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Central bank interventions and implied exchange rate correlations☆

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ABSTRACT

This paper examines the effects of the foreign exchange market interventions by the Bank of Japan on the ex ante correlations between the JPY/USD, EUR/USD, and GBP/USD exchange rates. The correlation estimates used in the analysis are derived from the market prices of OTC currency options. The results show that central bank interventions significantly affect the market expectations about future exchange rate co-movements. In particular, we find that interventions tend to temporarily increase the ex ante correlations among the major exchange rates. However, our results also suggest that intervention episodes are associated with lower-than-average levels of exchange rate correlations.

1. Introduction

The debate on whether central banks can affect exchange rate dynamics with interventions has stimulated a large body of literature over the last ten years (for surveys, see e.g. Schwartz, 2000; Sarno and Taylor, 2001; Galati et al., 2005). Although monetary authorities seem to view intervention as an effective instrument of exchange rate policy (Neely, 2000), there is widespread skepticism among academics about the effectiveness of interventions in achieving the alleged objectives of either changing the level of an exchange rate or reducing its volatility.[2]

The empirical evidence on the effects of interventions on exchange rate dynamics is mixed. Several studies find that interventions affect the level of the exchange rate (e.g., Fatum and Hutchison, 2003, 2006; Chaboud and Humpage, 2005; Kearns

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[2] According to official central bank statements, interventions may be conducted, for instance, in order to counter disorderly market conditions (U.S. Federal Reserve), or to stabilize excessive exchange rate movements (Bank of Japan). Nevertheless, it should be noted that the stated intervention objectives are not necessarily the true objectives. Recent empirical findings indicate that interventions are often conducted in response to deviations of the exchange rate from past levels or fundamentals (see e.g., Ito and Yabu, 2007; Beine et al., 2009).

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and Rigobon, 2005; Fratzscher, 2006; Fatum, 2008) and may reduce market uncertainty (e.g., Kim et al., 2000; Beine et al., 2003; Hillebrand et al., 2009).[3] However, there is also considerable evidence suggesting that interventions are not particularly effective in affecting exchange rate movements (e.g., Baillie and Osterberg, 1997; Aguilar and Nydahl, 2000; Morana and Beltratti, 2000; Brandner et al., 2006) nor market expectations regarding future exchange rate developments (e.g., Rogers and Siklos, 2003; Galati et al., 2005). Furthermore, instead of stabilizing exchange rates, interventions are often found to increase volatility in the foreign exchange markets (Bonser-Neal and Tanner, 1996; Beine and Laurent, 2003; Frenkel et al., 2005; Dominguez, 2006). While no consensus has yet emerged, the previous studies, in general, suggest that interventions may be effective in affecting exchange rate dynamics, but not necessarily in achieving the objectives that central banks pursuit.

In this paper, we take an alternative approach to examine the effects of central bank interventions on exchange rates. Specifically, rather than assessing the impact of interventions on the dynamics of a given spot exchange rate, we focus on the co-movements of exchange rates around interventions. Assuming that the triangular parity condition holds among a triplet of currencies, an effective intervention should not only affect the exchange rate in which the intervention is conducted, but also the cross-dynamics among the exchange rate triplet. Hence, to address whether central bank attempts to affect the dynamics of a particular exchange rate induce changes in the cross-dynamics of exchange rates, we examine the effects of the official Bank of Japan (BoJ) yen-selling interventions on the ex ante correlations between the major exchange rates.[4] Our analysis is based on the ex ante correlation estimates derived from the market prices of currency options.

Given the vast empirical work on central bank interventions, it is rather surprising that the impact of interventions on the co-movements of exchange rates has so far been largely neglected in the literature.[5] Our idea to focus on the exchange rate co-movements is not, however, completely novel. In a recent paper, Beine (2004) examines the effects of central bank interventions on the ex post exchange rate correlations. Using multivariate GARCH modeling, Beine (2004) shows that interventions not only affect exchange rate volatility but also tend to increase the conditional correlations among exchange rates.

In contrast to Beine (2004), we use ex ante exchange rate correlation estimates extracted from the prices of currency options.[6] These ex ante correlations implied by option prices may be regarded as the market expectation of the degree of future co-movements between two exchange rates over the remaining life of the option contracts. Given that central bank interventions are often considered to affect exchange rate dynamics by changing market participants' expectations, it is of interest to examine whether the expected exchange rate co-movements are affected by interventions.[7] The potential intervention induced changes in market expectations should be immediately reflected in option prices, and thus, also in implied correlations. Hence, the use of option-implied correlations, instead of ex post correlation estimates, may provide new insights about the effects of central bank interventions on exchange rate dynamics.

Previously, a number of papers have used option-implied volatilities and probability distributions to examine the behavior of market expectations around central bank interventions. In general, these studies find that implied volatilities in the foreign exchange markets are increased by interventions (see e.g., Bonser-Neal and Tanner, 1996; Dominguez, 1998; Frenkel et al., 2005; Fratzscher, 2006), while the higher-order moments of expected exchange rate distributions appear to be virtually unaffected (Rogers and Siklos, 2003; Galati et al., 2005). Some studies, however, report evidence for stabilizing effects of interventions over certain periods (see e.g., Dominguez, 1998; Aguilar and Nydahl, 2000), and Castren (2004), Morel and Teiletche (2008), and Gnabo and Teiletche (2009) document systematic changes in implied probability distributions around central bank actions. In this paper, we attempt to extend the above literature by examining the effects of interventions on option-implied exchange rate correlations.

Our empirical findings demonstrate that central bank interventions significantly affect the market expectations about future exchange rate co-movements. In particular, the results show that implied exchange rate correlations increase on the first day of a period of successive intervention days. Furthermore, we find that the size of the intervention, as measured by the BoJ's daily net purchase of U.S. dollars against the yen, is positively related to the change in implied correlations. However, this positive effect of interventions on implied correlations does not continue after the first intervention day. Instead, we find that implied correlations typically decrease during the remaining days of an intervention episode. Finally, our findings suggest that the ex ante exchange rate correlations are somewhat lower during the intervention episodes than during periods with no central bank activity.

[3] Several transmission channels through which central bank interventions may affect exchange rates and/or exchange rate expectations have been proposed in the literature. For discussions of these alternative channels, see e.g. Dominguez (1998), Sarno and Taylor (2001), Kearns and Rigobon (2005), Fratzscher (2006), and Gnabo and Teiletche (2009).

