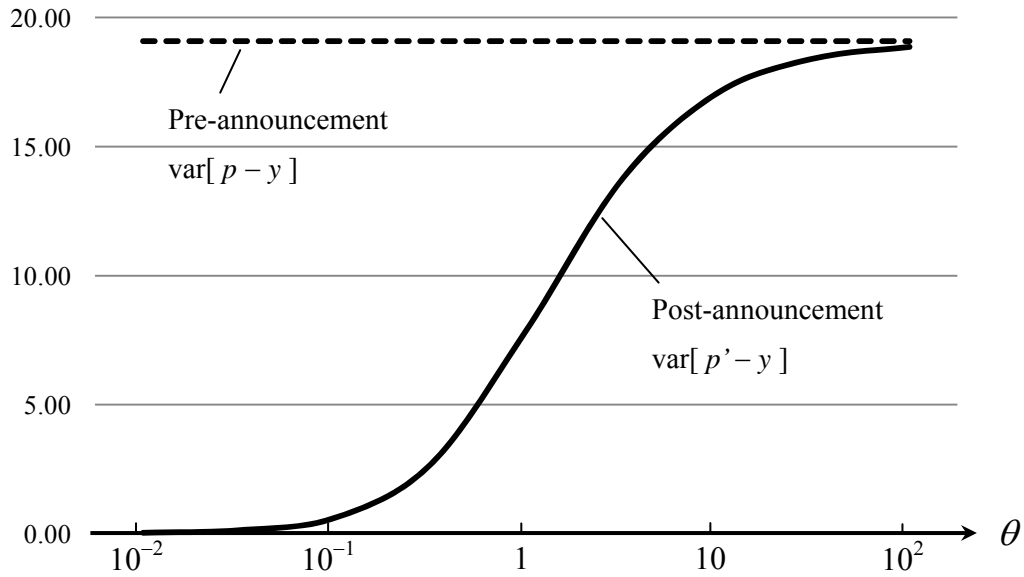
Standard errors are in parenthesis. *, ** and *** denote statistical significance at the 10%, 5% and 1% levels, respectively. There were no US interventions in Periods 3 and 4. The scales are 100 million yen for JP interventions and 1 million dollars for US interventions. The implied volatility is calculated from the yen/dollar option price (at the money).

