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Intraday evidence of efficacy of 1991-2004 Yen intervention by the Bank of Japan*

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Abstract:

This paper investigates the intraday efficacy of Yen intervention conducted by the Bank of Japan. Segmenting a 24 hour calendar day into three business hours – onshore and two offshore hours – I examine both contemporaneous and *ex post* intervention effects on the Yen/USD exchange rate. Prior to June 1995, intervention moved the exchange rate in the wrong direction and the level of volatility is significantly raised during Tokyo business hours. This is due to the well-known simultaneity bias. However, during the first overnight hours (London business hours) the simultaneity bias is significantly reduced and by the second overnight hours (New York afternoon hours) intervention successfully reversed the exchange rate trends and reduced the volatility. Post June 1995, intervention had an immediate effect of reversing the exchange rate trend and it remained effective, although at reduced magnitude, throughout overnight horizons. A volatility reducing effect is significant from the first overnight horizon and its effectiveness rises in the second overnight horizon.

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1. Introduction

The paper examines the relationship between intraday exchange rate movements and the Bank of Japan's (BOJ) interventions in the Yen/USD spot market. The BOJ has been one of the most active central banks in the foreign exchange market in the last fifteen years. It has the distinction of having made perhaps the biggest ever intervention in a day (USD20.3 billion sales on April 10 1998), when all East Asian currencies were depreciating, and Japan, on the brink of a full scale financial crisis, was proposing a massive fiscal expansion package. Since then the continued USD purchase interventions led to the BOJ accumulating USD 653 billion of foreign exchange reserves by the end of 2003, which represented almost 22% of all official reserves held globally. US FED, the other contributor in the Yen intervention scene, however, has been abstaining from the market since its last Yen purchase on 17 June 1998.

Until the release of historical intervention data by the Japanese Ministry of Finance in July 2001, researchers had to rely on secondary and often inaccurate sources of data such as press reports (Chang and Taylor, 1998; Frenkel, Pierdzioch and Stadtmann, 2004a). Since the release, a long list of researchers has investigated various aspects of the BOJ interventions. This literature has tested the effectiveness of intervention by determining whether the level and volatility of exchange rate returns are affected in the desired direction, or if prominent trends are reduced (Chabound and Humpage, 2003; Fatum and Hutchison, 2003; Beine, 2004; Nagayasu, 2004b; Frenkel, Pierdzioch and Stadtmann, 2005). A common finding is that the BOJ's intervention was able to influence the Yen only after 1995, especially when the interventions were coordinated with the US FED. However, pre-1995 period shows a somewhat disappointing pattern of a Yen purchase (sale) being associated with a Yen depreciation (appreciation) which might lead to an erroneous conclusion of intervention ineffectiveness. In addition, some researchers report a positive association between Yen intervention and Yen/USD volatility (Beine, 2004; Nagayasu, 2004a; Frenkel et al., 2005) and most claim the causal direction runs from intervention to volatility. The literature has also tested for possible determinants of central bank responses to exchange rate returns (Ito, 2002; Beine and Bernal, 2004; Frenkel, Pierdzioch and Stadtmann, 2004b; Ito and Yabu, 2004), and various definitions of exchange rate trend deviations were found to be useful in explaining BOJ's interventions.

The intervention literature, including Yen interventions, produced an overwhelming empirical conclusion that intervention moves the target exchange rate in the wrong direction and fuels volatility. This is mostly due to a simultaneity problem, which arises because of endogeneity of intervention and market conditions. The majority of the studies simply ignore the problem, whilst proposed solutions have made little leeway into distilling the precise *ex post* volatility effects of intervention from the *ex ante* volatility that motivates intervention. Neely (2005a) provides a thorough survey of the issue of simultaneity in the recent literature and discusses the shortfalls of various proposed solutions to the issue.

The central contribution of this paper is to employ an innovative approach to addressing the simultaneity problem and investigate intraday patterns of intervention effectiveness applied to the BOJ's intervention operations in the Yen/USD spot market for the period 13 May 1991 to 16 March 2004. Recognising the fact that currency trading occurs twenty-four hours per day, whilst intervention occurs almost exclusively within a small time range: respective business hours of various central banks (Dominguez, 2003; Neely, 2001), a 24-hour trading day is divided into three trading time horizons isolating the segment of the trading day in which intervention and market conditions are endogenous. The breakdown of returns data this way allows us to examine the immediate *ex post* volatility effects of intervention at an intraday level, despite the availability of only daily intervention data, providing parsimonious but more powerful tests of intervention efficacy than prior studies[1]. It also allows the investigation of the time path of intervention effectiveness to ascertain the potential differential speed of intervention effectiveness in the first and second moments of exchange rate changes.

The main results of this paper are summarized as follows. i) Prior to June 1995, Yen interventions moved the Yen/Dollar exchange rate in the wrong direction and the level of volatility is significantly raised during Tokyo business hours. This is due to the well-known simultaneity bias. ii) More importantly, during the first overnight horizon (London hours and New York morning business hours) the simultaneity bias is significantly reduced and by the second overnight horizon (New York afternoon hours) intervention successfully reversed the

[1] Due to unavailability of time stamped intervention data, higher frequency analysis in not an option. However, even if such data were to be made available, tick by tick analysis of intervention effectiveness would not produce meaningful results as interventions tend not to be in one transaction, rather they are spread across trading day. Further discussion is provided in section 2.

exchange rate trend and reduced the volatility. iii) Post June 1995, intervention had an immediate effect in reversing the exchange rate trend and remains effective, although at reduced magnitudes, throughout the two overnight horizons. However, intervention has a volatility reducing effect only from the first overnight horizon and its effectiveness rises in the second overnight horizon. iv) In general, intervention effect on the exchange rate trend is shown immediately during Tokyo business hours and decays or reverses through overnight hours, whereas volatility response is either small or insignificant at first and then intensifies through overnight hours. Thus, this paper provides a significant contribution to the literature by providing unambiguous evidence of BOJ's intervention effectiveness and presenting important insights into the differing speeds of exchange level and volatility responses to intervention.

The rest of the paper is organised as follows. Section 2 discusses the literature with a focus on the issue of simultaneity. Section 3 contains data description, and the modelling issues are discussed in Section 4. The estimation results and their implications are presented in Section 5. Finally, Section 6 provides conclusions.

2. Literature review – Unresolved simultaneity bias in intervention

Despite the existence of voluminous literature on the effectiveness of foreign exchange intervention, there has been much confusion regarding intervention efficacy in influencing the direction and volatility of exchange rate movements. Considering the magnitude of daily volume in the foreign exchange market - 1.9 trillion USD per day in 2004 (BIS, 2005) - successful reversal of exchange rate trends by intervention depends crucially on a number of factors (e.g. size of intervention, whether intervention is a part of a continued campaign, whether intervention is coordinated between two affected central banks, credibility of intervention, etc.). More realistically, however, trend reduction would be a more realistic aim, and if so, one would find intervention purchase (sale) being associated with currency depreciation (appreciation) during the days of intervention even if the intervention aim is met.

As for the volatility effect, intervention has the potential to either fuel or calm exchange rate volatility by either increasing or decreasing imbalances in the distribution of information, opinions, and inventories across the market microstructure. The empirical literature, in general, has been unable to determine whether or not intervention successfully breaks bandwagon effects and calms volatility in practice, due to the simultaneity problem. The primary problem with the general conclusion of the existing literature arises from the use of daily data frequencies in intervention studies (largely because intervention data are usually released in daily frequency). However, detecting high volatility on intervention days may indicate that high volatility is a motivation for, as opposed to manifestation of, intervention. Intervention authorities specify that they aim to calm disorderly market conditions, with strong empirical evidence that they do react to high volatility (Kim and Sheen, 2002, for the Reserve Bank of Australia; and Dominguez and Frankel, 1993; Almekinders and Eijffinger, 1996; Baillie and Osterberg, 1997b; and Dominguez, 1998 for the US FED). Thus, the direction of causality between intervention and volatility is ambiguous at daily frequency. This problem is overwhelmingly ignored by the empirical literature, which assumes that the decision to intervene is made exogenously, without considering prevailing market conditions. Kearns and Rigobon (2005) describe this as the "critical barrier" to distilling the true efficacy of intervention.

The majority of the literature concludes, mostly with GARCH methodologies, that intervention fuels rather than calms volatility and moves exchange rates in the opposite direction to what is desired on the days of intervention. These include Connolly and Taylor (1994), Baillie and Osterberg (1997a, 1997b), Chang and Taylor (1998), Dominguez (1998), Baillie *et al* (1999), Doroodian and Caporale (2001), and Hillebrand and Schnabl (2003). Other studies have come to similar conclusions using other methodologies, such as the volatility implied in option prices (Bonser-Neal and Tanner, 1996; Dominguez, 1998; Galati and Melick, 1999). Neely (2005a) provides an excellent survey of most of these studies. The vast majority of the above literature pertains to the US Federal Reserve, the Bank of Japan and the Bundesbank interventions.

