CENTRAL BANK FOREX INTERVENTIONS ASSESSED USING REALIZED MOMENTS*

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Abstract

This paper studies and assesses the impact of G3 official central bank interventions on the DEM/USD exchange rate properties using daily realized moments of exchange rate returns (obtained from intraday data) for the period 1989-2001. Event studies in terms of the realized moments for the intervention day, the days preceding and following the intervention day illustrate the shape of this impact. Rolling regressions results for an AR(FI)MA model for realized moments are used to measure the intervention impact and characterize its significance.

The analysis confirms previous empirical findings of an increase of volatility after a coordinated CBI. It highlights new findings on the timing and the persistence of coordinated interventions on exchange rate volatility, on important volatility spillovers, on the impact on exchange rate covariances and correlations and on skewness coefficients. The empirical findings are partly in line with the predictions of a theoretical model for central bank interventions developed by Vitale (1999).

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1 Introduction

In a period of thirteen years (1989-2001) central banks of the US, Japan and Germany (Europe) intervened about 430 times in either the DM-Dollar (DEM/USD) or the Yen-Dollar (YEN/USD) market. On average almost three interventions occurred per month. It is perhaps not surprising to see central banks frequently intervening in markets that are of crucial importance for the international competitiveness. Given the importance of foreign exchange markets it is for scientific and policy reasons of interest to assess the impact of Central Bank Interventions (CBI’s) on exchange rates. This paper belongs to the growing literature using intraday information to study the impact of CBI’s on forex markets. Previous studies have used daily or weekly forex (FX) data to document level and variance effects of CBI’s. Among the more recent literature using intraday data, Dominguez (2003) pays particular attention to the influence of intraday market conditions on effectiveness of the CBI’s.

The objective of the paper is threefold. First, by conducting event studies of the periods preceding and following CBI’s our aim is to document most of its effects, whether desired or not. Using daily realized moments (see a.o. Andersen, Bollerslev, Diebold and Labys 1999, 2001) obtained from hourly FX data on the DEM/USD rates for the period from January 4, 1989 to February 28, 2001, the paper analyzes the shape of the impact of CBI’s on the volatility and other higher moments as well as on several spillover measures. Interestingly, under appropriate conditions, daily realized moments yield consistent and highly efficient estimates of return moments and superior forecasts (see e.g. Andersen, Bollerslev, Diebold and Labys 2003, on realized volatility). Moreover they have the advantage to correct for specific hour-of-the-day effects. Using boxplots covering the intervention day, the two preceding days and the two days after we carry out an event study describing the pattern of the market reactions to interventions.¹ We distinguish between unilateral interventions by the Bundesbank and the US Federal Reserve respectively and coordinated interventions of these central banks on the DEM/USD rate. We also study the impact of spillovers on the DEM/USD rate of unilateral interventions of the Bank of Japan and the US Federal Reserve respectively and coordinated interventions of these Banks in the YEN/USD market.

Second, the paper goes beyond describing the impact of CBI’s. Using rolling regressions it attempts to explain movements in realized moments by relating these moments to the type of interventions. This analysis is carried out to measure sign, size and significance of the various types of interventions. Thereby, we hope to measure the most important effects of CBI’s on the exchange rate distribution. Third, the findings are interpreted in terms of theoretical results from the microstructure literature and the implications of the findings for modeling are discussed.

While our analysis resembles that of Dominguez (2003) in some respects, there are important differences. Unlike Dominguez (2003), that uses squared returns as a proxy of the observed volatility, we rely on a less noisy and more efficient realized moment measures to assess the impact of CBI’s on the dynamics of the exchange rates. The realized moments used are measures of the integrated (daily) moments, whereas the use of a single return reflects an instantaneous moment. Interestingly, the use of realized moments allows us to document new impacts in terms of cross and higher moments. Indeed, we find certain CBI’s to affect the skewness, to have significant

¹Throughout the paper, we will use the term “boxplot” to refer to the graphs reporting the evolution over time of the quartiles of the exchange rate realized moments. While the term might not be strictly appropriate, we follow the practice of the literature.
spillover effects from other foreign exchange markets and to increase the correlation between the major exchange rates (namely the DEM/USD and the YEN/USD).

The empirical findings indicate that the impact of CBI’s on first, second and third realized moments of exchange rate returns is temporary. Coordinated interventions are found to have been more effective than unilateral interventions in the DEM/USD market. There have been spillover effects from the DEM/USD marker to the YEN/USD market. The findings partially confirm the predictions from a theoretical model for CBI’s by Vitale (1999) in which an intervention acts in fact as the disturbance in an AR(1) process with drift. The optimal policy rule in this model for the central banks is linear in the past exchange rate level.

The paper is organized as follows. In Section 2, we report boxplots of various realized moments for the different types of interventions mentioned above, starting two days before the day when the intervention occurred and including realized moments up to the end of the second day after the intervention. After this visual and model free inspection, rolling regressions (rolled over the various hours of the day) are estimated on the realized moments to quantify (and test) the impact of CBI’s across hours of the day. In Section 3 we discuss the modelling implications of our empirical findings. To conclude, Section 4 draws some general lessons both for modelling and for policy interventions from our analysis.

2 The Impact of CBI’s on Daily Realized FX Moments

2.1 Introduction

As they convey a large piece of information about fundamentals and future monetary policies (see Mussa 1981), direct sterilized CBI’s in the FX markets are expected to exert important effects on exchange rate dynamics. While the core of the empirical literature devoted to studying the impact of CBI’s focused mostly on returns and volatility (see for a recent survey Sarno and Taylor 2001), the CBI’s may have other possibly unintended side-effects on exchange rates. As we will show, the effects also highly depend on the type of CBI.

We study the impact of official interventions on the DEM/USD over a period ranging from January 1 1989 to February 28 2001. Since we also look at cross-market effects, we also include in our investigation the YEN/USD exchange rate and the interventions occurring on this market. We use hourly data referring to GMT+1 physical time. Appendix 1 gives the details and the sources relative to the exchange rate data as well as the central bank interventions variables.

For two major exchange rates (DEM/USD and YEN/USD), we distinguish between six different types of official interventions:

1. unilateral interventions by the US Federal Reserve on the DEM/USD market denoted FEDU (observed on 64 days),

2The central bank interventions considered here are obviously sterilized. This rules out any scope for the so-called monetary channel.

3In this paper, we focus on official interventions and do not make any distinction between secret and reported interventions (see Dominguez 1998). While being interesting, the so-called secret puzzle (Sarno and Taylor 2001) mostly applies to the eighties. Since the beginning of the nineties, most major central banks have increased the transparency of their FX operations. This evolution is obvious for the Fed but also for the BoJ (see Ito 2002 on this point). Central bank customer transactions resulting from the request for foreign currency by the government are excluded from CBI’s.
2. unilateral interventions conducted by the Bundesbank (ECB after 1999) on the DEM/USD market denoted BBU (observed on 33 days),

3. coordinated interventions defined as interventions conducted on the DEM/USD market the same day and in the same direction by the two involved central banks denoted COORD (observed on 58 days),

4. unilateral interventions by the US Federal Reserve on the YEN/USD market denoted FEDUY (observed on 31 days),

5. unilateral interventions conducted by the Bank of Japan (BoJ) on the YEN/USD market denoted BoJU (observed on 178 days),

6. coordinated interventions defined as interventions conducted on the YEN/USD market the same day and in the same direction by the two involved central banks denoted COORDY (observed on 72 days).

Note that sometimes we make the distinction between CBI’s involving purchases or sales of USD. For instance, unilateral purchases (resp. sales) of the Fed are denoted by FEDUp (resp. FEDUs). In line with the empirical literature and consistent with the signalling channel, we use only intervention days but not the amounts involved in these operations. Table A1 in Appendix 1 reports the number of intervention days for each type of interventions as well as for sales and purchases on the DEM/USD market taken separately.