[4] It should be noted that the conceivable impact of central bank interventions on exchange rate correlations is most likely indirect and unintended. Although monetary authorities tend to monitor exchange rate correlations, it is difficult to assume that they would actually attempt to affect the correlations by conducting interventions. However, it is nevertheless plausible that interventions affect market expectations about future exchange rate dynamics, and thereby cause changes in the ex ante correlations between exchange rates.

[5] Fatum and King (2005) and Fatum (2008) take into account exchange rate co-movements around the Bank of Canada (BoC) interventions in the CAD/USD exchange rate. They document that the observed effects of the BoC interventions are weakened when the CAD/USD rate is adjusted for general co-movements against the USD.

[6] Option prices are inherently forward-looking financial indicators that implicitly contain information about market expectations regarding future asset price developments. Hence, as noted e.g. by Campa and Chang (1998) and Walter and Lopez (2000), market prices of currency options can be used to derive ex ante estimates of correlations between exchange rates. Provided that market participants are rational, these option-implied correlations should incorporate all the available information that is relevant for forming expectations about future exchange rate developments.

[7] According to the signaling channel hypothesis, central banks may use interventions as a tool to signal their superior information about future fundamentals and policy intentions, and thereby affect exchange rates by changing market expectations. Also the noise-trading channel proposed by Hung (1997) and the microstructure (or order flow) channel of Vitale (1999) provide a plausible mechanism for intervention induced changes in market expectations. These alternative transmission channels may be particularly relevant in our context, as the sample period is largely characterized by secret interventions (see Beine and Lecourt, 2004; Beine and Bernal, 2007; Beine et al., 2009).

The results reported in this paper may have important implications for financial market practitioners and monetary authorities. Knowledge of the potential effects of interventions on exchange rate correlations may be useful for formulation and implementation of investment and risk management strategies.[8] From the viewpoint of monetary authorities, the documented effects of interventions on the expected co-movements of exchange rates may be important to consider for the purposes of policy assessment.

The remainder of this paper is organized as follows. Section 2 presents the methodology used to extract implied exchange rate correlations from option prices. Section 3 presents the OTC currency option data used in the analysis and also describes the data on the official Bank of Japan yen-selling interventions. Section 4 reports the empirical findings on the effects of central bank interventions on option-implied exchange rate correlations. Finally, Section 5 provides concluding remarks.

2. Option-implied exchange rate correlations

Consider a triplet of currencies x, y, and z, and let $s_{x/y,t}$, $s_{x/z,t}$, $s_{y/z,t}$ denote the corresponding triplet of logarithmic spot exchange rates at time t. In the absence of arbitrage opportunities, and assuming that the triangular parity condition holds, the triplet of log exchange rate returns satisfies:

$$\Delta s_{x/y,t} = \Delta s_{x/z,t} - \Delta s_{y/z,t}. \tag{1}$$

Thus, a change in $s_{x/y}$, induced for instance by a central bank intervention, should be instantaneously followed by offsetting movements in $s_{x/z}$ and/or $s_{y/z}$. Given Eq. (1), the conditional variance of $\Delta s_{x/y}$ for a horizon of T days can be expressed as:

$$\sigma^2_{t,T}\left(\Delta s_{x/y}\right) = \sigma^2_{t,T}\left(\Delta s_{x/z}\right) + \sigma^2_{t,T}\left(\Delta s_{y/z}\right) - 2\rho_{t,T}\left(\Delta s_{x/z}, \Delta s_{y/z}\right)\sigma_{t,T}\left(\Delta s_{x/z}\right)\sigma_{t,T}\left(\Delta s_{y/z}\right) \tag{2}$$

where $\sigma_{t,T}(i)$ denotes the return volatility of exchange rate i at time t, and $\rho_{t,T}(i,j)$ is the conditional correlation between exchange rate return series i and j at time t over a T-day horizon. This expression of conditional variance can be utilized to extract ex ante correlation estimates from the prices of currency options.

Option prices, as inherently forward-looking financial indicators, implicitly contain information about market expectations regarding future asset price developments. In particular, since the price of an option is decisively determined by the market's assessment of the volatility of the underlying asset, option prices are commonly used to extract implied volatilities that represent market participants' volatility expectations over the remaining life of the option contract. As noted e.g. by Campa and Chang (1998) and Walter and Lopez (2000), volatilities implied by a triplet of currency options can, in turn, be used to derive implied correlations that reflect market expectations about future co-movements between exchange rates.[9]

By substituting the observed implied volatilities into Eq. (2) and rearranging terms, the implied correlation $\hat{\rho}_{t,T}$ between the logarithmic exchange rate return series $\Delta s_{x/z,t}$ and $\Delta s_{y/z,t}$ at time t over the next T days is given by:

$$\hat{\rho}_{t,T}\left(\Delta s_{x/z}, \Delta s_{y/z}\right) = \frac{\hat{\sigma}^2_{t,T}\left(\Delta s_{x/z}\right) + \hat{\sigma}^2_{t,T}\left(\Delta s_{y/z}\right) - \hat{\sigma}^2_{t,T}\left(\Delta s_{x/y}\right)}{2\hat{\sigma}_{t,T}\left(\Delta s_{x/z}\right)\hat{\sigma}_{t,T}\left(\Delta s_{y/z}\right)} \tag{3}$$

where $\hat{\sigma}_{t,T}(i)$ denotes implied volatility of exchange rate i at time t extracted from currency options with T days to maturity. This option-implied correlation is an ex ante estimate of the degree of co-movements between two exchange rates. Provided that market participants are rational, option prices, and thereby also implied correlations, should incorporate all the available information that is relevant for forming expectations about future exchange rate developments. Hence, we consider implied correlations to provide an expedient setting to examine the effects of central bank interventions on the co-movements of exchange rates.

3. Data and descriptive statistics

The implied correlations used in the empirical analysis are extracted from currency options traded in the over-the-counter (OTC) markets. The options data cover the four most actively traded currencies, the U.S. dollar (USD), euro (EUR), Japanese yen (JPY), and British pound (GBP), and consist of daily one-month and three-month implied volatility quotes for options on the JPY–USD, EUR–USD, GBP–USD, JPY–EUR, JPY–GBP currency pairs.[10] According to the Bank for International Settlements (2005), these

[8] Beine (2004) provides a comprehensive discussion on the effects of intervention induced changes in exchange rate correlations for portfolio management purposes.

[9] Campa and Chang (1998) and Walter and Lopez (2000) show that option-implied correlation is superior to other correlation estimates in forecasting future correlations between exchange rates.

[10] In the OTC markets, currency options are quoted in terms of implied volatilities that are by convention converted into option prices using the Garman and Kohlhagen (1983) version of the Black and Scholes (1973) option pricing model.

Table 1
Descriptive statistics.