There are essentially two approaches in handling the simultaneity issue, modeling approach and data approach. The former aims to address the simultaneity by devising econometric models that avoid the endogeneity of intervention variables when modeling the intervention effects on exchange rates. This might be accomplished by utilizing instrument variables that are highly correlated with interventions but not correlated with exchange rate movements. If such instruments can be found, one might carry out an instrumental variable estimation on the first and second moments of exchange rate changes on the days of intervention. Alternatively, exchange rate changes and interventions can be jointly modelled as a part of systems estimation. However, parametric representation of such a system is very difficult, if not impossible, because of the non-standard nature of the distribution of the intervention variable. The intervention variable has three distinct types of observations, positive and negative values and zeroes, and so it would be appropriate to treat the intervention variable to have been generated from a mixture of three distributions rather than one continuous distribution. This makes it very difficult to jointly model intervention with exchange rate changes, which have a continuous distribution.[2] Kearns and Rigobon (2005) make a contribution in this regard. They estimated a simulated GMM model of the mean equations of intervention reaction function and exchange rate changes. However, Neely (2005a) states that their approach might be subject to the well-known Lucas critique. Neely (2005b) instead proposes that a properly identified system of exchange rate change and intervention equations incorporating nonlinearity in the reaction function (via a friction model) supports the idea of intervention effectiveness. The development of equivalent variance equation frameworks would also be meritorious.

On the other hand, the data oriented approach mostly aims to circumvent simultaneity by examining the lagged effects of intervention, so that the decision to intervene is pre-determined. However, lagged results using daily data are usually statistically insignificant (Baillie and Osterberg, 1997a; Lewis, 1995). Daily data are of too low a frequency to effectively distil the *ex post* effects of intervention. This has led to the use of ultra-high frequency (UHF) of 5 or 10-minute quote data, particularly for the USD, the Yen and the Deutschemark. Identifying the precise time-stamp of intervention trades is vital in these studies, yet transaction data are not released by most intervention authorities.[3] The UHF literature is forced to employ a rough proxy of intervention, the time stamp of Reuters newswire reports, requiring arbitrary assumptions regarding the time lag between intervention transaction and news reports. The assumed lag varies substantially, between 10 minutes and 2 hours, introducing greater ambiguity into results.

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[2] Kim and Sheen (2002) use a friction model which specifically addresses this mixture of distributions in the intervention variable, albeit with a partial equilibrium framework, in investigating the reaction function of the RBA intervention. Ito and Yabu (2004) applied a simplified friction model to the BOJ intervention data.

[3] A recent notable exception is the release of Swiss National Bank transaction data (see Fischer and Zurlinden, 1999, Pasquariello, 2002, Payne and Vitale, 2003).

Further, Fischer (2003) finds the Reuters news reports are in fact highly “deficient in capturing the timing of intervention rounds” (p.2), leading him to directly challenge the findings of the UHF literature. In all, the inaccuracy of the Reuters reports, and the ambiguity introduced by the assumption of arbitrary time lags, leaves the UHF studies impotent to distil the *ex post* volatility effects of intervention, as there is an over-disaggregation of returns. This fact is highlighted by the conclusions of the UHF studies themselves. Peiers (1997), Chang and Taylor (1998), Dominguez (2003) all find that volatility precedes their intervention proxy, but still conclude that this volatility is caused by intervention, due to order flow learning.

In this paper, I adopt an innovative approach to isolating holding periods that are endogenous and those that are relatively free from this endogeneity.[4] Thus, this is a data oriented approach to investigating intervention effectiveness that would yield credible and important insights into the intraday intervention efficacy.

3. Data analysis

3.1. Intervention data

The BOJ intervention is measured in billions of Yen, and the data cover the period 13 May 1991 to 16 Mar 2004, containing 344 intervention transactions. A positive value indicates a purchase of USD (or sale of Yen), a negative value a sale of USD (or purchase of Yen), in line with the standard definition in the literature. Yen intervention is normally carried out by the BOJ in the Tokyo market, however, on some occasions, the US FED followed up with its own Yen intervention in the same direction during the New York business hours. There were 22 such coordinated interventions in the sample. The historical data on the BOJ and the US FED interventions in the Yen/USD market are publicly available[5]. The full sample can be split into two sub-samples to account for the two distinct phases of BOJ interventions. The emergence of Dr. Sakakibara (better known as ‘Mr. Yen’ in the Western markets) as the new Director of

[4] In a similar vein, Neely (2002) analysed intraday (over several hours) trading rule profits against central bank interventions and, in the cases of the U.S., German and Swiss cases, he reports that highest returns preceded interventions by less than 24 hours.

[5] The BOJ data are available from www.mof.go.jp/english/e1c021.htm, and the U.S. FED data is available from www.newyorkfed.org/pihome/news/forex/. The intervention statistics are released with a lag in both cases. The BOJ does not announce its interventions when they occur so the foreign exchange market participants generally find out, contemporaneously, through informal channels. However, Frenkel et al (2004a) reports that the interventions are not, in general, perceived by the public when they occur.

International Finance Bureau at the Ministry of Finance and Economics in 1995 marked a new era where interventions were less frequent but substantially larger in size. In order to account for this structural break I split the sample on 20 June 1995 (as in Ito, 2002, Ito and Yabu, 2004). Except for a handful of occasions (six) in 1997 and 1998, the BOJ sold Yen in second 2.

Table 1 reports the intervention statistics for the full and the two sub-samples. For the full sample, there were 344 BOJ interventions and most were positive (311 positives compared to 33 negatives). The widely-held belief is that the BOJ was mostly attempting to reduce the level of excess demand for Yen by these interventions. The average size of intervention is 198.5 billion Yen and it ranges from as low as 0.1 (3.2) to 1,666.4 (2,620.1) billion Yen for intervention purchases (sales) of USD. Interventions were often followed by reinforcing interventions in the same direction. Given that there was a BOJ intervention, the probability of another intervention in the same direction the following day is 0.62 The probability of a three successive interventions is 0.44. Most of the interventions were concentrated in sample 1, accounting for 166 out of 213 days. However, the size of transactions increased drastically, with the average Yen sale (purchase) increasing from Yen 50.2 (29.2) to 328 (684.4) billion in sample 2. The US FED interventions were modest in size compared to the BOJ transactions, and were designed to support the BOJ transactions initiated in the Tokyo market shortly before the New York market opening, as shown by the probability of the FED intervention being coordinated with a prior BOJ intervention being one. As with the BOJ activities, the FED interventions were concentrated in the first sample (18 out of total of 22 transactions).

3.2. Yen/USD exchange rate

The foreign exchange market is global and decentralised, trading continuously 24 hours a day. Trading of Yen occurs through the Tokyo business hours, continuing into London and then New York business hours, and then back to the Tokyo hours, and so forth. Neely (2001) and Dominguez (1998, 2003) report that central banks typically intervene within their own business hours, and Canales-Kriljenko et al (2003) prescribes that intervention should generally be conducted on-shore, as this will improve access to market intelligence. The Bank of Japan (2000) states that “Foreign exchange interventions are usually conducted in the Tokyo market.

However, as most of the trading shifts to European markets after around 5:00 pm JST and then to the New York market, in cases where it is considered necessary to intervene during these hours, the Bank of Japan, as the agent of the Minister of Finance, requests foreign monetary authorities to conduct interventions on behalf of the Bank (entrustment intervention)." Dominguez (2003) notes that "According to the Reuters times-stamp, on average….. the BOJ intervenes at 3:56:36 GMT (or around the Tokyo lunch hour), p. 29".

A 24-hour trading day is broken down into smaller, intraday horizons in order to isolate that part of the trading day in which intervention mostly occurs and is thus endogenous with exchange rate movements. Figure 1 illustrates this parsimonious isolation of the endogenous part of the trading day, showing a full 24-hour period from JST $7am_t$ to $7am_{t+1}$. The ⊗ symbol indicates the points at which Yen/USD indicative quotes are gathered. The exchange rate is collected at three points during the 24 hour period: i) Tokyo opening at 07:00 JST (GMT 22:00, t-1), ii) Tokyo closing at 17:00 JST (GMT 08:00), and iii) London closing at 17:00 GMT (02:00 JST, t+1). The two Tokyo quotes are sourced from Bloomberg and the London close rate is from Datastream. Using the three exchange rate series, the following return horizons (holding periods) are constructed:

Daily (D): Daily return measured as continuously compounded return from 7am JST at day t (22:00 GMT, t-1) to 7 am JST at day t+1, $\log(ER_{t+1}^{J-Open} / ER_t^{J-Open}) \times 100$.