We study six potential effects:

1. effects in terms of exchange rate returns,

2. effects in terms of exchange rate volatility on the market on which the CBI takes place,

3. volatility spillover, i.e. effects on the volatility of a CBI in another market,

4. effects on the covariance between exchange rates,

5. effects on the correlation between exchange rates,

6. and effects on higher moments of exchange rates, namely skewness.

A major contribution of this paper is to provide new evidence of the impact of CBI’s on realized moments of intraday hourly exchange rate returns during the two days preceding an intervention, the intervention day itself and the two days after the intervention occurred. This allows to highlight several important findings in terms of CBI impacts, namely impact persistence and the importance of choosing the appropriate quotation time of the exchange rates. In the following subsections, we report for each case our findings and relate them to the literature.

\footnote{We neglect Bundesbank and BoJ interventions on the DEM/YEN market as they were relatively rare (5 occurrences).}

\footnote{Notice that the amounts of the recent ECB operations are unknown to external researchers.}

\footnote{For the sake of comparison with previous findings (Galati and Melick 1999), we focus only on skewness and do not consider kurtosis. Such an investigation is left for future work.}
2.2 Intradaily approaches

The use of intradaily data has been found to yield interesting insights on the impact of CBI’s, as documented for instance by Dominguez (2003). Actually, Dominguez (2003) relies on news reports provided by the wire services to capture the exact timing of the interventions. By contrast, no official release of the exact timing of the intervention operation is available. Therefore, one has to rely on reported rather than official interventions to assess the efficiency of FX operations conducted by the central banks. Nevertheless, there might be some discrepancy between both types of interventions. First, by using reported interventions rather than official interventions one neglects the so-called secret interventions, i.e. official interventions that are unknown to dealers in the FX markets. In this respect, Dominguez (2003) mentions that over the 1989-1995 period, 25% of the Fed interventions were not reported by Reuters. While the bulk of secret interventions took place mostly in the eighties, a significant number of CBI’s conducted by the BoJ in the early nineties remained secret. Our investigation period ranging from 1989 to 2001 obviously includes some secret interventions, which calls for an alternative approach to the use of intradaily data. Second, there might be a significant lag between the effective operation(s) and the reporting of CBI’s. Such a presumption is confirmed by the recent results obtained by Payne and Vitale (2003). Using reported interventions of the Fed they find that exchange rates react up to 45 minutes ahead of Reuters intervention reports. Importantly, the lengths of these lags may be variable as the reporting depends on the dealers willingness to release the information.

Intraday FX data are known to exhibit a complex seasonality, which gives rise to a striking repetitive (U-shape) pattern in the autocorrelations of the absolute or squared returns (proxies for the volatility). Importantly, Andersen and Bollerslev (1997) have shown that neglecting this seasonality pattern leads to misspecification biases and thus to misleading economic interpretations. One way to deal with this issue is to use a seasonal filter. As the CBI’s occur at regular time during business hours (as we will document from our subsequent estimations), the filtering procedure may remove much of the effect of these interventions.

As an alternative, one can include the seasonal dynamics in the GARCH specification as illustrated by Andersen and Bollerslev (1998). Nevertheless, relying on a standard intraday GARCH approach to characterize the impact of CBI’s on the first four moments would lead to a complicated and hardly manageable model. Furthermore, extending this approach to a multivariate GARCH framework would not be feasible (recall that the purpose of the analysis is also to investigate the impact of CBI’s on the covariance and the correlation between the DEM/USD and the YEN/USD).

Using the square of hourly returns might be an alternative but this leads to quite a noisy measure of instantaneous volatility (see Appendix 3). Furthermore, using intraday realized moments

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7One exception concerns the CBI’s carried out by the Swiss National Bank. See Payne and Vitale (2003).

8Interestingly, Dominguez (1999) uses two methods in order to account for intraday seasonal patterns in exchange rate volatility. This makes the estimation of the impact of reported interventions quite cumbersome. One question in using this approach concerns the relationship between the observed seasonal patterns and the occurrence of news or interventions. Dominguez (2003) does not include seasonal filtering but compares intraday volatilities (captured by the squared 5-minutes returns) between episodes of interventions and days of non intervention and tests for the equality of the two variances. While straightforward, this procedure does not rely on regressions allowing to capture the effects in terms of volatility persistence.

9In this respect, Martens, van Dijk and de Pooter (2004) show that both the squared daily returns and the realized volatility of the S&P500 stock index for the period 1994-2000 have almost the same mean (around 1.2 %) but as we would expect the standard deviation of the realized variance is (at 1.770) much smaller than the standard
(computed over a 24-hour period), as we propose in this paper, avoids having to worry about the intraday seasonality pattern. The implicit underlying hypothesis we make is that there is no interference between the seasonal components of volatility and the CBI’s. In other words, it is implicitly assumed in our regression analysis that the seasonal process characterizing exchange rate volatility is similar on interventions and non intervention days.

2.3 Effects on Daily Returns

Intervention policies may be prompted by different objectives. Amongst these objectives, influencing trend movements in the level of exchange rate returns is obviously the most frequent one. Estimations of central bank reaction functions (Almekinders and Eijffinger 1995; Baillie and Osterberg 1997) suggest that central banks “lean against the wind”. Trying to reverse undesirable trends has been the main objective of the Fed, the Bundesbank and the BoJ since the late seventies, with an important exception after the Louvre Agreement in February 1987 until the beginning of the nineties. One obvious recent example is provided by the very active intervention policy followed by the BoJ (Ito, 2002), leading to a weaker yen with the aim to improve the recent economic and financial situation in Japan.

In the theoretical study by Vitale (1999), central banks are assumed to minimize the expected costs which depend on the squared deviation of the exchange rate from its target value and on the square of the change of the exchange rate itself (see appendix 4). The resulting model for the exchange rate is an AR(1)-model with drift. The optimal policy rule of the central bank is linear in the level of the exchange rate in the past period. The impact of central bank orders on the return is ambiguous in this model. In particular, the effect might be weak when the degree of misalignment is low or when the CB targets a level which differs from the fundamental equilibrium exchange rate. In contrast, central bank orders are found to result in higher exchange rate volatility.

Unilateral interventions aiming at influencing exchange rate returns have been used by the three major central banks. However, as illustrated by the Plaza Agreement in September 1985 that promotes central bank cooperation in order to depreciate the dollar, coordinated interventions are considered as more effective for influencing the level of exchange rates (Catte et al. 1992). On the whole, the empirical literature provides very weak evidence on systematic impacts of CBI’s on exchange rate returns at a daily frequency. In general, authors do not identify any robust effect in the conditional mean of exchange rate returns (Baillie and Osterberg 1997). When effects on the spot exchange rate returns are detected, they are contrary to the objectives, i.e. purchases of US dollar leading to a depreciation of the dollar (Baillie and Osterberg 1997, Beine et al. 2002). This perverse result tends to hold for both unilateral and coordinated interventions. This result has usually been interpreted as a lack of credibility of central banks adopting a leaning-against-the wind policy. Recently however, focusing on the interventions conducted by the National Bank of Switzerland, Payne and Vitale (2003) find evidence of effective operations in the very short run (15 to 30 minutes).

In an extended version of the paper, Beine, Laurent and Palm (2004) have investigated the effect of CBI’s on the dynamics of the level of the DEM/USD exchange rate returns. Using the deviation of the daily squared returns (around 3.242 during this period).

10Focusing on the Fed policies, Dominguez (1999) reports four different aims: influencing trend movements in the level of exchange rates, calming disorderly markets (i.e. eliminating excess volatility), rebalancing the foreign exchange reserves and intervening in support of other central banks.
same methodology, no significant impact of CBI’s on the mean exchange rate is found. For the
details, the reader is referred to Beine et al. (2004).