	Mean	Median	St.Dev.	Min	Max
Panel A: BoJ interventions and the yen–dollar spot rate					
Interventions in USD millions (136 obs.)	2872.81	1899.50	3639.91	1.00	16664.00
¥/$ spot rate (978 obs.)	115.52	116.74	8.51	102.09	134.78
Log-return on the ¥/$ spot rate	0.000	0.000	0.006	−0.030	0.024
Panel B: implied volatilities and implied correlations					
1-month horizon					
σ(¥/$)	0.095	0.095	0.011	0.074	0.140
σ(£/$)	0.082	0.081	0.012	0.052	0.116
σ(€/$)	0.098	0.098	0.011	0.069	0.129
σ(¥/£)	0.090	0.089	0.011	0.070	0.124
σ(¥/€)	0.094	0.092	0.013	0.068	0.139
ρ(€/$, ¥/$)	0.524	0.534	0.092	0.265	0.740
ρ(£/$, ¥/$)	0.490	0.512	0.097	0.136	0.751
3-month horizon					
σ(¥/$)	0.094	0.094	0.008	0.077	0.119
σ(£/$)	0.084	0.083	0.011	0.059	0.116
σ(€/$)	0.101	0.101	0.009	0.082	0.126
σ(¥/£)	0.095	0.094	0.010	0.076	0.125
σ(¥/€)	0.096	0.093	0.010	0.076	0.131
ρ(€/$, ¥/$)	0.523	0.531	0.070	0.318	0.695
ρ(£/$, ¥/$)	0.441	0.446	0.068	0.210	0.635

Panel A reports the descriptive statistics for the Bank of Japan (BoJ) interventions and the JPY/USD exchange rate. Panel B reports the descriptive statistics for the implied volatilities $\sigma(i)$ and implied correlations $\rho(i,j)$.

five currency pairs together account for about 65% of trading in the foreign exchange markets with a combined average daily turnover of about 1.2 trillion U.S. dollars.[11] The implied volatility quotes used in the analysis are for the OTC market's most actively traded instrument, so-called at-the-money forward options. These are European-style currency options for which the strike price equals, or is very close to, the forward exchange rate with the same maturity as the option.[12] Our currency option data set extends from October 1, 2001 through June 30, 2005, for a total of 978 trading days.

The use of OTC currency option volatility quotes, rather than data on exchange-traded options, may be considered to have several advantages. First, OTC currency options have superior liquidity in comparison to exchange-traded currency options. A survey by the Bank for International Settlements (2005) shows that the notional amount of outstanding exchange-traded currency options is less than 1% of the amount of OTC options. Moreover, the OTC currency options market has been growing considerably over recent years, with a 95% increase in the average daily turnover between 2001 and 2004. Second, OTC options have a constant time to maturity, whereas the maturity of exchange-traded options varies from day to day. As a consequence, spurious inference due to the time-to-maturity effects of option prices may be avoided by using OTC data. Third, the at-the-money forward options used in this paper to extract implied correlation are, by definition, always exactly at-the-money. Exchange-traded options, in contrast, have fixed strike prices, and thus are usually never exactly at-the-money. By using at-the-money options, the well-known Black-Scholes pricing biases can be minimized. Corrado and Miller (1996), for instance, show that the implied volatilities derived from the Black-Scholes model are virtually identical to the volatilities based on stochastic volatility models for short maturity at-the-money options. Finally, as recently documented by Christoffersen and Mazzotta (2005), OTC currency options data are of superior quality for volatility forecasting purposes.

The intervention data consist of official interventions conducted by the Bank of Japan in the JPY/USD spot exchange rate markets between May 2002 and March 2004.[13] Our intervention observations are the officially disclosed daily net purchases of U.S. dollars against the yen by the BoJ. Due to the method of intervention implementation, the BoJ interventions can be regarded as automatically sterilized (see e.g., Ito, 2003). Foreign exchange interventions typically occur in clusters that are separated by prolonged periods without any central bank activity. During our sample period, the BoJ conducted interventions on 136 days. These interventions are clustered in 2003 and in the first quarter of 2004, when the Japanese monetary authorities attempted to weaken the yen with intensive dollar purchases.[14]

It should be noted that a high proportion of the BoJ interventions during our sample period have been conducted in a discreet way (see Beine and Lecourt, 2004; Beine and Bernal, 2007).[15] The secrecy of interventions has important implications for the potential transmission channels. In particular, given that secret interventions are not perceived by market participants, the

[11] The statistics on foreign exchange market activity are based on a global central bank survey coordinated by the Bank for International Settlements in April 2004.

[12] OTC currency options are typically quoted in implied volatilities with respect to deltas rather than strike prices. Also the volatilities for the at-the-money forward options used in this study are quoted with respect to delta. The delta for these options is, by definition, equal to 0.5.

[13] Institutionally, the Japanese Ministry of Finance has the authority to conduct interventions and the Bank of Japan acts only as an agent for the implementation of intervention operations. Ito (2003) provides a further discussion of the institutional details of Japanese interventions.

[14] The motivation for the extensive yen-selling interventions during 2003–2004 is discussed e.g. in Ito (2005).

[15] Beine and Bernal (2007) estimate that almost 80 % of interventions conducted by the Bank of Japan during 2003–2004 have been secret interventions.