IntraDaily (ID) - Tokyo business hours: Intra-daily return measured from 7am JST at day t (22:00 GMT, t-1) to 5pm JST (08:00 GMT at day t), $\log(ER_t^{J-Close} / ER_t^{J-Open}) \times 100$.

Overnight hours 1 (ON1) - GMT 08:00–17:00: First overnight return measured from 5pm JST (08:00 GMT at day t) to 5pm London close (17:00 GMT at day t), $\log(ER_t^{LD-Close} / ER_t^{J-Close}) \times 100$. This is London business hours and New York morning trading hours

Overnight hours2 (ON2) - GMT 17:00-22:00: Second overnight return measured from 5pm London close at day t (17:00 GMT at day t) to 7 am JST at day t+1, $\log(ER_{t+1}^{J-Open} / ER_t^{LD-Close}) \times 100$. This is New York afternoon trading hours.

Bank of Japan (2000) states that the BOJ and the Ministry of Finance make intervention decisions on the basis of overnight and daily exchange rate developments and so the known exchange rate just before the interventions is the Tokyo opening rate.[6] Thus, I chose the Tokyo opening rate for the exchange rate so that not only the BOJ interventions but also the US FED interventions are relevant when calculating daily returns (D). Tokyo hours (ID) suffer from

[6] This essentially is New York closing rate.

simultaneity, whilst overnight hours (London hours, ON1 and New York afternoon hours, ON2) do not. Therefore, the simultaneity bias is isolated and the *ex post* effects of intervention are investigated over the overnight horizons. This is despite the availability of only daily intervention data, and the analyses do not rely on rough proxies of intervention.

Table 2 reports the summary statistics of the exchange rate returns for the four holding periods over the three time periods – pre-1995, post-1995 and full sample. It is evident that returns are non-normal and leptokurtic. Negative skewness is observed in all cases except for the second overnight hours. It is shown that most of the daily volatility is emanating from the two overnight hours and this confirms the common finding in the literature that report higher volatility being associated with overnight asset returns compared to intraday returns. This volatility pattern may be attributable to a number of factors, such as liquidity, volume, and information arrival.[7] Most important, however, is the fact that the three horizons are of unequal length. Longer horizons allow more time for price movements, and will be typified by a wider distribution of returns. The longest horizon is overnight 1 (10 hours), followed by Tokyo hours (9 hours) and overnight 2 (5 hours). In addition, the unconditional distribution of the returns data is leptokurtic, indicating a relative abundance of extreme returns. The Jarque-Bera test statistic shows strong evidence of non-normality in all cases. Significant serial correlation is observed in the second moments in all cases except for the second overnight horizon in sample 1. In general, first moment serial correlation is not present in the returns. The observed characteristics of the return series - skewed, leptokurtic, non-normal and volatility clustering - warrants the use of a conditional heteroskedasticity model such as GARCH (see Bollerslev, Engle and Nelson, 1994).

4. Econometric methodology

To capture the intraday mean and volatility effects of intervention, an AR-log-GARCH (1,1) model is fitted to each of the three intraday as well as daily horizons.

$$s_t^h = \alpha_0 + \alpha_{h1} s_t^{h-1} + \alpha_{h2} s_t^{h-2} + \alpha_{h3} s_{t-1}^h + \alpha_{IntvBOJ} IntvBOJ_t + \alpha_{IntvFED} IntvFED_t + u_t \quad (1)$$

$$u_t = \sigma_t \varepsilon_t \qquad \varepsilon_t \sim i.i.d.(0,1)$$

$$\begin{aligned} \log(\sigma_t^h)^2 &= \beta_0 + \beta_1 \log(\sigma_{t-1}^h)^2 + \beta_{h1} \left| s_t^{h-1} \right| + \beta_{h2} \left| s_t^{h-2} \right| + \beta_\varepsilon \left| \varepsilon_{t-1} \right| \\ &+ \beta_{IntvBOJ} \left| IntvBOJ_t \right| + \beta_{IntvFED} \left| IntvFED_t \right| \end{aligned} \quad (2)$$

[7] See Harvey and Huang (1991), and Dacorogna *et al* (1993).

Where h denotes horizons (D, ID, ON1 and ON2), and t denotes calendar day. The dependent variable in (1), s_t^h, is the log holding period return of the exchange rate during horizon h on day t. Each of the three intraday horizons is modelled separately, with h being equal to ID, ON1 or ON2 to denote the horizon being modelled. u_t is the residual from the mean equation. It can be broken down into the square root of the conditional variance $(\sigma_t^h)^2$, and an *i.i.d.* noise term ε_t. The variance equation (equation 2) models the log of $(\sigma_t^h)^2$ to allow for negative coefficients.[8] The lagged return variables in the model differ depending on which of the three intraday horizons is being modelled. The variables s_t^{h-1} and s_t^{h-2} are the returns from one and two horizons prior to the horizon being modelled.[9,10] For example, for ID on day t, the two lagged intraday returns are for ON1 and ON2 on day t-1, and for ON2 on day t, ID and ON1 on day t, etc. The coefficients β_{h1}, β_{h2} and β_{ε} can be thought of as capturing autoregressive behaviour in the variance for 1, 2 and 3 lagged horizons respectively. $IntBOJ_t$ is the BOJ intervention activity on day t, defined as the magnitude of intervention (Yen '00 billions), rather than a dummy variable. Work by Doornik and Ooms (2001) demonstrates that dummy variables introduce multimodality into the GARCH likelihood function. The use of magnitudes is also consistent with the methodology of Kim and Sheen (2002). The absolute value of $IntBOJ_t$ enters the variance equation, as both buy and sell interventions are used to calm volatility. $IntvFED_t$ is the Yen intervention carried out by the US FED during New York morning hours[11] and so is contemporaneous with overnight 1 and *ex post* to overnight 2.

Except for the intervention variables, all others in the system are univariate return series variables. Controlling for intervention in the mean equation reduce the extent to which the first moment effects are captured when modelling the second moment.[12] For example, if BOJ's selling of Yen is systematically followed by a sharp Yen appreciation, but this price adjustment

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[8] This is similar to the multiplicative ARCH model of Geweke (1986) and Pantula (1986). However, I do not log the ARCH term (ε_{t-1}) since absolute, instead of squared, term is used. More importantly, log variance is used to permit negative parameters, which serve to explain a fall in the level of volatility.

[9] The model was also extended by replacing s_t^{h-1} and s_t^{h-2} with error terms (ie u_t^{h-1} and u_t^{h-2} from an equivalent GARCH model applied to two prior return horizons), purging the variables of any relationship with intervention. However, the inclusion of the error terms rather than the raw return variables made no material difference to the results, and considerably complicated the model. For brevity, I present the model using the raw returns throughout.

[10] Note that $s_t^{h-3} = s_{t-1}^h$, as there are three horizons per day.

[11] Humpage (1998) report that the FED interventions generally occurs before the close of London market.

[12] Inclusion of ε_t in the volatility equation acts to reduce the extent of the first moment effects. However, the lagged exchange rate change terms would still influence the volatility.

occurs efficiently with no price instability, then this is not genuine volatility. Crude volatility measures, as employed by Edison *et al* (2003), and most UHF studies, do capture orderly first moment effects in the second moment. GARCH simultaneously models the first and second moments, so orderly movements in the price level are captured by the mean equation, and only genuine volatility is captured by the variance.

The primary focus of this study is on $\alpha_{IntvBOJ}$ and $\beta_{IntvBOJ}$ – the relationship between the exchange rate return and volatility with the BOJ intervention. If intervention were of leaning against the wind (LATW) variety, one expects a Yen appreciation (depreciation) and a fall in volatility following a Yen purchase (sale). This requires a positive intervention coefficient for the conditional mean equation and a negative coefficient for the volatility equation. However, since the BOJ intervention was mostly concentrated during Tokyo hours, the intervention effect measured over Tokyo hours is expected to suffer from the simultaneity problem, as the BOJ will tend to buy Yen (sell the USD) in a down trending market, and sell in an up-trending market. *A priori*, $\alpha_{IntvBOJ}$ is expected to be negative as a result in Tokyo hours on the day of intervention, indicating Yen is moving in the 'wrong' direction to that desired (in line with the finding in the literature, see Dominguez and Frankel, 1993, Baillie and Osterberg, 1997a).[13] A positive coefficient in subsequent overnight horizons will indicate that intervention has broken the bandwagon, and 'corrected' the exchange rate movements. As for the Yen volatility, $\beta_{IntvBOJ}$ is expected to be positive in Tokyo hours of the day of intervention, due to simultaneity. During overnight hours, a negative coefficient is expected if intervention successfully calms volatility.