2.4 Effects on Daily Volatility

Examples of explicit attempts to smooth exchange rate volatility through unilateral interven-
tions are provided by the policy followed by the Bank of Canada before 1995. Indeed, the Bank
of Canada adopted the rule of an automatic intervention when absolute daily changes of the
CAD/USD exchange rate (often used in the past together with squared daily returns as a proxy
of the volatility) exceeded some threshold. The Louvre Agreement promoted central bank co-
operation in order to counteract excess exchange rate volatility on the major FX markets. This
agreement resulted in frequent coordinated intervention operations of the Bundesbank and the

The literature provides some evidence that a CBI tends to increase exchange rate volatility.
Furthermore, such a finding is robust to the measurement of exchange rate volatility: this holds for
ex post volatility captured by univariate GARCH models (Baillie and Osterberg 1997, Dominguez
1998, Beine et al. 2002)\(^{11}\) and for ex ante or expected volatility measured by implied volatilities
extracted from currency option prices (Bonser-Neal and Tanner 1996, Dominguez 1998, Galati
and Melick 1999).

Following recent work of Andersen et al. (2001), we compute the daily realized volatility \(\sigma^2_{t,\theta}\) of
day \(t\) observed at time \(\theta\) (GMT+1) as the sum of the current and the 23 previous squared hourly
returns:\(^{12}\)

\[
\sigma^2_{t,\theta} = \sum_{j=0}^{23} r^2_{t,\theta-j},
\]

where \(r_{t,j}\) denotes the intraday hourly return (in percent) of the corresponding exchange rate on
day \(t\) between time \(j - 1\) and \(j\) (by convention \(r_{t,-j} = r_{t-24-j}\) for \(j = 1, 2, \ldots, 23\)). Preliminary
investigation and results reported in the literature (Andersen et al. 2001) suggest that the log of
FX daily realized volatility, i.e. \(\log(\sigma^2_{t,\theta})\), is nearly gaussian (and thus symmetrically distributed).

As shown in Appendix 3, unlike the daily squared returns that provide unbiased but very noisy
volatility proxies, the daily realized volatility yields consistent and highly efficient estimates of the
volatility (see Andersen et al. 2001 for more details about the properties of the realized volatility
in a continuous time framework).

An important issue in the empirical literature is that of simultaneity between the dynamics
of the exchange rate and the CBI’s. While this might be an issue with respect to the first
moment, several reasons suggest that a simultaneity bias is much more unlikely to occur for our
investigation on volatility.\(^{13}\) First, most investigations on central bank reaction functions using
daily data (Baillie and Osterberg 1997; Almekinders and Eijffinger 1994) suggest that in general,
central banks intervene in response of detrimental past exchange rate trends but not directly in
response to excess volatility. Second, given the practices of the monetary authorities and their
optimal time horizon (see Neely 2001) it is quite unlikely that a particular central bank will react
within a few hours to a perceived burst of exchange rate volatility. This is even more unlikely

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\(^{11}\)Such a positive impact of CBI is also confirmed by Beine (2004) in a multivariate GARCH framework.

\(^{12}\)We make use of the fact that at an hourly frequency, FX returns remain serially uncorrelated.

\(^{13}\)Notice that in the Vitale (1999) model sketched out in Appendix 4, there is no reverse causality between
interventions and returns.
when the central bank decides to coordinate with another central bank. This is in line with the microstructure theory as illustrated by the model sketched out in Appendix 4: past and current volatility are not supposed to trigger interventions. As mentioned before in the theoretical model of Vitale (1999) the central bank’s optimal policy rule for the amount of intervention is linear in the past level of the exchange rate. This rule therefore is a feedback rule. Even though it is not the case, the intra-daily dimension of our analysis somewhat protects our estimations against such a simultaneity bias since this would require very fast reaction of central bank to not directly observable variables.

2.4.1 Event study analysis

First of all, to assess the impact of CBI’s on the observed realized volatility, we perform an event study. In order to evaluate the effects of unilateral interventions by the Fed (denoted by FEDU) on the DEM/USD, Panel 1 of Figure 1 (labelled ‘FEDU’) plots the mean (solid line) as well as the first and third quartiles (dotted lines) of the subsample of daily log realized volatility $\log(\sigma^2_{t,\theta})$ for each intervention day, the two preceding days and the two days after. As shown by Barndorff-Nielsen and Shephard (2004), in the absence of jumps, realized volatility converges to integrated volatility as the intraday sampling frequency is increased. When jumps are present, realized volatility consistently estimates the sum of integrated volatility and the impact of the jumps. To the extent that CBI’s can be interpreted as jumps, the asymptotic result provides the basis for measuring their impact by the deviations of the pattern of realized volatility on intervention days from that on days with no intervention.

Since we have no precise information about the timing of the official interventions, we vary $\theta$ between 0 and 23 to describe the pattern of the market reactions to interventions. This gives a set of 24 points per trading day on each figure (ranging from 0 to 1 on the graph for the intervention day), each tick corresponding to an increment of $\theta$ (starting at 0 each day). Furthermore, to give a more comprehensive overview of the impact of CBI’s, the boxplots for the two days preceding (from -2 to 0 on the graphs) and following the intervention days (from 1 to 3 on the graphs) are provided as well.\footnote{We do not investigate here the presence of potential long run effects of interventions (such as J-shape effects), i.e. effects beyond 2 business days. This is consistent with the recent empirical literature (Dominguez 2003) stressing the importance of short-run effects and the evidence against persistent impacts.}

For the sake of illustration, point A on Panel 1 of Figure 1 corresponds to an estimate of $E[\log(\sigma^2_{t,0})|FEDU_t = 1]$, i.e. the conditional expected value of the log realized volatility computed at 0 hour (GMT+1) ($\theta = 0$) on day $t$ at which occurred a unilateral intervention of the Fed on the DEM/USD market ($FEDU_t = 1$). Similarly, point B is an estimate of $E[\log(\sigma^2_{t,1})|FEDU_t = 1]$. Using the definition of the realized volatility given in (1), it follows that $B - A = E[\log(r^2_{t,1}) - \log(r^2_{t-1,1})|FEDU_t = 1]$ so that if unilateral interventions of the Fed on the DEM/USD have no impact on the log realized volatility of day $t$, $B - A$ should be close to 0. In this case, the solid line should display a flat pattern. For the sake of understanding, the figures include vertical bars corresponding to specific hours. The bars allow to highlight specific dynamics such as sharp variations in the moments at the opening of local markets. The same comment applies to the conditional 25 and 75% quantiles. From that, one can infer that if the effect lasts for 24 ticks, this implies that the intervention caused a jump on the returns. If this lasts longer, this means that
we face a more lasting effect. If the effect lasts for less than 24 ticks, this indicates that the effects tend to be reverted.

From this graph, one can conclude that FEDU has no impact on the log realized volatility of the DEM/USD. Conclusions about BBU (Panel 2) are rather mixed. One hardly identifies a positive impact around 10.00 am GMT+1 on intervention days, i.e. shortly after the opening of the German market (in general at 8.00 am GMT+1). This suggests that in general, unilateral operations exert more limited impacts on the volatility dynamics compared to coordinated interventions.

Figure 1: Boxplots of CBI’s in terms of daily log realized DEM/USD volatility.

\[ A = E[\log(\sigma^2_{t,i,\theta}) | FEDU_t = 1] \]

\[ B = E[\log(\sigma^2_{t,1,\theta}) | FEDU_t = 1] \]

Note: On the horizontal axis of the graph, time is denoted by day \( i \), \( i \in \{-2, -1, 0, 1, 2\} \) and hour \( \theta \), \( \theta \in \{0, \ldots, 23\} \). The solid line denotes \( \hat{E}[\log(\sigma^2_{t+i,\theta}) | CBI_t = 1] \) as a function of \( i \) and \( \theta \) for \( t \in \{1, 2, \ldots, T | CBI_t = 1\} \). Each tick corresponds to an increment of \( \theta \) (starting at 0 each day). Similarly, the solid line and the two dotted lines correspond to the 50% and the 25% and 75% conditional quantiles.