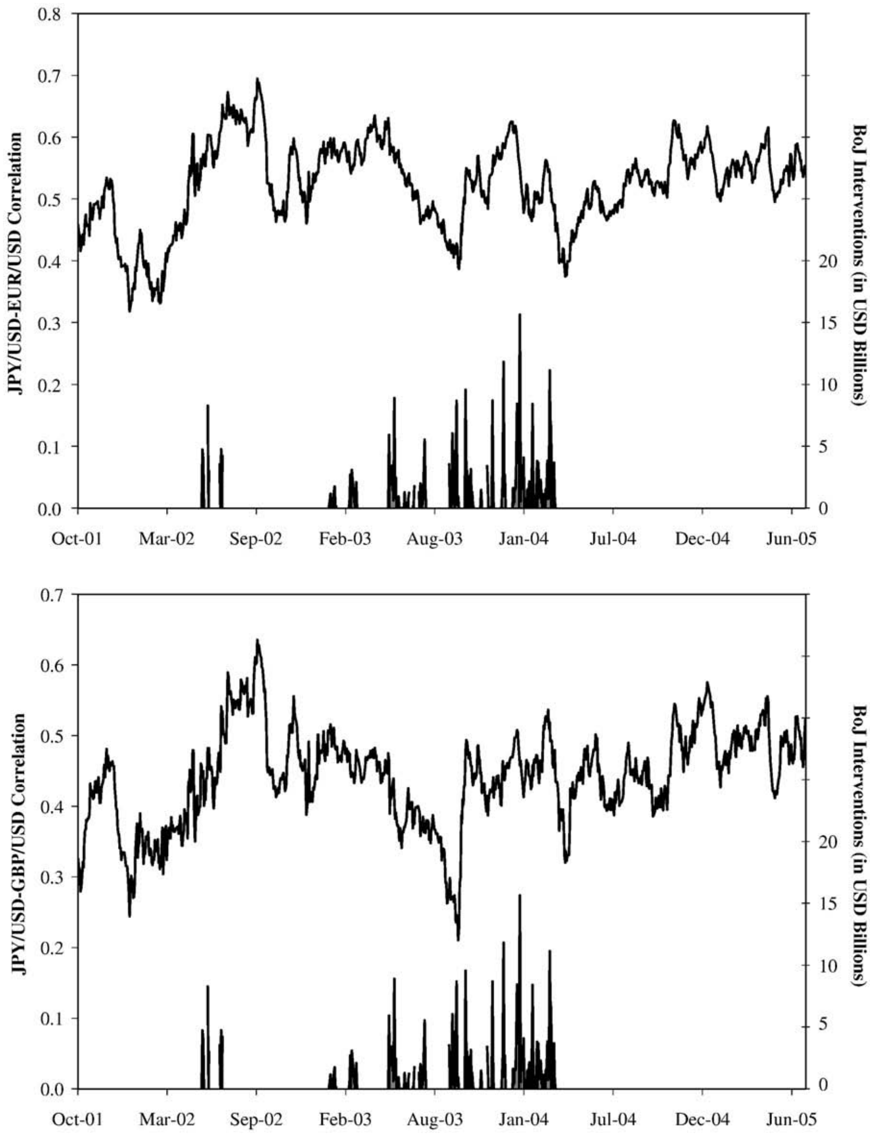

Fig. 1. Implied correlations and Bank of Japan interventions.

signaling channel of interventions cannot be operating, at least in the short-run. Thus, these secret interventions are more likely to affect exchange rates through the portfolio-balance channel or through noise-trading (Hung, 1997) and microstructure effects (Vitale, 1999). Consistent with Gnabo and Teiletche (2009), we presume that market expectations are affected by both reported (i.e., perceived) and secret interventions.[16]

Panel A of Table 1 reports the summary statistics for the Bank of Japan yen-selling interventions and the yen-dollar exchange rate. Panel A shows that the Bank of Japan intervened in the JPY/USD spot exchange rate on a total of 136 days during our 978 day sample period. The average size of intervention by the BoJ was about 2.9 billion U.S. dollars.[17] The size of the daily interventions, however, has varied considerably, ranging from 1 million to 16.6 billion dollars during the sample period. In comparison to the average daily turnover in the JPY/USD spot markets of about 296 billion (Bank for International Settlements, 2005), the dollar amounts of interventions may be considered relatively small. Nonetheless, in 2003 alone, the Bank of Japan purchased over 175 billion U.S. dollars in its intervention operations, corresponding to about 4% of the Japanese gross domestic product. Regarding the JPY/USD exchange rate, Panel A shows that the mean spot rate during the sample period was 155.52, while the mean daily log return on the exchange rate was indistinguishable from zero.

[16] Gnabo and Teiletche (2009) discuss alternative transmission channels of secret interventions. Their empirical findings demonstrate that option-implied exchange rate expectations are affected by both reported and secret interventions. Nevertheless, Gnabo and Teiletche (2009) document that the effects of reported interventions are more pronounced.

[17] During the period of intervention activity between May 2002 and March 2004, the average daily intervention was about 1.2 billion U.S. dollars.

Descriptive statistics for the one-month and three-month implied volatility quotes and for the corresponding implied correlation time-series are reported in Panel B of Table 1. It can be noted that the exchange rate implied volatilities, on average, are around 9%. The GBP/USD exchange rate appears to be the least volatile, whereas the EUR/USD rate exhibits the highest level of volatility among the five exchange rates. Furthermore, Panel B shows that the average option-implied correlation between the yen and euro exchange rates against the dollar is about 0.52, regardless of the maturity of the options. The implied correlation between the yen and British pound exchange rates against the dollar is somewhat lower, with a mean one-month (three-month) correlation estimate of about 0.49 (0.44). However, the range of implied correlation estimates is relatively large, suggesting that exchange rate correlations are varying considerably over time. Panel B shows that the correlations have ranged from 0.27 to 0.74 between the JPY/USD and EUR/USD exchange rates, and from 0.14 to 0.75 between the JPY/USD and GBP/USD rates.

Fig. 1 plots the developments of the implied exchange rate correlations together with the amount of BoJ interventions (in USD billions) over the period from October 2001 to June 2005. Several interesting features can be noted from this figure. First, it is apparent that the option-implied exchange rate correlations exhibit considerable time-variation, and may change substantially in a short period of time. Interestingly, it can be noted from Fig. 1 that the implied correlations between the JPY/USD–EUR/USD and the JPY/USD–GBP/USD exchange rates exhibit somewhat similar patterns over time. This suggests that some common fundamentals or information arrivals may affect the time-varying correlation between exchange rates. Finally, Fig. 1 shows that the Bank of Japan has intervened in sporadic clustered episodes. The BoJ conducted intensive yen-sellings during 2003 and the first quarter of 2004, and after March 2004, it has withdrawn from the intervention operations completely.

4. Do central bank interventions affect implied exchange rate correlations?

Since central bank interventions are typically conducted in clusters on several successive days, the empirical analysis of the effects of interventions on exchange rate dynamics is somewhat complicated. Fig. 2 illustrates the clustering of interventions in our intervention sample. The figure presents a distribution of interventions across a period, hereafter referred to as the intervention period, of successive intervention days. To be more specific, we define the intervention period as a period during which interventions are conducted on successive trading days allowing a one day break in the implementation of intervention. As can be seen from Fig. 2, the lengths of the intervention periods in the sample range from 1 to 14 days. In general, a vast proportion of the dollar amount of interventions occurs on the first day of the intervention period. Because of the clustering, interventions need to be analyzed as periodic events.