5. Empirical results

The model shown in (1) and (2) are estimated via Quasi-Maximum Likelihood Estimation method and the results are reported in Table 3. The preliminary aspects of these results are provided before assessing the intervention coefficients. The daily autocorrelation coefficient, α_{h3}, is generally positive and significant in the two overnight hours (ON1 and ON2) in sample 2 and daily (D) and Tokyo hours (ID) in full sample. There is evidence of negative intraday autocorrelation in the mean equation for the three intraday horizons (ID, ON1 and

[13] For comprehensive reviews of the theoretical and empirical literature pertaining to the direction objective of intervention, see Kim and Sheen (2002), Baillie *et al* (1999) or Sarno and Taylor (2001).

ON2) in the two subsamples, as indicated by negative α_{h1} and α_{h2}. Similar results are also reported in Bollerslev and Domowitz (1993) and Evans (2002), using UHF data, and is evidence of intra-daily seasonality in the inventory behaviour patterns of dealers. The variance process shows strong daily GARCH behaviour, except for overnight 2 in sample 1, as indicated by the significance of the relevant GARCH coefficients (β_1 and β_ε). In many cases the variance also has intraday autoregressive behaviour as shown by the significant β_{h1} and β_{h2}, indicating volatility persistence both on daily and intraday level. The diagnostic tests indicate that there are serial correlations still remaining in mostly overnight 2 estimations. Inclusion of additional GARCH lags in the model largely addressed this issue without materially altering the key coefficients of interest. Interested readers can obtain alternative estimations upon request.

5.1. Intraday responses to intervention

The intervention coefficients reported in Table 3 are graphically summarized in Figure 2 where plots of the coefficients are presented in a chronological order for the three intraday horizons on the days of intervention. The first column shows the intervention effects on the mean of the exchange rate changes and the second shows the volatility responses.

5.1.1. Sample 1: 13 May 1991 to 20 Jun 1995

In sample 1, the BOJ intervention coefficient in the mean equation, $\alpha_{IntvBOJ}$, is significant and negative during Tokyo hours indicating a Yen appreciation (depreciation) at the time of BOJ's selling (buying) of Yen. Yen moved in the 'wrong' direction, as expected, and this reflects simultaneity and does not necessarily imply a causal relationship. On average, an intervention transaction of 100 billion Yen moved the exchange rate by 0.32% in the wrong direction during Tokyo hours on intervention days. During the first overnight horizon, however, the intervention coefficient is reduced to near zero (-0.0103) and insignificant before turning positive (0.0128) and significant (at 5%) during the second overnight horizon. Thus, intervention starts to have the desirable effect of reversing the exchange rate trend from the second overnight horizon (New York afternoon hours). The intervention influence on the conditional volatility is also showing a sign of simultaneity bias during Tokyo hours. A positive (0.3224) and significant intervention coefficient, $\beta_{IntvBOJ}$, suggests a positive correlation between volatility and intervention. Due to simultaneity, it is difficult to distinguish whether volatility has motivated intervention, or if intervention has fuelled volatility by creating imbalances in the distribution of information, opinions or inventory. More importantly, the simultaneity influence is reduced in magnitude (however, it is still positive (0.0621) and significant) during overnight 1 and it becomes negative and significant (-1.0915) during overnight 2. Thus, the strong simultaneity bias present in Tokyo hours is eliminated and the interventions show desirable trend correcting and volatility calming influences during New York afternoon hours.

There are three possible interpretations of the high, then low volatility that follows intervention. These explanations are not exclusive and may occur together. First, the high volatility that prompts the BOJ to enter the market is not reined in immediately. Interventions take a while to reduce imbalances in information and inventories in the market. The fact that interventions do not immediately break bandwagons suggests this may be the case. Second, interventions temporarily disturb the market, fuelling volatility before a second effect comes into play and then calm volatility. This is consistent with the dynamics of information flow. Interventions signal information that provides a valuation landmark, reducing uncertainty and volatility. However, the disaggregated nature of the foreign exchange markets means that this intervention information signal reaches different traders at different times, temporarily widening information asymmetries and fuelling volatility. As the signal filters through the market, information homogenises and volatility falls.[14] Third, Hung (1997)'s noise trading channel of influence might be at work. Essentially, the BOJ could have aimed to stimulate volatility by a way of secret intervention so as to elevate the level of uncertainly and help break bandwagon effects. Frenkel et al (2004a)'s reporting that a significant portion of BOJ interventions were not perceived by the market lends support to this explanation.

Combining the mean and the volatility responses to the BOJ intervention, it can be surmised that the simultaneity bias that is present during Tokyo business hours evaporates and intervention starts to have desirable effect during New York afternoon hours.

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[14] Central banks differ in the degree of secrecy that envelops their intervention activities. For example, the Swiss National Bank always publicly announces intervention operations, and this allows one to investigate the hypotheses that differentiate between public and private interventions. In this vein, Frenkel et al (2005) report that those BOJ interventions that were not reported in the financial press were positively correlated with the Yen/USD volatility. Beine and Bernal (2004) suggest that the BOJ used secret interventions when aiming to influence Yen/USD values.

5.1.2. Sample 2: 21 Jun 1995 to 16 Mar 2004

The post-1995 period is characterised by larger and infrequent interventions which marks a clear departure from the pre-1995 period. The middle section of Table 3 shows the estimation results. The graphical summary of the intervention coefficients are shown in Panel B of Figure 2. The BOJ intervention coefficient in the conditional mean equation, $\alpha_{IntvBOJ}$, is now significantly positive (at 1%) during Tokyo hours (0.0305) and, although falling in magnitude, remains positive and significant throughout the two overnight horizons (0.0128 in overnight 1 and 0.0013 in overnight 2). The evidence suggests that the larger and less frequent interventions had elicited the desirable effect in influencing the exchange rate movement. When interventions occur they overwhelm the simultaneity influence and the exchange rate is moved in the desired direction even during Tokyo hours. As for the conditional volatility the intervention coefficient, $\beta_{\text{Intv-BOJ}}$, is positive (0.0015), however is insignificant, in Tokyo hours. It turns significantly negative in overnight 1 (-0.0085) suggesting a volatility calming effect starts to emerge. In overnight 2, more intensified volatility reducing effect, significant at 1%, is shown (-0.0365).

In short, the sheer size (340 billion Yen on average or 2.96 billion USD at sample average exchange rate) and the relative rarity of intervention in sample 2 (only 7.8% of trading days compared to 12% in sample 1) helped to increase the visibility and the credibility of intervention thus maximizing the signalling effect. This resulted in Yen moving in the desirable direction even during contemporaneous Tokyo business hours. However, the volatility reducing effect is shown only from overnight 1.

5.1.3. Full sample: 13 May 1991 to 16 Mar 2004

The full sample estimation results are reported in the last four columns of Table 3 and the intervention coefficients are summarized in Panel C of Figure 2. As there is a distinct structural break in 1995, the full sample results may not be informative. However, I present the results for completeness. The pattern of intervention effect in the mean is similar to that of sample 2. That is, in all three horizons, effectiveness of intervention is shown. In the conditional variance equation, the simultaneity effect is persisting through to overnight 1 and a significant volatility calming effect is observed in overnight 2.

5.1.4. US FED interventions

The US FED interventions in the Yen/USD market occur during New York Morning hours and so they are contemporaneous to overnight 1. The mean effect in sample 1 is shown to be ineffective in influencing the Yen movements (i.e. insignificant $\alpha_{IntvFED}$). Worse still, it significantly increased the level of volatility during the two overnight horizons as shown by positive and significant $\beta_{IntvFED}$. In sample 2, however, both the trend correcting and volatility reducing influences are strongly present for the US FED interventions confirming the literature that coordinated interventions tend to have desirable influences.

In general, the FED intervention coefficients ($\alpha_{IntvFED}$ and $\beta_{IntvFED}$) are larger in magnitudes than their BOJ intervention counterparts. I can put forward two explanations. First, the FED interventions in both subsamples were coordinated in nature. All twenty two occasions when the FED intervened, they were preceded by the BOJ intervention in the same direction. The literature reports enhanced intervention effects for coordinated interventions. Thus, the FED transactions represent coordinated intervention activities with the BOJ so whenever it entered the New York foreign exchange market it amplified the intervention influence, and hence the larger magnitudes for the FED intervention coefficients for a given intervention size. Second, the average size of the FED intervention in the full sample is 38 billion Yen which is significantly smaller than the average of the BOJ part of the coordinated interventions which is 100 billion Yen. Considering that the FED interventions were an extension of the BOJ interventions, their impact would have been much more pronounced despite the smaller magnitude of their transactions, and this is translated into larger FED intervention coefficients.