From Panel 3 of Figure 1 (labelled ‘COORD’), one identifies an important increase of the log realized volatility related to coordinated interventions of the Fed and the Bundesbank (COORD). This result is fully consistent with the empirical literature (Beine et al., 2002; Dominguez, 2003). The documented positive impact on volatility is also in line with the theoretical microstructure approach in general (Lyons 2001) and with the predictions of the Vitale (1999) model (see Appendix 4) in particular. Nevertheless, two additional interesting features emerge from this picture. First, for coordinated interventions, one identifies a sharp increase in FX log realized volatility between 14:00 and 15:00 GMT+1 (see point C on the graph), i.e. less than two hours after the beginning of the overlap period (simultaneous opening of both markets). Notice that the time lag between the opening of the European FX market (in Frankfurt) and the US market ranges between 5 and 7 hours, depending on the light saving time. As reported by several authors including
Dominguez (1998, 2003), coordinated interventions between the Fed and the BB (ECB) primarily occur during the opening overlap period. Therefore, this means that the response of FX volatility to coordinated interventions is very fast, less than 3 hours, which is consistent with the findings of Dominguez (2003).

The shape of the graphs illustrates the importance of quotation time of exchange rates for capturing the impact of FX interventions in a consistent way. Regarding the persistence of these effects, this figure suggests that the effect of coordinated interventions is of very short duration. Indeed, the conditional mean of the log realized volatility reverts to its initial level (before the interventions) around point D. This point corresponds to the estimate of $E[log(\sigma^2_{t+1,17})|COORD_t = 1]$. Given that a particular squared hourly return $r^2_{t,i,j}$ will be included in the next 24 measures of realized FX volatility, this means that this impact lasts for about 3 hours.

The results suggest first that in general, unilateral operations exert more limited impacts on the volatility dynamics compared to coordinated interventions. This finding has strong implications for approaches based on daily data. Choosing a wrong quotation time of the exchange rate is likely to lead to underestimation of the impact of CBI’s on exchange rate volatility. The relevance of this result is illustrated further in Section 3.

2.4.2 Regression based approach

While the boxplots provide details about the timing and the persistence of the CBI’s on the investigated realized moment, it is not suited to make inference. Furthermore, unlike an event study type of analysis like the boxplot analysis, a regression analysis also includes the non interventions days, allowing to disentangle the impact of CBI’s from those possibly related to other macroeconomic announcements or seasonal effects peculiar to these intervention days. For this reason, rolling over all the possible values for $\theta$ ($\theta = 0, ..., 23$), we regress the log realized FX volatilities on the daily CBI’s data. We pay attention to the statistical properties of the FX realized volatilities. Preliminary investigation and results reported in the literature suggest that the log of FX daily realized displays some long memory (Andersen et al. 2001) and is sensitive to a day of the week effect (Hsieh 1989). Furthermore, the log transformation is a normality inducing transformation, which is useful for inference purposes. The DEM/USD realized volatilities tend to be higher on Monday than on other trading days of the week. In order to account for these features, we follow Andersen et al. (1999) in estimating an ARFIMA$(1,d,0)$ model which we extend by including a Monday dummy and more importantly dummy variables accounting for the types of CBI’s as additional explanatory variables:

$$(1 - \phi L)(1 - L)^d \left[ \log(\sigma^2_{t,\theta}) - \mu \right] = \epsilon_t + \mu_t,$$

where

$$\mu_t = \beta_0 MONDAY_t + \beta_1 FEDU_{t-i} + \beta_2 BBU_{t-i} + \beta_3 COORD_{t-i} + \beta_4 FEDUY_t + \beta_5 BoJU_t + \beta_6 COORDY_t,$$

in which $d$ (the fractional integration parameter), $\phi$, $\mu$, and the $\beta_j$’s, ($j = 0, ..., 6$) are parameters to be estimated, $MONDAY_t$ is a dummy variable taking value 1 on Monday, and 0 otherwise.

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15 We could nevertheless check for the significance of the moments given that we have the empirical distribution for any $i$ and $\theta$. However, the observations are not necessarily independent.
$FEDU_t, BBU_t, COORD_t, FEDUY_t, BoJU_t, COORDY_t$ are dummy variables taking value 1 when respectively a unilateral intervention of the Fed on the DEM/USD market, a unilateral intervention of the Bundesbank/ECB on the DEM/USD market, a coordinated intervention on the DEM/USD market, a unilateral intervention of the Fed on the YEN/USD market, a unilateral intervention of the BoJ on the YEN/USD market, a coordinated intervention on the YEN/USD market took place on day $t$, 0 otherwise. $\epsilon_t$ is the error term which is assumed to be normally and identically distributed. Estimating model (2) for each combination of the various possible values of indexes $i$ ($i = -2, -1, 0, 1, 2$) and $\theta$ ($\theta = 0, ..., 23$) one obtains a sequence of estimates of coefficients $\beta_j$ ($j = 1, 2, 3$), allowing to capture the evolution of the impact and the persistence of interventions across hours and days. The interventions carried out on the YEN/USD market are introduced as control variables. Our interest lies at this point in the evolution over time of $\beta_1, \beta_2$ and $\beta_3$. Their effect is therefore constrained to be contemporaneous ($i = 0$), which is in line with the evidence provided by the boxplot analysis. The models are estimated over the period January 4 1989 to February 28, 2001 (3061 points). Figure 2 reports the sequence of point estimates of respectively $\beta_1, \beta_2$ and $\beta_3$ as well as their 95% confidence intervals. Note that the information on the confidence intervals allows one to test the significance of the slope coefficients for specific values of $\theta$. Estimation of the ARFIMA models is carried out by exact maximum likelihood under the normality assumption using the ARFIMA 1.01 package of Doornik and Ooms (1999).

Figure 2: Rolling regressions and DEM/USD volatility

Note: The solid lines correspond to the sequence of $\hat{\beta}_j$ ($j = 1, 2, 3$) parameters of the ARFIMA(1, $d$, 0) model 

$$(1 - \phi L)(1 - L)^d \log(\sigma^2_t) = \epsilon_t + \mu_t,$$

where $\mu_t = \beta_0 \text{MONDAY}_t + \beta_1 \text{FEDU} _{t-1} + \beta_2 \text{BBU} _{t-1} + \beta_3 \text{COORD} _{t-1} + \beta_4 \text{FEDUY} _t + \beta_5 \text{BoJU} _t + \beta_6 \text{COORDY} _t$ for each combination of the various possible values of indexes $i$ ($i = -2, -1, 0, 1, 2$) and $\theta$ ($\theta = 0, ..., 23$). The two dotted lines correspond to the 95% confidence interval.
Results from rolling regressions confirm the conclusions drawn from the investigation of the boxplots but they also bring new insights. First, unilateral interventions by the Fed on the DEM/USD market (FEDU) have no significant impact on the log realized volatility (see Panel 1 of Figure 2, labelled ‘FEDU ($\beta_1$)’), regardless the time quotation. Second, Panel 2 of Figure 2, labelled ‘BBU ($\beta_2$)’ suggests that unilateral interventions of the Bundesbank on the DEM/USD (BBU) exert significant effects on FX log volatility (which was not identifiable from the boxplot reported in Figure 1), albeit less important than those exerted by coordinated interventions. Third, the timing of the impact on FX log volatility is quite different from the one particular to coordinated interventions: FX volatility seems to react to BBU intervention in the morning (European time), i.e. around $\theta = 7$ while coordinated interventions have their impact during the overlap period, i.e. around $\theta = 15$.\(^{16}\) This is consistent with the fact that, without the need to coordinate and thus to take advantage of the market overlap, US and German authorities also choose to conduct FX operations when only their local market is opened (see Dominguez 2003). Fourth and importantly, rolling estimates allow to characterize the persistence of coordinated and unilateral intervention. This is an important point, as there is a striking lack of consensus (both among academics and practitioners) about the typical horizon over which CBI’s exert some significant impact (see the survey of Neely 2001 on this point). For coordinated interventions, in line with the evidence drawn from the boxplots (Figure 1), the pattern of $\beta_3$ estimates sharply increases at 15:00 GMT+1, i.e. one hour after the opening of the US market, confirming that the response to CBI’s is very fast. The significance of the $\beta_3$ estimates at time $t + 1$ sharply drops after 16:00 GMT+1, i.e. one hour before the closing of the German market. Given that a particular squared hourly return $r^2_{t,j}$ will be included in the next 24 measures of (log) realized FX volatility, this means that this impact is of short duration, at most 2 hours. This finding has strong implications for approaches based on daily data. Choosing a wrong quotation time of the exchange rate is likely to lead to underestimation of the impact of CBI on exchange rate volatility. This point will be illustrated further in Section 4. The persistence of the Bundesbank interventions is even shorter since one identifies a drop in the $\beta_2$ coefficient estimated at $\theta = 7$ on day $t + 1$. This confirms that the impact is weaker, both in terms of magnitude and persistence.