4.1. Effects of interventions on implied correlations

Table 2 reports the preliminary statistics on the effects of periodic intervention episodes on implied exchange rate correlations. Panel A of Table 2 presents the means and medians of the log-differenced implied correlations on the first day of the intervention period, during the whole intervention period ('from 1 to n'), and during the whole period excluding the first intervention day ('from 2 to n'). *t*-test and the Wilcoxon signed rank test are applied to ascertain whether the reported means and medians are statistically different from zero. Several interesting features emerge from this table. Although all the reported means and nearly all medians appear to be positive on the first day of the intervention episode, Panel A shows no evidence of statistically significant changes in implied correlations. In contrast, it may be noted from Panel A that the spot exchange rate exhibits a significant negative change on the first intervention day. This indicates that an intervention event, regardless of the size of the intervention, affects the

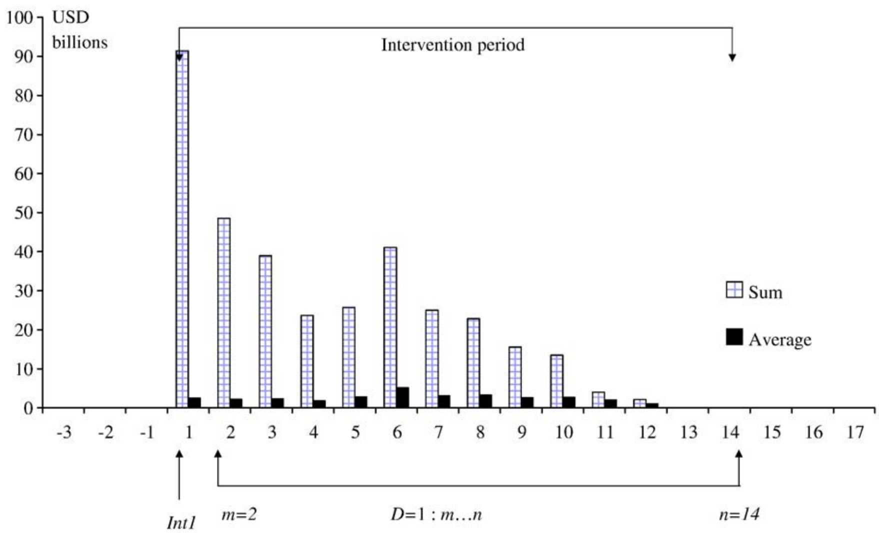

Fig. 2. Distribution of interventions across an intervention period.

Table 2
Effects of interventions on implied correlations.

Days in intervention period	1-month ρ(€/$,¥/$)	1-month ρ(£/$,¥/$)	3-month ρ(€/$,¥/$)	3-month ρ(£/$,¥/$)	¥/$ spot rate
Panel A: event effects					
Means					
1st intervention day	0.007	0.033	0.007	0.010	−0.003***
From 1 to *n*	−0.005	0.002	−0.003	−0.004	0.000
From 2 to *n*	−0.010**	−0.009*	−0.006**	−0.009**	0.001
Medians					
1st intervention day	0.012	−0.002	0.009	0.004	−0.003***
From 1 to *n*	−0.006	−0.010	−0.002	−0.002	0.000
From 2 to *n*	−0.008**	−0.012*	−0.007**	−0.006*	0.000
Panel B: size effects (Pearson correlation coefficients)					
1st intervention day	0.085***	0.123***	0.096***	0.086***	−0.010
From 1 to *n*	−0.005	0.032	0.004	−0.009	0.051
From 2 to *n*	−0.053*	−0.034	−0.050	−0.059*	0.064*

Panel A reports the means and medians of the log-differenced implied exchange rate correlation series. Panel B reports the Pearson correlation coefficients for the dollar amounts of interventions and changes in implied correlations. *n* denotes the length of an intervention period, 'From 1 to *n*' denotes *n* days from the first day of the intervention period, and 'From 2 to *n*' denotes $n-1$ days following the first day of an intervention period. The statistical significance of the reported means and medians are tested with the *t*-test and the Wilcoxon signed rank test, respectively. ***, **, and * denote significance at the 0.01, 0.05, and 0.10 levels, respectively.

spot JPY/USD exchange rate. Furthermore, Panel A shows that when the first day of the intervention period is excluded from the analysis, all mean and median changes in implied correlations are negative and statistically significant at least at the 10% level. Hence, our findings suggest that an intervention event has a negative impact on implied correlations after the first day of the intervention period. Finally, although most of the mean and median figures for the whole intervention period in Panel A appear negative, none of them is statistically significant.

Next, we extend the analysis by considering also the size of the interventions, as measured by the BoJ's daily net purchase of U.S. dollars against the yen. Panel B of Table 2 reports the Pearson correlation coefficients for the dollar amounts of interventions and changes in implied correlations on the first day of the intervention period, during the whole intervention period ('from 1 to n'), and during the whole period except for the first intervention day ('from 2 to n'). As can be seen from Panel B, the Pearson correlation coefficients for the first day of the intervention period are positive and statistically significant at the 1% level, thereby suggesting that the size of the intervention matters. As discussed above in Section 3, a significant proportion of the BoJ interventions have been secret interventions (see Beine and Lecourt, 2004; Beine and Bernal, 2007), which are likely to affect exchange rates through the portfolio-balance channel or through microstructure and noise-trading effects. Given that the size of the intervention has an important role in these transmission channels, the findings reported in Table 2 may be partially related to the secrecy of the BoJ interventions. However, we are unable to find significant size effects for either the whole intervention period or for the period from which the first intervention day is excluded.

In order to control for the potentially related factors and to further analyze the behavior of implied correlations during the intervention period, we first estimate some standard multivariate regressions. Following Frenkel et al. (2005), we attempt to control for the impact of economic and/or political events by including the return on the JPY/USD spot rate as an independent variable.[18] Furthermore, we also include the lagged implied correlation estimate in the model in order to control for the level of exchange rate correlation. Thus, the following regression is estimated for each implied exchange rate correlation time-series:

$$ln\left(\hat{\rho}_t / \hat{\rho}_{t-1}\right) = \alpha + \sum_{i=1}^{m-1} \beta_i Int_t^i + \beta_m D_t^{m \dots n} + \gamma_1 \Delta s_{JPY/USD,t} + \gamma_2 \hat{\rho}_{t-1} + \varepsilon_t \tag{4}$$

where $\hat{\rho}_t$ denotes the estimate of implied exchange rate correlation, Int_t^i is the dollar amount of intervention on the *i*th intervention day, *m* indicates the day after the *i*th intervention day, *n* is the length of the intervention period, $D_t^{m \dots n}$ is a dummy variable indicating that a given day belongs to a sub-period of an intervention period ranging from day *m* to day *n*, and $\Delta s_{JPY/USD,t}$ denotes the difference between successive logarithmic JPY/USD spot rates. Since the Lagrange Multiplier test for ARCH effects indicates conditional heteroskedasticity in the error terms, we specify a GARCH(1,1) error structure. The Durbin-Watson statistics and the Godfrey test for serial correlation indicate no autocorrelation in the error terms of this specification.