5.2. Comparison to UHF results

The time-varying intraday responses of the first and second moments of the Yen/USD exchange rate changes to the BOJ's interventions documented above contrast the findings of the UHF literature where the intervention effect lasts no more than two hours (see Dominguez, 2003, Payne and Vitale, 2003). There are two explanations. First, it is important to note that intervention, in general, is not carried out in isolation in one transaction. Rather, central banks spread intervention over a number of transactions within the day of intervention and also over a number of days. Recall that the probability of BOJ intervention at day *t* given there was an intervention at day *t-1* is 0.61 (see Table 1). This is done so as to maximize the visibility of the central bank's presence in the market thus reinforcing the signaling effect of intervention. This is one of the reasons why UHF studies such as Payne and Vitale (2003) is rather limited in ascertaining intervention effectiveness with respect to the stated aims. Instead, effectiveness should be measured over the series of intervention transactions considered to be a part of a campaign rather than investigating them in isolation. Thus, it is likely that intervention effects are felt in the market with a 'time lag' of several hours. Neely (2001) reports approximately 40 % of central banks surveyed believe it takes a few days for intervention to have its full effect.

Second, if intervention was conducted in secrecy, it might take the market a few hours to discover the presence of central bank. Certainly, central banks have the ability to make their presence under wraps if so desired (Becker and Sinclair (2004) discuss this mode of operation in relation to the Reserve Bank of Australia). Further, Neely (2005a) suggests that the secrecy with which intervention is conducted may delay the adjustment so it might take hours or days for the full effects of intervention to register.

5.3. Comparison to lower frequency results

To demonstrate the power of our results to isolate the *ex post* effects of intervention, I present in the first column of each sections in Table 3 the results of model estimations on 24-hour returns, open-to-open (Daily). The two intraday autoregressive coefficients, α_{h1} and $\alpha_{h2,}$ are dropped and only the own lag term is used with the coefficient, α_{h3}. Similarly, β_{h1} and β_{h2} are omitted from the variance equations, as they are no longer relevant.

The results indicate that the exchange rate is moving in the opposite direction to intervention and volatility is significantly raised in sample 1. In sample 2, the mean effect is now strongly positive but the volatility effect is insignificant. In short, sample 1 results are dominated by the simultaneity bias and the sample 2 results only partially reveal the intervention effectiveness. Thus, the results from estimating the daily model clearly highlight the power of the intraday data in distilling the *ex post* effects of intervention.

6. Conclusions

The foreign exchange intervention literature is plagued with simultaneity bias when it comes to the investigation of intervention efficacy. This is due to the endogeneity of intervention to exchange rate movements. Prior attempts to circumvent the simultaneity problem have lacked power. The primary contribution of this paper is to exploit the characteristics of both the Yen/USD exchange market, and BOJ's intervention itself, to allow a more powerful circumvention of simultaneity. Doing so, I distinguish the *ex post* effects of intervention, separate from the trend and volatility of exchange rate movements that motivate intervention on an intraday level, despite the availability of only daily intervention data.

I find that the first moment response to intervention was concentrated during the Tokyo business hours and declines over the London and New York trading hours, whereas the second moment effect grows stronger over the two overnight trading hours. In pre-1995 sample, Yen purchases (sales) were associated with a depreciation of the currency and a higher volatility during the Tokyo business hours. This is due to the well-known simultaneity bias and does not necessarily imply intervention ineffectiveness. This simultaneity issue is significantly reduced during the London business hours and is reversed during the New York afternoon hours indicating that intervention successfully reversed exchange rate trends and reduced volatility. In post-1995 sample, intervention had an immediate contemporaneous effect in reversing the exchange rate trend and remained effective, although at reduced magnitude, throughout the two overnight horizons. However, intervention had insignificant volatility response during the Tokyo business hours, while market calming effect is significant during the London trading hours and it intensified during the New York afternoon hours.

By disaggregating daily horizon into three consecutive periods, I showed intraday patterns of market behavior following the BOJ interventions. Thus, this paper provides significant insights into the time varying nature of the BOJ's intervention effectiveness. The next logical step in the analysis, following this approach of circumventing the simultaneity issue, is to simultaneously model the first and second moment exchange rate changes and intervention activities. This requires overcoming a number of non trivial econometrical challenges that I leave as a direction of future research.

References

Almekinders, G.J., Eijffinger, S.C.W., 1996. A friction model of daily Bundesbank and Federal Reserve intervention. Journal of Banking and Finance 20, 1365-1380.

Baillie, R., Humpage, O.F., Osterberg, W.P., 1999. Intervention as information: A survey. Federal Reserve Bank of Cleveland Working Paper No. 9918.

Baillie, R., Osterberg, W., 1997a. Why do central banks intervene? Journal of International Money and Finance 16, 909-919.

Baillie, R.T., Osterberg, W.P., 1997b. Central Bank Intervention and risk in the forward market. Journal of International Economics 43, 483-97.

Bank for International Settlement, 2005. Triennial Central Bank Survey of Foreign Exchange and Derivatives Market Activity 2004 (http://www.bis.org/publ/rpfx05.htm).

Bank of Japan, 2000. Outline of the BOJ's Foreign Exchange Intervention Operations. www.boj.or.jp/en/about/basic/etc/faqkainy.htm

Becker, C., Sinclair, M., 2004. Profitability of Reserve Bank foreign exchange operations: Twenty years after the float. Reserve Bank of Australia Research Discussion Paper 2004-06, September 2004.

Beine, M., 2004. Conditional covariances and direct central bank interventions in the foreign exchange markets. Journal of Banking and Finance 28, 1385-1411.

Beine, M., Bernal, O., 2004. Why do central banks intervene secretly? SSRN Working paper, http://papers.ssrn.com/sol3/papers.cfm?abstract_id=639961.

Bollerslev, T., Domowitz, I., 1993. Trading patterns and prices in the interbank foreign exchange market. Journal of Finance 48, 1421-1443.

Bollerslev, T., Engle, R.F., Nelson, D.B., 1994. ARCH models. In: Engle RF & McFadden D (eds.) The Handbook of Economterics 4. North Holland, Amsterdam.

Bonser-Neal, C., Tanner, G., 1996. Central bank intervention and the volatility of exchange rates: Evidence from the options market. Journal of International Money and Finance 15, 853-878.

Canales Kriljenko, J.I., Guimaraes, R., Karacadag, C., 2003. Official Intervention in the Foreign Exchange Market: Elements of Best Practice. International Monetary Fund IMF Working Papers: 03/152.

Chabound, A.P., Humpage, O.F., 2003. An analysis of Japanese foreign exchange interventions, 1991-2002. Federal Reserve Bank of Cleveland Working Paper: 0309.

Chang, Y., Taylor, S.J., 1998. Intraday effects of foreign exchange intervention by the Bank of Japan. Journal of International Money and Finance 17, 191-210.

Connolly, R., Taylor, W., 1994. Volume and intervention effects on the Yen/Dollar volatility: 1977-1979. In: Advanced Financial Planning and Forecasting. JAI Press, Greenwich, Connecticut, pp. 181-200.

Dacorogna, M.M., Müller, U.A., Nagler, R.J., Olsen, R.B., Pictet, O.V., 1993. A geographical model for the daily and weekly seasonal volatility in the foreign exchange market. Journal of International Money and Finance 12, 413-438.

Dominguez, K.M., 1998. Central bank intervention and exchange rate volatility. Journal of International Money and Finance 17, 161-190.

Dominguez, K.M., 2003. The market microstructure of central bank intervention. Journal of International Economics 59, 25-45.

Dominguez, K.M., Frankel, J.A., 1993. Does foreign exchange rate intervention work? Institute for International Economics

Doroodian, K., Caporale, T., 2001. Central bank intervention and foreign exchange volatility. International Advances in Economic Research 7, 385-392.

Edison, H.J., Cashin, P., Liang, H., 2003. Foreign exchange intervention and the Australian Dollar: Has it mattered? IMF Working Paper, May 2003.

Evans, M.D.D., 2002. FX trading and exchange rate dynamics. Journal of Finance 57, 2405-2447.

Fatum, R., Hutchison, M., 2003. Effectiveness of official daily foreign exchange market intervention operations in Japan. National Bureau of Economic Research Inc NBER Working Papers: 9648.

Fischer, A.M., 2003. Reuters news reports versus official interventions: A cautionary warning. Working Paper, September.

Frenkel, M., Pierdzioch, C., Stadtmann, G., 2004a. The accuracy of press reports regarding the foreign exchange interventions of the Bank of Japan. Journal of International Financial Markets, Institutions and Money 14, 25-36.

Frenkel, M., Pierdzioch, C., Stadtmann, G., 2004b. On the determinants of "small" and "large" foreign exchange market interventions: the case of the Japanese interventions in the 1990s. Review of Financial Economics 13, 231-43.