2.5 Daily Volatility Spillover Effects

In the literature little attention is devoted to volatility spillover effects of intervention in one market on the FX volatility to another market. The regression (2) accounts for contemporaneous spillover effects on volatility.\(^{17}\) Nevertheless, in line with the extensive evidence on volatility spillovers between international stock markets, major exchange rate markets are likely to be highly interdependent. Therefore, news and financial events particular to a market are likely to exert volatility effects on the other markets. Using univariate GARCH models of DEM/USD and YEN/USD exchange rates over the 1985-1995 period, Dominguez (1998) does not detect any robust effect of this type. By contrast, in a multivariate GARCH framework, Beine (2002) finds that coordinated

---

\(^{16}\)The sharp increase in the $\beta_2$ coefficient at $\theta = 7$ is somewhat puzzling as the European market is in general closed at this time. Nevertheless, as stressed by Dominguez 2003, while central banks tend to operate on their own local markets, there is a wide range of time interventions. For example, the Fed is reported to intervene also during Japanese trading time.

\(^{17}\)Note that one could of course also study the spillover effects on FX returns and higher moments. This has not been done as the impact of direct CBI’s on these statistical measures has not been found to be substantial.
Interventions on the YEN/USD market (COORDY) tend to increase exchange rate volatility on the DEM/USD market. Likewise, Dominguez (2004) finds that BoJ interventions tend to raise exchange rate volatility in the DEM/USD market.

In this section, we propose to test specifically whether CBI’s conducted on the YEN/USD have an impact on the volatility of the DEM/USD. This type of volatility spillover effect can be displayed if the $\beta_j$ ($j = 4, 5, 6$) coefficients in the ARFIMA model defined in (2) are significant, where $\mu_t$ is now specified as follows:

$$
\mu_t = \beta_0 \text{MONDAY}_t + \beta_1 \text{FEDU}_t + \beta_2 \text{BBU}_t + \beta_3 \text{COORD}_t + \beta_4 \text{FEDUY}_{t-1} + \beta_5 \text{BoJU}_{t-1} + \beta_6 \text{COORDY}_{t-1}.
$$

(3)

Estimating this model for each combination of the various possible values of indexes $i$ ($i = -2, -1, 0, 1, 2$) and $\theta$ ($\theta = 0, \ldots, 23$) one obtains a sequence of estimates of coefficients $\beta_j$ ($j = 4, 5, 6$), allowing to capture the evolution of the impact and the persistence of interventions across hours and days. The interventions carried out on the DEM/USD market are here only control variables and therefore introduced only in a contemporaneous way. The models are estimated over the period January 4, 1989 to February 28, 2001 (3061 points).

The sequence of estimates of parameters $\beta_4, \beta_5$ and $\beta_6$ provide a measure of these volatility spillover effects. Figure 3 exhibits the presence of important volatility spillovers for all types of interventions, albeit less significant for unilateral Fed interventions. Once more, Figure 3 documents the intra-day variation of these effects. Volatility spillover effect of unilateral BoJ interventions ($\beta_5$) shows up at 1:00 (GMT+1), i.e. one hour after the opening of the Japanese market. Interestingly, like for volatility effects, the pattern of $\beta_5$ estimates suggests that the response to a CBI is very fast, at most two hours. Not surprisingly, the timing of BoJ impact contrasts with the one related to coordinated interventions ($\beta_6$) which shows up in the US afternoon trading time. Basically, due to the absence of overlap between the Japanese and the US market and given that central banks generally prefer to intervene on their own market, coordinated interventions exert some impact when the Fed follows the BoJ, i.e. during the opening of the US market.\textsuperscript{18}

### 2.6 Daily Effects on Covariances and Correlations

As suggested in the extensive literature on market contagion, a CBI could also exert some significant spillovers in terms of covariance and correlation between exchange rates. One obvious reason is related to two distinct pieces of evidence. First, as reported in the empirical literature and fully confirmed by evidence reported above, CBI’s tend to increase exchange rate uncertainty. Second, there is also strong evidence that correlations and/or covariances between asset prices vary over time. Furthermore, there is evidence on the existence of a positive link between correlation and volatility pattern (see Andersen et al. 2001 for empirical evidence about exchange rates). Therefore, one might expect that CBI’s that increase FX volatility also lead to a positive impact on cross-moments of exchange rates, especially on the covariance and to a lesser extent on the correlation. This feature has not been extensively investigated in the literature. The only evidence we are aware of is Beine (2004) showing for a multivariate GARCH model estimated on

\textsuperscript{18} Once again, the increase in volatility after the close of the New York market suggests that some of the Fed interventions occur during Japanese trading time, which is consistent with the evidence provided by Dominguez 1999, 2003.
daily data that coordinated interventions on the YEN/USD market induced a strong and positive impact on both the covariance and the correlation between the YEN and the DEM against the USD. This result does not hold however for unilateral interventions.

The empirical investigation in this particular field is constrained by the difficulties in handling and estimating multivariate GARCH models, especially when covariates enter both the conditional variances and conditional covariance/correlation equations. From this perspective, realized covariances and correlations directly built from the intraday returns are a useful alternative for capturing such impacts. Realized covariances between the DEM/USD and the YEN/USD (denoted $\sigma_{xy}^{dy}$) can be computed in a similar way as realized variance:

$$
\sigma_{xy}^{dy} = \sum_{j=0}^{23} c_{t,\theta-j},
$$

(4)

where $c_{t,j}$ denotes the instantaneous covariance (cross-product) between the DEM/USD and the YEN/USD for interval $j$ of day $t$. Realized correlation ($\rho_{t,\theta}$) may also be directly computed as:

$$
\rho_{t,\theta} = \frac{\sigma_{xy}^{dy}(t,\theta)}{\sigma_{x}^{dy}(t,\theta)\sigma_{y}^{dy}(t,\theta)}
$$

(5)
in which \( \sigma^d_{t, \theta} \) and \( \sigma^y_{t, \theta} \) are the realized standard deviations of respectively the DEM/USD and the YEN/USD (see Subsection 2.4).

Using the same approach to that described above, boxplots have been obtained for patterns of the covariances and correlations between the DEM/USD and the YEN/USD associated with coordinated and unilateral interventions. The graphs reported in Figure 4 provide the effect associated with coordinated interventions on the DEM/USD market (COORD). The first two graphs (top) correspond to the boxplots obtained respectively for the realized covariance (left) and the realized correlation (right). Unlike the log realized volatility, these two realized moments are not symmetrically distributed. Therefore, in addition to the conditional mean (solid line), the conditional median (dashed line) as well as the first and third conditional quartiles (dotted lines) are reported. The figures clearly suggest a strong positive response to coordinated interventions both on the covariance and the correlation. Interestingly, the timing of the response of covariances is fully in line with that associated with exchange rate volatility (see Figure 1).