Table 3 presents the estimates of Eq. (4). The estimation results for the one-month and three-month implied exchange rate correlations are reported in Panel A and Panel B of Table 3 respectively. The results show that the coefficients for Int_t^1, the dollar amount intervened on the first day of the intervention period, are positive and statistically highly significant in all 12 regression specifications. In contrast, the estimated coefficients for Int_t^i on the second and third days of the intervention period appear negative and statistically insignificant. Hence, our estimation results clearly indicate that the implied exchange rate correlations

[18] It should be noted that the return on the JPY/USD rate is affected by interventions and, on the other hand, that JPY/USD returns are likely to prompt interventions. Therefore, as a robustness check, we have also used the return on the JPY/EUR rate as an alternative control variable in Eq. (3). These estimations are consistent with the results reported in Table 3.

Table 3
Behavior of implied correlations during an intervention period.

Estimate	Change in 1-month €/$–¥/$ correlation				Change in 1-month £/$–¥/$ correlation			
	Model 1	Model 2	Model 3	Model 4	Model 1	Model 2	Model 3	Model 4
Panel A: 1-month horizon								
Constant	0.001	0.001	0.001	0.030***	−0.001	0.000	0.000	0.053***
	(0.39)	(0.51)	(0.61)	(3.73)	(−0.52)	(−0.19)	(0.07)	(7.31)
Int_t^1	0.027*	0.027*		0.029*	0.086***	0.085***		0.062***
	(1.79)	(1.78)		(1.88)	(6.88)	(7.03)		(6.44)
Int_t^2	−0.030		−0.032		−0.029		−0.020	
	(−1.09)		(−1.21)		(−1.31)		(−1.50)	
Int_t^3	−0.024				−0.033			
	(−0.45)				(−0.75)			
$D_t^{2\ldots n}$		−0.010***		−0.011**		−0.012***		−0.018***
		(−2.41)		(−2.61)		(−3.62)		(−5.63)
$D_t^{3\ldots n}$			−0.009**				−0.011**	
			(−2.08)				(−2.46)	
$D_t^{4\ldots n}$	−0.009*				−0.003			
	(−1.94)				(−0.56)			
$\Delta s_{\mathrm{JPY/USD},t}$				−0.338*				−1.600***
				(−1.85)				(−13.34)
ρ_{t-1}				−0.052***				−0.098***
				(−3.65)				(−7.17)
ARCH(0)	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
	(3.62)	(3.59)	(3.6)	(3.31)	(6.25)	(6.00)	(5.91)	(5.73)
ARCH(1)	0.093***	0.092***	0.091***	0.085***	0.220***	0.212***	0.208***	0.172***
	(6.58)	(6.6)	(6.53)	(6.33)	(12.54)	(12.57)	(13.15)	(14.98)
GARCH(1)	0.893***	0.896***	0.896***	0.904***	0.775***	0.783***	0.787***	0.825***
	(57.95)	(59.38)	(59.22)	(61.85)	(44.57)	(46.7)	(49.48)	(72.64)
Estimate	Change in 3-month €/$–¥/$ correlation				Change in 3-month £/$–¥/$ correlation			
	Model 1	Model 2	Model 3	Model 4	Model 1	Model 2	Model 3	Model 4
Panel B: 3-month horizon								
Constant	0.000	0.001	0.001	0.020***	0.000	0.001	0.000	0.030***
	(0.52)	(0.71)	(0.86)	(3.10)	(0.13)	(0.36)	(0.3)	(3.53)
Int_t^1	0.027***	0.027***		0.028***	0.075***	0.074***		0.074***
	(2.84)	(2.79)		(2.88)	(6.47)	(6.37)		(6.76)
Int_t^2	−0.014		−0.017		0.001		0.000	
	(−0.87)		(−1.09)		(0.04)		(−0.01)	
Int_t^3	−0.008				−0.021			
	(−0.41)				(−0.32)			
$D_t^{2\ldots n}$		−0.006**		−0.006**		−0.009**		−0.010**
		(−2.40)		(−2.36)		(−2.43)		(−2.48)
$D_t^{3\ldots n}$			−0.006**				−0.020**	
			(−2.08)				(−1.97)	
$D_t^{4\ldots n}$	−0.006				−0.010**			
	(−1.88)				(−2.16)			
$\Delta s_{\mathrm{JPY/USD},t}$				−0.380***				−0.656***
				(−3.32)				(−3.57)
ρ_{t-1}				−0.036***				−0.065***
				(−2.99)				(−3.41)
ARCH(0)	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
	(3.31)	(3.32)	(3.18)	(3.09)	(5.22)	(5.26)	(5.14)	(4.43)
ARCH(1)	0.098***	0.100***	0.093***	0.081***	0.148***	0.149***	0.140***	0.128***
	(5.33)	(5.38)	(5.24)	(5.03)	(8.48)	(8.53)	(8.17)	(7.92)
GARCH(1)	0.867***	0.864***	0.878***	0.892***	0.787***	0.788***	0.797***	0.829***
	(35.04)	(34.51)	(37.89)	(41.31)	(33.63)	(34.08)	(34.45)	(39.09)

The table reports the estimates of the following regression specification:

$$ln\left(\hat{\rho}_t/\hat{\rho}_{t-1}\right) = \alpha + \sum_{i=1}^{m-1} \beta_i Int_t^i + \beta_m D_t^{m\ldots n} + \gamma_1 \Delta s_{JPY/USD,t} + \gamma_2\,\hat{\rho}_{t-1} + \varepsilon_t$$

where $\hat{\rho}_t$ denotes the estimate of implied exchange rate correlation at time t, Int_t^i is the dollar amount of intervention on the ith intervention day, m indicates the day after the ith intervention day, n is the length of the intervention period, $D_t^{m\ldots n}$ is a dummy variable indicating that a given day belongs to a sub-period of an intervention period ranging from day m to day n, and $\Delta s_{\mathrm{JPY/USD},t}$ denotes the difference between successive logarithmic JPY/USD spot rates. t-values for the coefficient estimates are reported in parentheses. ***, **, and * denote significance at the 0.01, 0.05, and 0.10 levels, respectively.

increase on the first day of the intervention period, and furthermore, that the size of this increase is related to the dollar amount of the intervention.

Moreover, the results in Table 3 suggest that the increasing effect of interventions on implied correlations does not continue after the first day of the intervention period. It may also be noted from Table 3 that the estimated coefficients for dummy variables

Table 4
Reported and secret interventions.