Frenkel, M., Pierdzioch, C., Stadtmann, G., 2005. The effects of Japanese foreign exchange market interventions on the Yen/U.S. Dollar exchange rate volatility. International Review of Economics and Finance 14, 27-39.

Galati, G., Melick, W., 2002. Central bank intervention and market expectations. BIS Papers 10, April.

Geweke, J., 1986. Comments on modelling the persistence of conditional variances. Econometric Reviews 5, 57-61.

Harvey, C.R., Huang, R.D., 1991. Volatility in the foreign currency futures market. Review of Financial Studies 4, 543-569.

Hillebrand, E., Schnabl, G., 2003. The effects of Japanese foreign exchange intervention GARCH estimation and change point detection. Working Paper, August.

Humpage, O., 1998. U. S. intervention: Assessing the profitability of success. Journal of Money, Credit and Banking 31, 731-747.

Hung, J.H., 1997. Intervention strategies and exchange rate volatility: A noise trading perspective. Journal of International Money and Finance 16, 779-793.

Ito, T., 2002. Is foreign exchange intervention effective? The Japanese experiences in the 1990s. National Bureau of Economic Research Inc NBER Working Papers: 8914.

Ito, T., Yabu, T., 2004. What promotes Japan to intervene in the forex market? A new approach to a reaction function. NBER Working Paper 10456

Kearns, J., Rigobon, R., 2005. Identifying the efficacy of central bank intervention: Evidence from Australia and Japan. Journal of International Economics 66, 31-48.

Kim, S.-J., Sheen, J.R., 2002. The determinants of foreign exchange intervention by central banks: Evidence from Australia. Journal of International Money and Finance 21, 619-649.

Lewis, K.K., 1995. Are foreign exchange intervention and monetary policy related, and does it really matter? Journal of Business 68, 185-214.

Nagayasu, J., 2004. The effectiveness of Japanese foreign exchange interventions during 1991–2001. Economics Letters 84, 377–381.

Neely, C.J., 2001. The practice of central bank intervention: Looking under the hood. Federal Reserve Bank of St. Louis Review 83, 1-10.

Neely, C.J., 2002. The temporal pattern of trading rule returns and exchange rate intervention: Intervention does not generate technical trading profits. Journal of International Economics 58, 211-232.

Neely, C.J., 2005a. An analysis of recent studies of the effect of foreign exchange intervention. Federal Reserve bank of St. Louis Working paper 2005-030B, http://research.stlouisfed.org/wp/2005/2005-030.pdf.

Neely, C.J., 2005b. Identifying the effects of U.S. intervention on the levels of exchange rates. Federal Reserve bank of St. Louis Working paper 2005-031, http://research.stlouisfed.org/wp/2005/2005-031.pdf.

Pantula, S.G., 1986. Comments on modelling the persistence of conditional variances. Econometric Reviews 5, 71-74.

Pasquariello, P., 2002. Informative trading or just noise? An analysis of currency returns, market liquidity, and transaction costs in proximity of central bank interventions. Stern School of Business - New York University.

Payne, R., Vitale, P., 2003. A transaction level study of the effects of central bank intervention on exchange rates. Journal of International Economics 61, 331-352.

Peiers, B., 1997. Informed traders, intervention and price leadership: a deeper view of the microstructure of the foreign exchange market. Journal of Finance 52, 1589-1614.

Sarno, L., Taylor, M., 2001. Official intervention in the foreign exchange market: Is it effective and, if so, how does it work? Journal of Economic Literature XXXIX, 839-868.

Table 1: Intervention Statistics – BOJ and US FED
13 May 1992 to 16 Mar 2004

	BOJ			FED		
	Sample 1:	Sample 2:	Full Sample:	Sample 1:	Sample 2:	Full Sample:
	13 May 1991 to 20 Jun 1995	21 Jun 1995 to 16 Mar 2004	13 May 1991 to 16 Mar 2004	13 May 1991 to 20 Jun 1995	21 Jun 1995 to 16 Mar 2004	13 May 1991 to 16 Mar 2004
Number of days of Interventions						
Positive	139	172	311	15	3	18
Negative	27	6	33	3	1	4
Total	166	178	344	**18**	**4**	**22**
Unilateral BOJ Interventions	148	174	322			
Co-ordinated interventions	18	4	22			
Average Size of Intervention (in Yen bn)						
Positive	50.2	328.1	203.9	40.3	34.4	39.3
Negative	-29.2	-684.4	-148.3	-8.5	-114.6	-35.0
Total (average of absolute values)	**46.8**	**340.1**	**198.5**	**38.5**	**54.5**	**37.2**
Largest Intervention (in in Yen bn)						
Positive	338.8	1666.4	1666.4	77.5	45.4	77.5
Negative	-76.9	-2620.1	-2620.1	-12.7		-114.6
Smallest Intervention (in in Yen bn)						
Positive	5.1	0.1	0.1	16.9	28.9	16.9
Negative	-3.2	-76.4	-3.2	-6.4		-6.4
Cumulative Intervention Probabilities						
Prb(BOJ-$I_t \neq 0$ | BOJ-$I_{t-1} \neq 0$)	0.61	0.62	0.62			
Prb(BOJ-$I_t \neq 0$ | BOJ-$I_{t-1} \neq 0$ & BOJ-$I_{t-2} \neq 0$)	0.42	0.46	0.44			
Prb(FED-$I_t \neq 0$ | BOJ-$I_t \neq 0$)				1.00	1.00	1.00

TABLE 2: Descriptive statistics for Yen/UD exchange rate return series 13 May 1991 to 16 Mar 2004

	Daily (D)	IntraDaily (ID)	Overnight 1 (ON1)	Overnight 2 (ON2)
	Sample 1: May 13 1991 to June 20 1995			
Mean	-0.0460	-0.0003	-0.0186	0.0013
Variance	0.4518	0.0000	0.0972	0.1400
Skewness	-0.4249	-0.1717	-0.4310	-0.7682
Kurtosis	4.8972	5.2697	22.1852	15.3762
J-B	1100.37	1242.17	21955.81	10636.00
Q2(20)	20.6527	15.6636	25.5991	17.3466
	{0.4178}	{0.7373}	{0.1795}	{0.6304}
$Q^2(20)$	62.8660 ***	76.7319 ***	38.9899 ***	20.1339
	{0.0000}	{0.0000}	{0.0067}	{0.4496}
	Sample 2: June 21 1995 to Mar 16 2004			
Mean	0.0100	0.0000	-0.0056	0.0162
Variance	0.5421	0.0001	0.1814	0.1566
Skewness	-1.1862	-1.2965	-0.2749	0.3187
Kurtosis	11.3818	13.2245	4.5289	7.3084
J-B	12880.83	17313.62	1984.15	5128.46
Q2(20)	27.8338	27.4398	30.9047 *	28.4085
	{0.1134}	{0.1233}	{0.0565}	{0.1001}
$Q^2(20)$	457.8646 ***	635.2033 ***	86.2315 ***	145.8190 ***
	{0.0000}	{0.0000}	{0.0000}	{0.0000}
	Full Sample: May 13 1991 to Mar 16 2004			
Mean	-0.0079	-0.0001	-0.0097	0.0114
Variance	0.5136	0.0000	0.1545	0.1512
Skewness	-0.9779	-1.0042	-0.2951	0.0145
Kurtosis	9.7846	11.3799	7.2194	9.5489
J-B	13930.53	18689.40	7343.42	12757.98
Q(20)	25.0317	26.1885	32.7187 **	26.2521
	{0.2002}	{0.1597}	{0.0362}	{0.1576}
$Q^2(20)$	550.3065 ***	772.4163 ***	133.7937 ***	112.5723 ***
	{0.0000}	{0.0000}	{0.0000}	{0.0000}

Daily (D): Daily return measured as continuously compounded return from 7am JST at day t (22:00 GMT, t-1) to 7 am JST at day t+1, $\log(ER_{t+1}^{J-Open} / ER_t^{J-Open}) \times 100$.

IntraDaily (ID): Intra-daily return measured from 7am JST at day t (22:00 GMT, t-1) to 5pm JST (08:00 GMT at day t), $\log(ER_t^{J-Close} / ER_t^{J-Open}) \times 100$.

Overnight 1 (ON1): First overnight return measured from 5pm JST (08:00 GMT at day t) to 5pm London close (17:00 GMT at day t), $\log(ER_t^{LD-Close} / ER_t^{J-Close}) \times 100$.

Overnight 2 (ON2): Second overnight return measured from 5pm London close at day t (17:00 GMT at day t) to 7 am JST at day t+1, $\log(ER_{t+1}^{J-Open} / ER_t^{LD-Close}) \times 100$

Q(20) and $Q^2(20)$ are Ljung-Box Q-statistics for autocorrelation to 20 lags for the return, and return squared respectively.
***,** and *: Significance at 1,5 and 10%, respectively.