Table 4. Implied volatility estimation with intervention dummies

| % change in IV(1m) | Full sample period | Period 1 (Pre-Sakakibara) | Period 2 (Sakakibara) | Period 3 (Kuroda) | Period 4 (Mizoguchi) |
|--|-----------------------|---------------------------|-----------------------|-----------------------|----------------------|
| Constant | 1.597 *** (0.587) | 2.726 *** (0.891) | 1.506 (1.029) | 3.415 *** (1.020) | 5.399 (3.304) |
| IV(-1, 1m) | -0.196 *** (0.054) | -0.349 *** (0.089) | 1.120 *** (0.406) | -0.361 *** (0.096) | -0.616 * (0.344) |
| Holiday | 1.704 *** (0.220) | 2.109 *** (0.434) | 1.120 *** (0.406) | 1.598 *** (0.348) | 2.436 *** (0.668) |
| JP intervention volume | -1.224 ** (0.530) | 19.277 ** (7.870) | -1.075 (2.356) | 1.836 (2.019) | -0.637 (1.465) |
| US intervention volume (-1) | -5.274 (7.599) | -8.062 (7.069) | -23.428 (20.235) | - | - |
| JP announced intervention dummy | 18.282 *** (6.020) | 10.284 (9.785) | 15.700 (13.302) | -1.284 (12.546) | 7.667 ** (3.474) |
| JP unannounced but reported int. dummy | 6.207 ** (2.497) | -2.421 (4.575) | 12.690 (14.053) | - | 0.381 (7.621) |
| JP secret intervention dummy | 1.792 (2.134) | -1.519 (3.958) | 19.770 *** (2.578) | - | 4.333 (5.600) |
| US announced intervention dummy | 7.572 (4.951) | 4.119 (3.224) | 24.375 * (13.173) | - | - |
| US unannounced but reported int. dummy | 7.782 * (4.104) | 6.950 * (3.963) | - | - | - |
| JP int. volume × IV(-1, 1m) | 0.134 *** (0.047) | -1.207 ** (0.581) | 0.111 (0.180) | -0.057 (0.161) | 0.075 (0.153) |
| JP announced int. × IV(-1, 1m) | -1.307 *** (0.479) | -0.745 (0.824) | -1.172 (0.922) | 0.035 (1.009) | - |
| JP unannounced int. × IV(-1, 1m) | -0.437 ** (0.214) | 0.203 (0.367) | -0.825 (1.117) | - | -0.024 (0.764) |
| JP secret int. × IV(-1, 1m) | -0.209 (0.210) | 0.094 (0.333) | -1.196 *** (0.200) | - | -0.571 (0.601) |
| Obs. | 3429 | 1071 | 1056 | 918 | 384 |
| Adj. R ² | 0.058 | 0.087 | 0.046 | 0.087 | 0.085 |
| % change in IV(3m) | Full sample period | Period 1 (Pre-Sakakibara) | Period 2 (Sakakibara) | Period 3 (Kuroda) | Period 4 (Mizoguchi) |
| Constant | 0.961 ** (0.388) | 1.827 *** (0.708) | 0.952 (0.687) | 2.366 *** (0.777) | 5.030 * (2.588) |
| IV(-1, 3m) | -0.106 *** (0.035) | -0.213 *** (0.070) | -0.089 (0.055) | -0.229 *** (0.072) | -0.547 ** (0.275) |
| Holiday | 0.609 *** (0.136) | 0.979 *** (0.238) | 0.381 (0.262) | 0.431 * (0.245) | 0.647 (0.405) |
| JP intervention volume | -0.792 ** (0.372) | 12.435 * (6.532) | -1.962 (1.653) | 0.201 (0.878) | -0.459 (1.450) |
| US intervention volume (-1) | -3.515 (3.913) | -4.764 (3.188) | -15.780 (14.462) | - | - |
| JP announced intervention dummy | 8.993 ** (4.378) | 7.519 (7.794) | 20.546 * (11.450) | -3.272 (8.173) | 5.576 ** (2.382) |
| JP unannounced but reported int. dummy | 3.305 * (1.749) | -2.316 (3.431) | 15.040 (9.861) | - | -0.602 (7.314) |
| JP secret intervention dummy | 1.135 (1.730) | -1.476 (3.302) | 6.065 *** (1.782) | - | 2.671 (4.478) |
| US announced int. dummy (-1) | 4.298 (2.947) | 1.975 (1.580) | 15.169 (9.866) | - | - |
| US unannounced but reported int. dum. (-1) | 3.838 * (2.028) | 3.321 * (1.739) | - | - | - |
| JP int. volume × IV(-1, 3m) | 0.082 ** (0.033) | -0.849 (0.522) | 0.158 (0.125) | 0.027 (0.065) | 0.050 (0.157) |
| JP announced int. × IV(-1, 3m) | -0.629 * (0.367) | -0.572 (0.677) | -1.548 * (0.811) | 0.313 (0.645) | - |
| JP unannounced int. × IV(-1, 3m) | -0.228 (0.156) | 0.206 (0.289) | -1.043 (0.775) | - | 0.077 (0.783) |
| JP secret int. × IV(-1, 3m) | -0.124 (0.176) | 0.088 (0.302) | -0.276 ** (0.136) | - | -0.330 (0.484) |
| Obs. | 3429 | 1071 | 1056 | 918 | 384 |
| Adj. R ² | 0.030 | 0.065 | 0.025 | 0.048 | 0.028 |