Estimate	1-month ρ(€/\$,¥/\$)	1-month ρ(£/\$,¥/\$)	3-month ρ(€/\$,¥/\$)	3-month ρ(£/\$,¥/\$)
Constant	0.030***	0.052***	0.021***	0.032***
	(3.89)	(6.65)	(3.33)	(3.74)
$IntRep_t^1$	0.043**	0.071***	0.039***	0.091***
	(2.55)	(4.14)	(3.54)	(7.12)
$IntSec_t^1$	−0.062	0.021	−0.025	−0.039
	(−1.47)	(1.29)	(−1.09)	(−1.13)
$DRep_t^{2\ldots n}$	−0.026**	−0.062***	−0.011	−0.047***
	(−2.33)	(−4.09)	(−1.39)	(−3.74)
$DSec_t^{2\ldots n}$	−0.010**	−0.017***	−0.005*	−0.006
	(−2.03)	(−4.82)	(−1.68)	(−1.40)
$\Delta s_{JPY/USD,t}$	−0.387**	−1.659***	−0.411***	−0.730***
	(−2.15)	(−14.08)	(−3.60)	(−3.98)
ρ_{t-1}	−0.053***	−0.096***	−0.038***	−0.068***
	(−3.78)	(−6.52)	(−3.21)	(−3.62)
ARCH(0)	0.000***	0.000***	0.000***	0.000***
	(3.45)	(4.65)	(3.19)	(4.302)
ARCH(1)	0.077***	0.189***	0.072***	0.124***
	(5.82)	(11.42)	(5.11)	(7.60)
GARCH(1)	0.905***	0.824***	0.899***	0.825***
	(61.70)	(67.38)	(46.15)	(36.27)

The table reports the estimates of the following regression specification:

$$ln\left(\hat{\rho}_t/\hat{\rho}_{t-1}\right) = \alpha + \beta_1 IntRep_t^1 + \beta_2 IntSec_t^1 + \beta_3 DRep_t^{2..n} + \beta_4 DSec_t^{2..n} + \gamma_1 \Delta s_{JPY/USD,t} + \gamma_2 \hat{\rho}_{t-1} + \varepsilon_t$$

where $\hat{\rho}_t$ denotes the estimate of implied exchange rate correlation at time t, $IntRep_t^1$ is the dollar amount of intervention on the 1st reported intervention day, $IntSec_t^1$ is the dollar amount of intervention on the 1st secret intervention day, $DRep_t^{2\ldots n}$ and $DSec_t^{2\ldots n}$ are dummy variables indicating that a given day belongs to a sub-period of a reported or secret intervention period ranging from day 2 to day n, n is the length of the intervention period, and $\Delta s_{JPY/USD,t}$ denotes the difference between successive logarithmic JPY/USD spot rates. t-values for the coefficient estimates are reported in parentheses. ***, **, and * denote significance at the 0.01, 0.05, and 0.10 levels, respectively.

$D_t^{m\ldots n}$ are all negative and almost always statistically significant. This suggests that implied correlations decrease after the first day of the intervention period. Regarding the control variables, Table 3 shows that the exchange rate returns and the lagged implied correlations are negatively related to the changes in implied correlations. In all four regression specifications in which the control variables are included, their coefficients are statistically significant.

The results discussed above are robust to alternative definitions of an intervention period. Our estimates remain virtually unchanged if we allow a two day break or no breaks in the implementation of intervention. Furthermore, we have tested the robustness of our findings with several alternative regression specifications. First, we replaced the dummy variable $D_t^{m\ldots n}$ by the actual dollar amounts of interventions. Although the coefficient estimates for this alternative specification appear also to be statistically significant, the overall significances are somewhat lower, and thus, it is concluded that specifications reported in Table 3 are more appropriate. This conclusion is also consistent with the preliminary statistics reported in Table 2. Second, we have included two additional dummy variables that equal one around the intervention periods. Both of these dummy variables are statistically insignificant, thereby confirming that the implied exchange rate correlations are affected neither before the intervention period nor after it. By adding additional dummy variables, the analysis was also extended to cover the three days after the intervention period. None of these dummies either appears statistically significant, thereby further supporting the selected model specification.

We have also estimated a distributed lag model to further analyze how the effect of the size of intervention occurring at the first day of an intervention period is distributed across time. These estimations confirm that the implied exchange rate correlations increase on the first day of the intervention period. The magnitude of the increasing effect is positively related to the dollar amount intervened. Our distributed lag estimates, however, also indicate that the long-run effects of interventions on implied correlations are usually negative.

Finally, we divide the interventions into reported (i.e., perceived) and secret operations.[19] An intervention is considered as a secret intervention if it has not been reported to market participants on the day the intervention was conducted. As noted by Beine and Lecourt (2004) and Beine and Bernal (2007), the intervention policy adopted by the BoJ over recent years tends to favor the use of secret operations.[20] Although the signaling channel cannot be operating in case of secret interventions, these interventions may nevertheless affect exchange rate expectations through noise-trading and microstructure effects. This argument is supported by the empirical evidence in Frenkel et al. (2005) and Gnabo and Teiletche (2009).

[19] The data on reported and secret interventions were kindly provided by Michel Beine. As discussed in Beine and Lecourt (2004), the interventions are classified as reported and secret interventions based on news wire reports of Reuters and Bloomberg.

[20] About 24% of the BoJ interventions were reported to market participants during our sample period. Nevertheless, it should be noted that the reported interventions are, on average, more than twice as large as secret interventions (5.2 vs. 2.1 billion U.S. dollars). Consequently, the reported and secret interventions are almost evenly distributed in terms of dollar amounts of interventions.

Table 5
Comparison of implied correlations.