Figure 4: Boxplots (top) and rolling regressions (bottom) for coordinated interventions by the Fed and Bundesbank (COORD) on the daily realized covariance (left) and correlation (right) between the DEM/USD and YEN/USD

![Boxplots and Rolling ARFIMA Diagram](image-url)

Note on the Boxplots: On the horizontal axis of the graph, time is denoted by day \( i, i \in \{-2, -1, 0, 1, 2\} \) and hour \( \theta, \theta \in \{0, \ldots, 23\} \). The solid lines of the first two graphs (labelled ‘Boxplot’) correspond to \( E[\sigma^d_{t+i, \theta}|\text{COORD}_t = 1 \) and \( E[\rho_{t+i, \theta}|\text{COORD}_t = 1 \) as a function of \( i \) and \( \theta \) for \( t \in \{1, 2, \ldots, T|\text{Coord}_t = 1 \) \). Each tick corresponds to an increment of \( \theta \) (starting at 0 each day). Similarly, the dashed lines and the two dotted lines correspond to the 50% and the 25% and 75% conditional quantiles.

Note on the rolling ARFIMA: The solid lines of the last two graphs (labelled ‘rolling ARFIMA’) correspond to the sequence of \( \beta_j \) \((j = 1, 2, 3)\) parameters of the ARFIMA model estimated respectively on the realized covariance (left) and realized correlation (right), where \( \mu_t = \beta_0\text{MONDAY}_t + \beta_1\text{FEDU}_t + \beta_2\text{BBU}_t + \beta_3\text{COORD}_t + \beta_4\text{FEDU}_t + \beta_5\text{BoJ}_t + \beta_6\text{COORD}_t \) for each combination of the various possible values of indexes \( i \) \((i = -2, -1, 0, 1, 2)\) and \( \theta \) \((\theta = 0, \ldots, 23)\). The two dotted lines correspond to the 95% confidence interval.

In order to complement the evidence of the boxplots, we run rolling regressions for the patterns of covariance and correlation responses to the different types of CBI’s. The hyperbolic decay of the
autocorrelations of these two realized moments calls for the use of a long memory model similar to the one fitted for the variances (see again Andersen et al. 2001). For this reason, we estimate model (2) for the realized covariance and correlation replacing $\log(\sigma_t^2, \theta)$ by $\sigma_{t, \theta}^d$ and $\rho_{t, \theta}$, respectively. Like for the volatility analysis, we account for the different kinds of interventions on the markets of both currencies since in the ARFIMA specifications, $\mu_t = \beta_0 \text{MONDAY}_t + \beta_1 \text{FEDU}_{t-1} + \beta_2 \text{BBU}_{t-1} + \beta_3 \text{COORD}_{t-1} + \beta_4 \text{FEDUY}_t + \beta_5 \text{BoJU}_t + \beta_6 \text{COORDY}_t$. The interventions carried out on the YEN/USD market are once more introduced only as control variables, so that our interest lies in the evolution over time of $\beta_1$, $\beta_2$ and $\beta_3$.

The patterns of coefficient estimates related to the variable COORD as well as their confidence intervals are reported at the bottom of Figure 4, respectively for the realized covariance (left) and the realized correlation (right). These two graphs confirm the previous findings that coordinated interventions of the Fed and the Bundesbank have a positive impact on the realized covariance and correlation. Interestingly, both the timing and the persistence of this effect are similar to those for exchange rate volatility.\footnote{The impact on correlation estimates becomes significantly positive for $\theta = 23$. This is due to the offsetting impacts on the covariance on one side and on both variances (direct and spillover effects) on the other.}

Figure 5 exhibits the sequences of parameters $\beta_1$ and $\beta_2$ in equation (3) applied to cross-moments. Boxplots are not reported here to save space. On one hand, the patterns of estimates suggest that unilateral interventions have a significant impact on the realized covariance, although much lower than that for coordinated operations. As claimed by Beine (2004), accounting for these effects on cross-moments is of high importance in many applications in portfolio and risk management of currencies. On the other hand, contrary to coordinated interventions, unilateral interventions have no impact on the realized correlation, suggesting that the impact on covariances is offset by that on variances.

The results related to the interventions on the YEN/USD market lead to similar conclusions. They are not reported here to save place. The findings can be summarized as follows. First, coordinated interventions tend to increase both the covariance and the correlation. In contrast, unilateral operations exert some positive impact only on the realized covariance. Second the timing of the impact on cross-moments and their persistence tend to match those documented for the volatility. Finally, as a whole, these results are consistent with those of Beine (2004). These impacts display much intraday variation, stressing once again the importance of the time quotation for empirical analysis.

### 2.7 Effects on Daily Higher Moments

Little research has been conducted in order to capture the impact on higher moments, i.e. skewness and kurtosis. Skewness dynamics may be of particular interest since it captures the evolution of downside or upside risk on a particular market. Galati and Melick (1999) have attempted to fill this gap. Using implied probability densities of market expectations at a one-month horizon drawn from currency option prices, they do not find any significant impact of perceived coordinated CBI’s on third moments. However they do not focus on unilateral interventions and limit their investigation to perceived rather than official interventions.\footnote{It is unclear whether the two series significantly differ from each other. The discrepancy depends on the occurrence of both secret interventions and false rumors.} We are not aware of any study of the impact on ex post third and/or fourth moments. The lack of such studies is probably...
Figure 5: Rolling regressions for unilateral Fed (top) and Bundesbank (bottom) interventions effects on the daily realized covariance (left) and correlation (right) between the DEM/USD and YEN/USD

Note: The solid lines correspond to the sequence of $\hat{\beta}_1$ (top) and $\hat{\beta}_2$ (bottom) parameters of the ARFIMA model estimated respectively on the realized covariance (left) and realized correlation (right), where $\mu_t = \beta_0_{\text{MONDAY}} + \beta_1FEDU_{t-i} + \beta_2BBU_{t-i} + \beta_3COORD_{t-i} + \beta_4FEDUY_t + \beta_5BoJU_t + \beta_6COORDY_t$ for each combination of the various possible values of indexes $i$ ($i = -2, -1, 0, 1, 2$) and $\theta$ ($\theta = 0, ..., 23$). The two dotted lines correspond to the 95% confidence interval.

due to the difficulty of handling parametric models based on more general distributions than the symmetric Gaussian and Student distributions. Estimation of a model with skewed distributions and time-dependent conditional moments is obviously more cumbersome.

Alternatively, a simpler approach is to consider the realized skewness defined as:\[21\]
\[Sk_{t,\theta} = \frac{\sum_{j=0}^{23} r_{t,\theta-j}^3}{\left(\sigma_{t,\theta}^2\right)^{3/2}}.\] \[6\]

The measure of realized skewness in (6) neglects any dependence between the terms $r_{t,\theta-j}^2$ and $r_{t,\theta-j}$.\[22\] The methodology presented in the previous sections has been applied on (6) to quantify the effect of CBI's on the realized skewness of the DEM/USD.