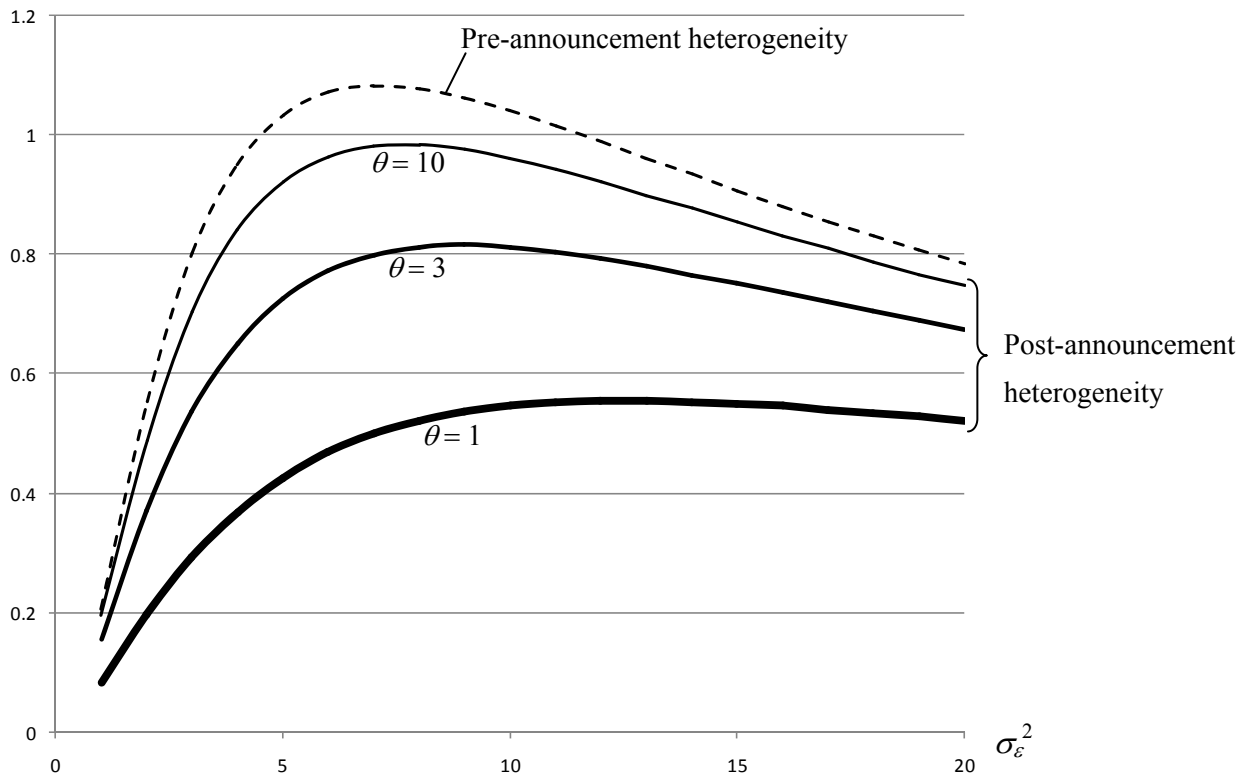
Standard errors are in parenthesis. *, ** and *** denote statistical significance at the 10%, 5% and 1% levels, respectively. There were no US interventions in Periods 3 and 4. The scales are 100 million yen for JP interventions and million dollars for US interventions. The implied volatility is calculated from the yen/dollar option price (at the money).

Figure 1. The effect of an announcement on the variance of a bubble.



The graph is drawn for the following parameters. $\sigma_y^2 = 5$, $\sigma_\varepsilon^2 = 3$, $\sigma_x^2 = 5$, $a = 1$.

Figure 2. The effect of an announcement on the heterogeneity of forecasts.



The graph is drawn for the following parameters. $\sigma_y^2 = 5$, $\sigma_x^2 = 5$, $a = 1$.