TABLE 3: Results for AR-Log-GARCH(1,1) Model

$$s_t^h = \alpha_0 + \alpha_{h1} s_t^{h-1} + \alpha_{h2} s_t^{h-2} + \alpha_{h3} s_{t-1}^h + \alpha_{IntvBOJ}\, IntvBOJ_t + \alpha_{IntvFED}\, IntvFED_t + u_t, \quad u_t = \sigma_t \varepsilon_t \qquad \varepsilon_t \sim i.i.d.(0,1) \tag{1}$$

$$\log(\sigma_t^h)^2 = \beta_0 + \beta_1 \log(\sigma_{t-1}^h)^2 + \beta_{h1}\left|s_t^{h-1}\right| + \beta_{h2}\left|s_t^{h-2}\right| + \beta_\varepsilon\left|\varepsilon_{t-1}\right| + \beta_{IntvBOJ}\left|IntvBOJ_t\right| + \beta_{IntvFED}\left|IntvFED_t\right| \tag{2}$$

	Sample 1: 13 May 1991 to 20 Jun 1995				Sample 2: 21 Jun 1995 to 16 Mar 2004				Full Sample: 13 May 1991 to 16 Mar 2004			
	Daily (D)	IntraDaily (ID)	Overnight 1 (ON1)	Overnight 2 (ON2)	Daily (D)	IntraDaily (ID)	Overnight 1 (ON1)	Overnight 2 (ON2)	Daily (D)	IntraDaily (ID)	Overnight 1 (ON1)	Overnight 2 (ON2)
	Conditional Mean Equation $s_t^h = \alpha_0 + \alpha_{h1} s_t^{h-1} + \alpha_{h2} s_t^{h-2} + \alpha_{h3} s_{t-1}^h + \alpha_{IntvBOJ}\, IntvBOJ_t + \alpha_{IntvFED}\, IntvFED_t + u_t$											
α_0	-0.0376 **	-0.0235	-0.0191 ***	-0.0115	0.0100	0.0069	-0.0083	0.0056 ***	-0.0119	-0.0019	-0.0147 ***	0.0025
	{0.0383}	{0.1075}	{0.0008}	{0.1240}	{0.5141}	{0.5323}	{0.3645}	{0.0000}	{0.3393}	{0.8181}	{0.0045}	{0.4951}
α_{h1}		-0.2655 ***	-0.1348 ***	-1.0093 ***		-0.6233 ***	-0.0169	-0.9082 ***	-0.0558	-0.5016	-0.0923	-0.8293
		{0.0000}	{0.0000}	{0.0000}		{0.0000}	{0.1001}	{0.0000}	{0.0003}	{0.0000}	{0.0000}	{0.0000}
α_{h2}		-0.1400 *	-0.0557 ***	0.0127		0.2851 ***	-0.0658 ***	0.0000	0.8458	0.3255	-0.0588	0.0063
		{0.0781}	{0.0000}	{0.1125}		{0.0004}	{0.0022}	{0.9396}	{0.0000}	{0.0000}	{0.0000}	{0.2966}
α_{h3}	-0.0371	0.0009	0.0363	0.0026	0.0194	0.0189	-0.0496 **	0.0008 ***	0.0778 ***	0.0574 ***	0.0003	0.0078
	{0.1337}	{0.9660}	{0.2141}	{0.7591}	{0.2554}	{0.4348}	{0.0106}	{0.0000}	{0.0000}	{0.0001}	{0.9831}	{0.3612}
$\alpha_{Int-BOJ}$	-0.3548 ***	-0.3166 ***	-0.0103	0.0128 **	0.0329 ***	0.0305 ***	0.0128 ***	0.0013 ***	0.0340 ***	0.0275 ***	0.0167 ***	0.0051 ***
	{0.0000}	{0.0000}	{0.7092}	{0.0441}	{0.0000}	{0.0069}	{0.0069}	{0.0007}	{0.0000}	{0.0006}	{0.0000}	{0.0041}
$\alpha_{Int-FED}$	0.5727		0.1518	1.3563	2.8293 ***		2.6489 ***	-0.2010	0.5002	***	0.5143 ***	14.2199 ***
	{0.2281}		{0.2496}	{0.2451}	{0.0014}		{0.0000}	{0.2379}	{0.1515}		{0.0000}	{0.0000}
	Conditional Variance Equation: $\log(\sigma_t^h)^2 = \beta_0 + \beta_1 \log(\sigma_{t-1}^h)^2 + \beta_{h1}\left|s_t^{h-1}\right| + \beta_{h2}\left|s_t^{h-2}\right| + \beta_\varepsilon\left|\varepsilon_{t-1}\right| + \beta_{IntvBOJ}\left|IntvBOJ_t\right| + \beta_{IntvFED}\left|IntvFED_t\right|$											
β_0	-0.2375 ***	-0.6447 ***	-0.4263 ***	-3.1310 ***	-0.1608 ***	-0.1623 **	-0.6939 ***	-3.0075 ***	-0.1847 ***	-0.1473 ***	-0.1200 ***	-3.5592 ***
	{0.0000}	{0.0000}	{0.0000}	{0.0000}	{0.0000}	{0.0322}	{0.0000}	{0.0000}	{0.0000}	{0.0000}	{0.0000}	{0.0000}
β_1	0.8833 ***	0.5914 ***	0.9550 ***	0.0899 ***	0.9415 ***	0.9741 ***	0.7401 ***	0.3764 ***	0.9178 ***	0.9729 ***	0.9954 ***	0.1748 ***
	{0.0000}	{0.0000}	{0.0000}	{0.0003}	{0.0000}	{0.0000}	{0.0000}	{0.0000}	{0.0000}	{0.0000}	{0.0000}	{0.0000}
β_{h1}		0.4838 ***	0.4095 ***	-0.3117		-0.0719	0.2881 ***	2.7905 ***	0.1848	0.0956	0.1158	2.1048
		{0.0000}	{0.0000}	{0.3643}		{0.5523}	{0.0000}	{0.0000}	{0.0000}	{0.0000}	{0.0000}	{0.0000}
β_{h2}		0.9117 ***	-0.4909 ***	0.0028		0.1218	0.4105 ***	0.2519 ***	-0.5586	-0.0166	-0.2761	0.1941
		{0.0000}	{0.0000}	{0.9840}		{0.4912}	{0.0000}	{0.0000}	{0.0000}	{0.0008}	{0.0000}	{0.0000}
β_ε	0.0460 ***	-0.1514 **	0.2969 ***	0.4335 ***	0.0605 ***	0.1503 ***	-0.0448 ***	-0.7773 ***	0.0274 ***	0.1289 ***	0.1733 ***	0.1820 ***
	{0.0000}	{0.0273}	{0.0000}	{0.0000}	{0.0000}	{0.0003}	{0.0000}	{0.0000}	{0.0000}	{0.0000}	{0.0000}	{0.0000}
$\beta_{Int-BOJ}$	0.0396 **	0.3224 ***	0.0621 ***	-1.0915 ***	0.0005	0.0015	-0.0085 *	-0.0365 ***	0.0008	0.0027	0.0044 ***	-0.0544 ***
	{0.0491}	{0.0000}	{0.0000}	{0.0000}	{0.8526}	{0.7968}	{0.0758}	{0.0000}	{0.7773}	{0.6092}	{0.0085}	{0.0000}
$\beta_{Int-FED}$	1.4457 ***		0.9106 ***	16.4444 **	0.9545 ***		-2.2479 ***	-2.5917 ***	1.2858 ***		0.8118 ***	22.1426 ***
	{0.0000}		{0.0000}	{0.0399}	{0.0000}		{0.0001}	{0.0000}	{0.0000}		{0.0000}	{0.0000}
	Diagnostics[(a)]											
LogL	-56.84	48.53	1078.58	1169.49	-216.72	303.58	955.11	3333.17	-290.05	260.36	1943.30	3936.11
Q(20)	19.7023	16.9749	18.3997	35.6110 **	19.1173	20.3710	22.3654	32.6968 **	20.4076	20.7453	22.7437	34.4300 **
	{0.4767}	{0.6546}	{0.5611}	{0.0171}	{0.5142}	{0.4350}	{0.3210}	{0.0364}	{0.4327}	{0.4123}	{0.3016}	{0.0234}
$Q^2(20)$	23.8157	18.7622	26.7351	36.1994 **	37.7730 ***	18.0922	9.8459	92.0259 ***	33.2817 **	44.2689 ***	15.6692	106.7115 ***
	{0.2505}	{0.5373}	{0.1429}	{0.0146}	{0.0094}	{0.5813}	{0.9709}	{0.0000}	{0.0314}	{0.0014}	{0.7369}	{0.0000}

(a) The *Q(20)* and *Q^2(20)* statistics are Ljung-Box test of linear and non-linear autocorrelation in the standardised residuals, respectively, to 20 lags. P-values for estimated coefficients are in the curley braces. Significance at the 1%, 5% and 10% significance levels is signified by ***, ** and * respectively.