	1-month ρ(€/$,¥/$)	1-month ρ(£/$,¥/$)	3-month ρ(€/$,¥/$)	3-month ρ(£/$,¥/$)
Panel A: means and medians				
Means				
Regular period	0.648	0.556	0.632	0.495
Intervention period	0.562	0.502	0.585	0.468
Difference	0.086***	0.054***	0.047***	0.027***
t-value	6.14	3.62	4.78	2.71
Medians				
Regular period	0.665	0.558	0.643	0.490
Intervention period	0.574	0.476	0.592	0.479
Difference	0.064***	0.063***	0.036***	0.009*
Z-value	−5.94	−4.27	−4.58	−1.68
Panel B: Newey-West regressions				
Constant	0.365***	1.247***	0.609***	0.584***
Intervention period	−0.066**	−0.093***	−0.044**	−0.030
JPY/USD spot rate	0.002	−0.006***	0.000	−0.001
Adjusted R^2	0.073	0.071	0.039	0.011
F-stat.	19.69***	19.3***	10.78***	3.65**

The table reports the comparisons of the Fisher transformed implied exchange rate correlations. Intervention period indicates a period during which the BoJ intervenes excluding the first day of the period. Regular period is a period during which there are no intervention operations. Panel A of the table reports the means and medians of the Fisher transformed implied correlations and comparisons based on the *t*-test and the Wilcoxon signed rank test, respectively. Panel B of the table reports the estimates of the following regression specification:

$$\hat{\rho}_t^* = \alpha + \beta D_t^{2\ldots n} + \gamma S_{JPY/USD,t} + \varepsilon_t,$$

where $\hat{\rho}_t^*$ is the Fisher transformed implied correlation, $D_t^{2\cdots n}$ denotes the intervention period excluding its first day, and $S_{\mathrm{JPY/USD},t}$ is the JPY/USD spot exchange rate. The Newey-West heteroskedasticisty consistent covariance matrix is used to compute the standard errors. ***, **, and * denote significance at the 0.01, 0.05, and 0.10 levels, respectively.

The estimation results for the reported and secret interventions are presented in Table 4. In brief, the results in Table 4 suggest that implied exchange rate correlations are affected by both reported and secret interventions, although the effect of reported interventions seems to be more pronounced. This finding is broadly consistent with Frenkel et al. (2005) and Gnabo and Teiletche (2009). Consistent with the results in Table 3, the coefficients for $IntRep_t^1$ are positive and statistically highly significant in all four regressions, thereby indicating that reported interventions tend to increase option-implied correlations. However, in the case of secret interventions, the coefficient estimates for the first intervention day are all statistically insignificant. As can be noted from Table 4, the coefficients for the dummy variables are consistently negative for both reported and secret interventions. Thus, our estimates provide further evidence to suggest that the long-run effects of interventions on implied correlations are negative.

Overall, our empirical findings suggest that central bank interventions significantly affect the market expectations about future exchange rate co-movements.[21] Our estimations indicate that interventions tend to temporarily increase option-implied exchange rate correlations, while the long-run effects appear to be negative. This contrasting behavior of implied correlations in the short- and the long-run may be related to the leaning-against-the-wind behavior of the Japanese monetary authorities (see e.g., Ito, 2003; Hillebrand and Schnabl, 2006; Beine and Bernal, 2007; Ito and Yabu, 2007). Thus, our findings may indicate that the leaning-against-the-wind interventions by the BoJ affect exchange rate expectations in the short-run but not necessarily in the long-run.

4.2. Intervention episodes and the level of implied correlations

Our preceding analysis suggests that the long-run effects of interventions on exchange rate correlations may be negative. Therefore, we next examine whether the implied correlations are lower during the intervention days than during the non-intervention days. To analyze the correlations as levels, we first apply the Fisher transformation:

$$\hat{\rho}_t^* = 0.5\left[ln\left(\hat{\rho}_t + 1\right) - ln\left(\hat{\rho}_t - 1\right)\right] \tag{5}$$

where $\hat{\rho}_t^*$ and $\hat{\rho}_t$ denote the transformed and untransformed option-implied correlation estimates at time t, respectively.

Table 5 reports the comparisons of the implied correlations for the period from June 2002 through March 2004. This period is characterized by intense intervention operations by the Bank of Japan. The means of the Fisher transformed implied correlations for the intervention days excluding the first day of the intervention period and for regular no-intervention days are reported in Panel A of Table 5. As can be seen from the table, implied correlations are, on average, higher during regular days than during the intervention periods. A standard *t*-test suggests that the equality of implied correlations can be soundly rejected as all the differences are statistically highly significant. Furthermore, Panel A also reports the medians of the transformed implied

[21] Morel and Teiletche (2008) and Gnabo and Teiletche (2009) document systematic changes in option-implied probability distributions around interventions. Thus, our empirical findings provide further evidence about the effects of interventions on option-implied market expectations.

correlations. The equality of the reported medians is tested with the Wilcoxon signed rank test. Consistent with our findings for the means, the results for the medians indicate that implied correlations are significantly lower during intervention periods than during regular days with no central bank activity.

Finally, Panel B of Table 5 presents the estimates of the following regression specification:

$$\hat{\rho}_t^* = \alpha + \beta D_t^{2\ldots n} + \gamma S_{JPY/USD,t} + \varepsilon_t \tag{6}$$

where $\hat{\rho}_t^*$ is the Fisher transformed implied correlation, $D_t^{2\cdots n}$ denotes the intervention period excluding its first day, and $S_{\mathrm{JPY/USD},t}$ is the JPY/USD spot exchange rate.[22] The Newey-West autocorrelation and heteroskedasticity consistent covariance matrix is applied to take into account the autocorrelation and heteroskedasticity in the error terms of this model. Panel B shows that the constant term, which represents the implied correlation on a regular non-intervention day, is positive and statistically highly significant in all four regressions. Moreover, the estimates in Panel B indicate that implied exchange rate correlations are lower on the intervention days, as the coefficients for the dummy variable $D_t^{2\cdots n}$ are negative and statistically significant in three out of four regressions. Hence, these estimation results provide further support for the findings reported in Tables 2 and 3.

5. Conclusions

Central bank interventions in the foreign exchange markets are a controversial tool of exchange rate policy. Although monetary authorities seem to view intervention as an effective instrument of exchange rate policy, the empirical evidence on effects of interventions is mixed. In this paper, we examine the effects of central bank interventions from a novel perspective by focusing on the co-movements of exchange rates around interventions. Assuming that the triangular parity condition holds among a triplet of currencies, an effective intervention should not only affect the exchange rate in which the intervention is conducted, but also the cross-dynamics among the exchange rate triplet. Hence, to address whether central bank interventions induce changes in the cross-dynamics of exchange rates, we examine the effects of the official Bank of Japan (BoJ) yen-selling interventions on the ex ante correlations between the major exchange rates. The ex ante correlation estimates used in the analysis are extracted from the prices of OTC currency options.

Our empirical findings demonstrate that central bank interventions significantly affect the market expectations regarding future exchange rate co-movements. In particular, interventions are found to temporarily increase the option-implied correlations among the major exchange rates. Implied correlations increase significantly on the first day of a period of successive intervention days, and then decline during the remaining days of the intervention episode. We also find that the intervention periods are, on average, associated with lower-than-average levels of implied exchange rate correlations. In general, the findings reported in this paper indicate that central bank interventions are effective, at least in the short-run, in affecting market expectations about future exchange rate dynamics.

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