Boxplots of skewness dynamics (see the top panels of Figure 6) suggest that the realized skewness reacts to coordinated USD purchases on the DEM/USD market. Indeed, coordinated purchases ($COORDp$) of dollars lead to strong decreases of the realized skewness of the DEM/USD during the intervention day. The timing of this effect seems consistent with the ones previously

\[21\] See Appendix 3 for technical details about the realized skewness.
\[22\] Using a standardized skewness measure as in (6) has the advantage of correcting for spurious time-dependence resulting possibly from time dependent conditional volatility (see e.g. Korkie, Sivakumar and Turtle 2003).
Figure 6: Boxplots (top) and rolling regressions (bottom) for the effects of coordinated sales (left, i.e. \( \text{COORD}_s \)) and purchases (right, i.e. \( \text{COORD}_p \)) of USD by the Fed and the Bundesbank on the DEM/USD market on the daily realized skewness

Note on the Boxplots: On the horizontal axis of the graph, time is denoted by day \( i \), \( i \in \{-2, -1, 0, 1, 2\} \) and hour \( \theta \), \( \theta \in \{0, \ldots, 23\} \). The solid lines of the first two graphs (labelled ‘Boxplot’) correspond to \( E[Sk_{t+i,\theta} | \text{COORD}_s t = 1] \) and \( E[Sk_{t+i,\theta} | \text{COORD}_p t = 1] \) as a function of \( i \) and \( \theta \) for \( t \in \{1, 2, \ldots, T | \text{COORD}_s t = 1\} \) and \( t \in \{1, 2, \ldots, T | \text{COORD}_p t = 1\} \) respectively. Each tick corresponds to an increment of \( \theta \) (starting at 0 each day). Similarly, the two dotted lines correspond to the 25% and 75% conditional quantiles.

Note on the rolling ARMA: The solid lines of the last two graphs (labelled ‘rolling ARMA’) correspond to the sequence of \( \hat{\gamma}_j \) \( (j = 1, 2) \) parameters of the ARMA model (7), where \( \gamma_1 = \gamma_1 \text{COORD}_s t + \gamma_2 \text{COORD}_p t + \gamma_3 \text{BBUs} t - \gamma_4 \text{FEDUs} t - \gamma_5 \text{FEDU} p t \) for each combination of the various possible values of indexes \( i \) \( (i = -2, -1, 0, 1, 2) \) and \( \theta \) \( (\theta = 0, \ldots, 23) \). The two dotted lines correspond to the 95% confidence interval.

documented for the volatilities and the cross-moments, i.e. occurring around 15.00 GMT+1. By contrast, unilateral interventions of the Fed and the Bundesbank do not seem to exert any significant impact on the realized third moment. These graphs are not reported here to save space but are available in Beine, Laurent and Palm (2004).

The general picture is confirmed by the results for the rolling regressions (bottom panels of Figure 6). The specification used for capturing the impact of interventions on skewness differs from volatility models defined in (2) with respect to both the type of parametric models and the way interventions are defined. Preliminary analysis shows that there is a very fast decrease in the autocorrelations of \( Sk_{t,\theta} \), regardless the value of \( \theta \). Therefore, a basic ARMA model seems sufficient to capture the dynamics of the daily realized skewness. Second, like for exchange returns, the sign of the intervention operation matters. Furthermore, boxplots reported in Figure 6 suggest that coordinated purchases of USD exert much more important effects than coordinated sales. This implies that one should account for distinct effects of purchases and sales in the rolling regressions.

The last two graphs (bottom) of Figure 6 display the patterns of the \( \gamma_1 \) are \( \gamma_2 \) coefficients estimated
from the following models ($\theta = 0, ..., 23; i = -2, ..., 2$):

$$(1 - \phi L)(S_{k,\theta} - \gamma) = \epsilon_t + \gamma_t$$

where

$$\gamma_t = \gamma_1 COORDs_{t-i} + \gamma_2 COORDp_{t-i} + \gamma_3 BBU_{s_{t-i}} + \gamma_4 FEDU_{s_{t-i}} + \beta_5 FEDU_{p_{t-i}}.$$ 

The time-variation of the $\gamma_2$ coefficient in Figure 6 suggests that coordinated purchases of the Fed and the Bundesbank have some impact within 2 hours after the beginning of the market overlap. Coordinated purchases of USD lead the market to put more weight on a appreciating dollar than on a weaker dollar, which confirms recent findings that CBI’s can be effective in the (very) short run (Payne and Vitale 2003). The effect of coordinated USD sales is much less striking. Note that, in line with the boxplot analysis, unilateral interventions were not found to affect the realized skewness in a significant way (the graphs are available in Beine, Laurent and Palm 2004).

The analysis can be extended to the investigation of the dynamics of the fourth realized moments. The time variation of the fourth moments is indicative of the time varying probability of occurrence of extreme events. A better understanding of its variation over time is of importance for financial applications such as risk management. This extension is left for future work.

2.8 Microstructure interpretation of the findings

On the whole, our findings suggest that CBI’s induce some jump in the dynamics of the exchange rate. The global picture is therefore fully consistent with the approach proposed by Vlaar and Palm (1993) in terms of a normal mixture specification with jumps. Beine and Laurent (2003) rely on a normal mixture model with a time varying jump probability related to the occurrence of (daily) CBI’s. They show that coordinated interventions significantly increase the probability of a jump in the exchange rate. While there is no significant systematic change in the level in one or another particular direction, it increases the volatility. These findings are thus consistent with our results regarding the first and second realized moments. Nevertheless, unlike the analysis provided here, the normal mixture specification does not appropriately capture effects on higher moments. In this respect, our results show that this jump induces a change in the third moment.

Given the intraday dimension of the analysis, it is interesting to relate our findings to the microstructure approach of financial assets. This literature distinguishes between two approaches, the inventory-based approach and the information-based approach respectively (see e.g. O’Hara 1995 and Lyons 2001). The inventory-based approach emphasizes the balancing problem on markets resulting from moderate (stochastic) deviations in inflows and outflows. These deviations could be the result of a CBI. In general, they are assumed to be unrelated to the future value of

\footnote{For the sake of robustness, we also carried out the boxplot and the regression analysis using isolated interventions. Interventions are defined as isolated if they are not followed by another intervention of the same type in the next two days. Alternatively, one could have suppressed sequences of successive interventions regardless the type of intervention (unilateral or coordinated) but this results in very few occurrences of events. On the whole, the results are robust for the second and third moments, somewhat less for the realized returns. Nevertheless, regarding this last case, one should emphasize that these results are found using quite a small number of events and are not uniform for each quantile. For the sake of brevity, these results are not reported here but are available upon request.}
the asset traded but they can affect the short-run behavior of the market in terms of order flows, bid-ask spreads, transactions and prices. For the long run, assuming that market participants can adjust their positions and quotes, these differences in the fluctuations of inflows and outflows are irrelevant. Our findings on the impact of the CBI’s appear to be of a temporary nature only. In that respect our results are in agreement with the predictions from the inventory approach stressing the rebalancing in the market following a CBI (see also Domínguez 2003). Our results appear to be in line with the predictions from the theoretical model by Evans and Lyons (2001), that the generally predicted strong price effect resulting from portfolio rebalancing, turns out to be small if the order flow following a CBI is expected to be reversed as central banks sterilize their intervention whereby key fundamentals such as the money supply and interest rates remain unaffected. The transitory spillover effects from one foreign exchange market to the other are also likely to result from temporary portfolio rebalancing by central banks.

The informational approach to micromarket structure focuses on the question how price formation takes place and how market participants learn about the market. High volatility corresponds to a period of much informed trading as informed traders can then hide the volume of their transactions more easily. The informational approach predicts an increase in transaction volume and volatility following a CBI. Once the intervention news has been revealed, transaction volume and prices should revert to pre-intervention levels. This is what we observe for volatility in our event studies of various types of interventions. Volatility increases in reaction to intervention news. Soon after a CBI, volatility returns to its pre-intervention level. Also, the finding that the CBI impact on volatility in high volatility periods is more pronounced than in low volatility regimes is in line with the prediction from the information-based approach that longer-run effect are related to factors such as information processing. Turbulent market conditions require more time to revert to initial levels. Actually, both types of approaches provide little insight into how long adjustment processes take. Our results concerning the volatility spillover effects are also consistent with some recent theoretical and empirical analyzes based on the informational approaches (Evans and Lyons 2002) showing that information revealed via order flows in a given exchange rate market is impounded in other currency markets.