FIGURE 1: Intra-daily decomposition of holding periods

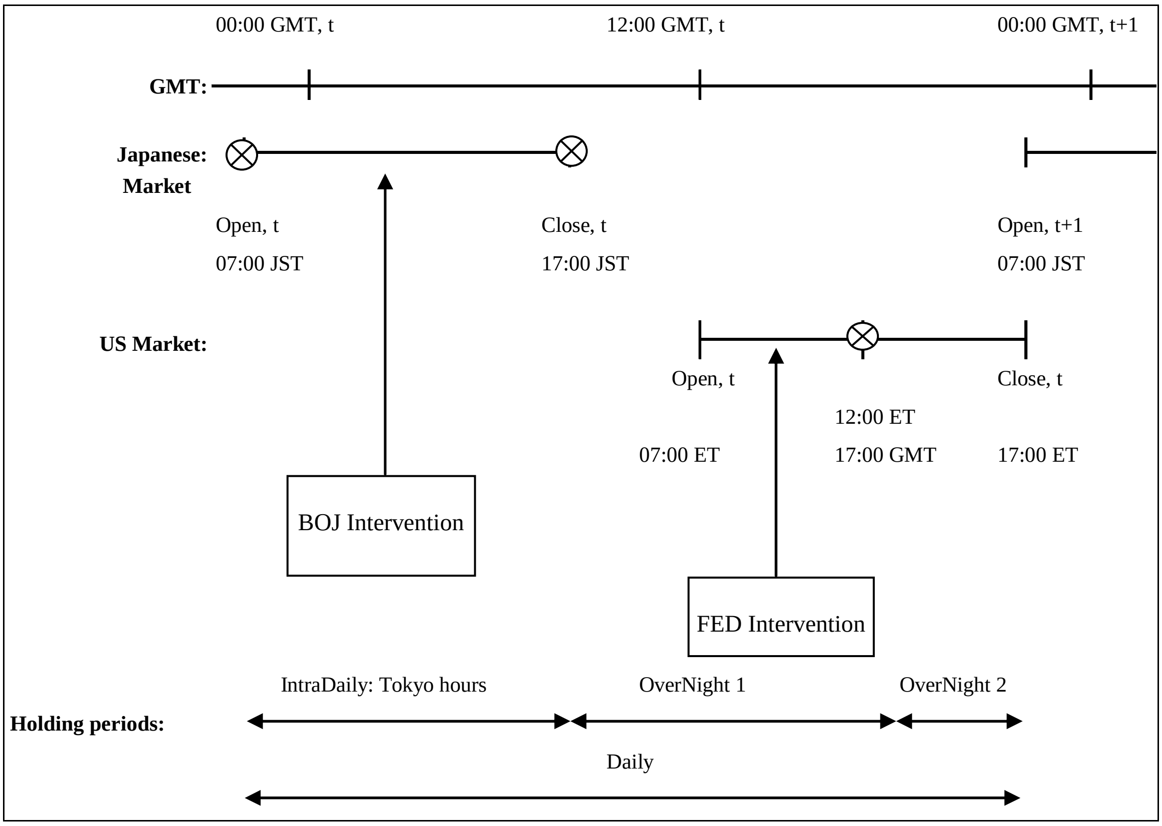
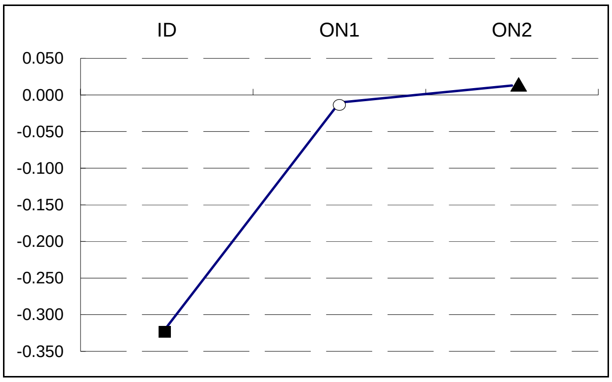
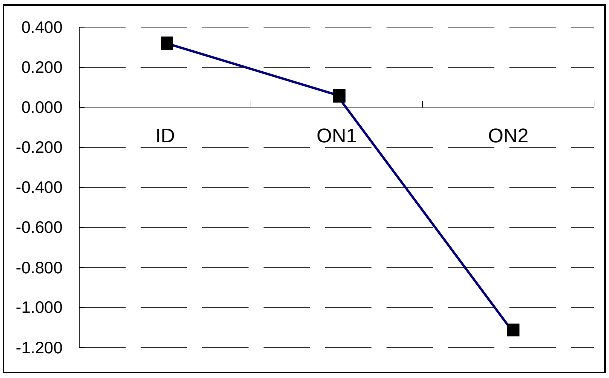


FIGURE 2: Summary of intervention variables over three intraday horizons

Panel A: Sample One – 13 May 1991 to 20 Jun 1995

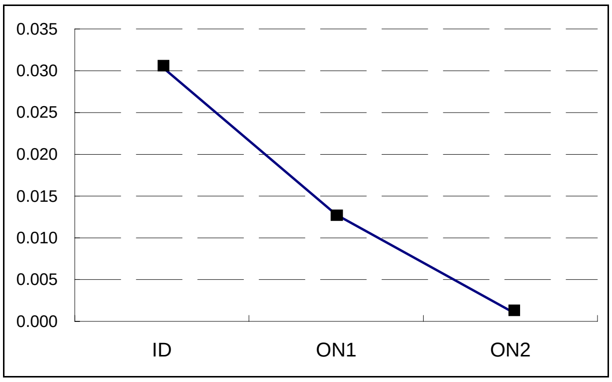


Mean – Sample 1

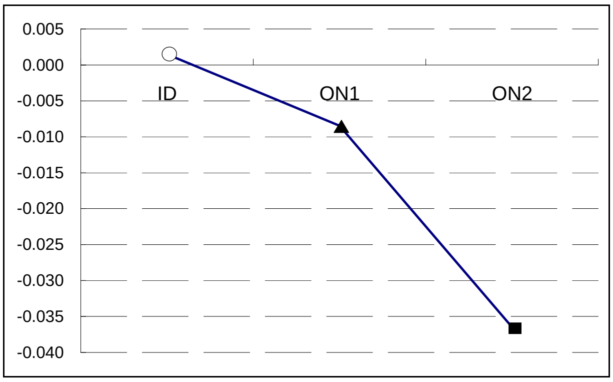


Variance – Sample 1

Panel B: Sample two – 21 Jun 1995 to 16 Mar 2004

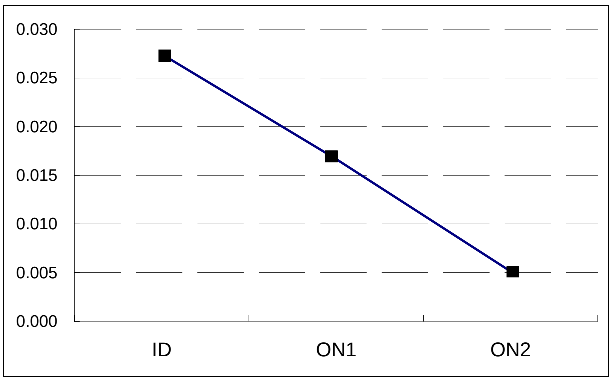


Mean – Sample 2

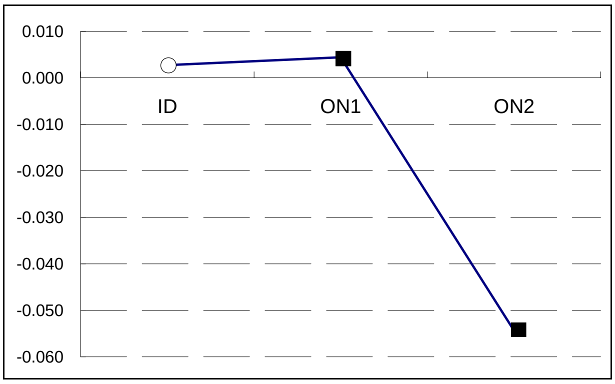


Variance – Sample 2

Panel C: Full sample – 13 May 1991 to 16 Mar 2004



Mean – Full Sample



Variance – Full Sample

KEY	
○	Insignificant at 10% significance level
▲	Significant at 10% significance level
■	Significant at 1% significance level