Figure 3. Japanese interventions and yen/dollar rate

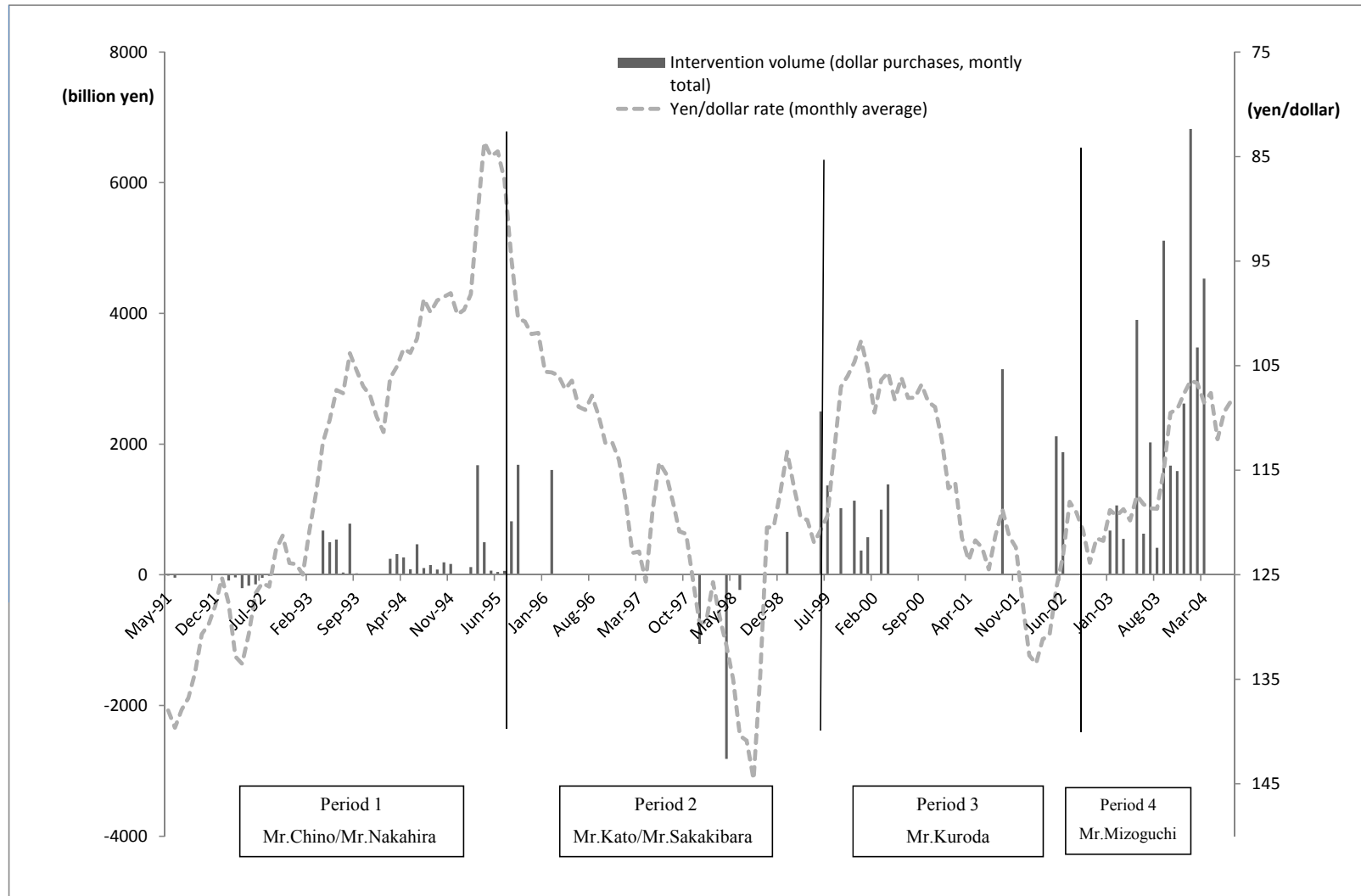


Figure 4. Implied volatility