Our findings are partially in line with the theoretical results of Vitale (1999) implying that in the presence of CBI’s, the exchange rate follows an AR(1)-process with drift and that the optimal policy rule for the amount of the intervention is linear in the past level of the exchange rate. On the one hand, the model implies significant impacts of CB interventions on the returns. On the other hand, Vitale (1999) identifies circumstances in which this impact is quite low. It is the case when the CB follows its own target, regardless of the level of misalignment of the exchange rate.24 Also, the model predicts a positive impact on volatility, which is clearly in line with the main finding of our analysis.

3 Implications for Modelling the Impact of CBI

One striking implication of our analysis lies in the emphasis on the importance of the quotation time of the exchange rate for capturing daily effects of CBI. The patterns of coefficients capturing

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24 It should be stressed that such a situation is not a pure theoretical curiosity. For instance, over the 1991-2004 period, more than 50 percent of the BoJ interventions against the USD were carried out in the direction opposite to the reduction of the misalignment of the USD with respect to the YEN (see also Ito, 2002 on this point.)
the responses of CBI’s in terms of volatility (Figure 1) suggest that the impact is of relatively short duration. Therefore, in a traditional analysis the choice of a particular quotation time may lead to underestimation of the impact on daily data.

In order to illustrate these effects, we conduct an analysis on daily data and capture the impact of CBI through the a GARCH analysis. We choose four different quotation times, following three representative analyses of this literature on daily data: Bonser-Neal and Tanner (1996) who rely on option prices quoted at 11.00 am on the Philadelphia market (around 17:00 GMT+1)\(^{25}\), Dominguez (1998) who uses New York market close data (21:00 GMT+1) and Beine, Bénassy and Lecourt (2002) who use mid-day exchange rate data on the Frankfurt market (13h00 GMT+1). For each quotation time \(\theta\) (\(\theta=13.00, 16.00, 17.00\) and 21.00 GMT+1), we capture the impact using the following GARCH model:

\[
\begin{align*}
    r_{t,\theta} &= \mu + \epsilon_{t,\theta} + \rho r_{t-1,\theta}, \\
    \epsilon_{t,\theta} | \Omega_t &\sim N(0, \sigma_{t,\theta}^2) \\
    \sigma_{t,\theta}^2 &= \omega + \alpha \epsilon_{t-1,\theta}^2 + \beta \sigma_{t-1,\theta}^2 + \delta_0 I_{m,t} + \delta_1 I_{COORD,t-i} + \delta_2 I_{FEDU,t-j} + \delta_3 I_{BBU,t-h}
\end{align*}
\]

in which \(r_{t,\theta}\) is the daily return of the DEM/USD exchange rate computed at time \(t\) and hour \(\theta\) and \(I_{COORD,t}, I_{FEDU,t}, I_{BBU,t}\) are the variables indicating intervention operations at time \(t\) as defined previously in (2). One well-known problem related to the use of daily data consists in ensuring that the intervention variables are predetermined in order to control for the simultaneity bias (excess volatility causing interventions). In order to capture the impact in an appropriate way, one has to make sure that the intervention operations occur before the quotation of the exchange rate. This means that depending on the time quotation, one has to lag some or all the intervention variables. For instance, the choice of the quotation time by Dominguez (1998) (21h00 GMT+1) ensures that all interventions of the Bundesbank and the Fed occurred before: this allows to use interventions at time \(t\) (\(i = j = h = 0\)). Nevertheless, such a quotation time might not be appropriate to capture volatility spillover effects due to unilateral BoJ interventions since these take place at the opening of the Tokyo market, i.e. after 0:00 GMT+1. The choice of the quotation time in Bonser-Neal and Tanner (1996) requires to lag unilateral intervention of the Fed (\(i = h = 0; j = 1\)). The lagging procedure for the coordinated interventions and the unilateral intervention of the Bundesbank is not required as the European markets are closed at that time. The same holds for the unilateral interventions of the Bundesbank when using the Beine, Bénassy and Lecourt (2002) quotation time if one assumes that most unilateral interventions of the Bundesbank occur in the morning trading time in Europe (this assumption might be too strong, of course); by contrast, it is strictly necessary to lag coordinated and unilateral interventions of the Fed (\(i = j = h = 1\)).

We focus here on the results for coordinated interventions.\(^{26}\) Table 1 reports the estimation results for the various quotation times. Strikingly, the results suggest that the quotation time of the exchange rate is crucial to capture both the size and the significance of the impact of coordinated interventions in terms of exchange rate volatility. If one uses the quotes at the close of the German market (\(\theta = 16.00\)), the impact of coordinated interventions is substantial and highly significant. If one uses the quotation time of Bonser-Neal and Tanner (1996) (one hour

\(^{25}\)Bonser-Neal and Tanner (1996) use implied volatilities drawn from currency option prices in order to capture the impact of CBI in terms of expected volatility. Nevertheless, this analysis obviously belongs to the core of studies based on daily data.

\(^{26}\)It turns out that the GARCH estimations do not capture any effect of unilateral interventions on the conditional volatility. This slightly contrasts with the results obtained from realized volatility.
Table 1: CBI volatility effects in a GARCH framework with different time quotations

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<td>$i = j = 1; h = 0$</td>
<td>$i = 0; j = 1; h = 0$</td>
<td>$i = 0; j = 1; h = 0$</td>
<td>$i = j = h = 0$</td>
<td></td>
</tr>
<tr>
<td>$\delta_1[COORD, t-i]$</td>
<td>0.076</td>
<td>0.204</td>
<td>0.117</td>
<td>0.023</td>
</tr>
<tr>
<td>$[0.031]$</td>
<td>$[0.057]$</td>
<td>$[0.041]$</td>
<td>$[0.022]$</td>
<td></td>
</tr>
<tr>
<td>$\delta_2[FEDU, t-j]$</td>
<td>0.000</td>
<td>-0.012</td>
<td>-0.011</td>
<td>0.002</td>
</tr>
<tr>
<td>$[0.041]$</td>
<td>$[0.011]$</td>
<td>$[0.009]$</td>
<td>$[0.009]$</td>
<td></td>
</tr>
<tr>
<td>$\delta_3[BBU, t-h]$</td>
<td>-0.003</td>
<td>-0.023</td>
<td>-0.013</td>
<td>0.005</td>
</tr>
<tr>
<td>$[0.041]$</td>
<td>$[0.051]$</td>
<td>$[0.042]$</td>
<td>$[0.032]$</td>
<td></td>
</tr>
</tbody>
</table>

Note: Robust standard errors are reported between brackets. The results correspond to a subset of parameters of the following GARCH(1,1) model: 

$$\sigma^2_{t,\theta} = \omega + \alpha \sigma^2_{t-1,\theta} + \beta \sigma^2_{t-1,\theta} + \delta_0 I_{m,t} + \delta_1 I_{COORD,t-i} + \delta_2 I_{FEDU,t-j} + \delta_3 I_{BBU,t-h},$$

where $\theta$ refers to the quotation time and $i$, $j$ and $h$ stand for the number of lagged days. All computations were performed with the G@RCH 3.0 software (see Laurent and Peters 2002).

later, $\theta = 17\,00$, while the model captures the high significance of these coordinated interventions, the impact has dramatically decreased. This is due to the short duration of volatility effects of these interventions which was previously documented through the pattern of realized volatility responses. The use of quotation time as in Dominguez (1998) -which makes sense because of the issue of simultaneity- does not allow to capture- at least over our investigation period- the impact of coordinated interventions. Both the size of the impact and the significance in the GARCH specification dramatically drop with respect to the previous quotation time. Once again, the reason is that the effect does not last beyond a 3 hours duration. Therefore, these results also shed a light on the crucial importance of choosing the appropriate quotation time in daily analysis of CBI’s. Interestingly, they suggest that due to the simultaneity bias and the short duration of the effects which was emphasized in Section 2, one single GARCH model may be insufficient to fully capture the various effects associated with each kind of intervention. This stresses one important drawback of using daily data.

4 Conclusions

In this paper we have studied the impact of CBI’s on foreign exchange markets for the DEM/USD and YEN/USD. We have carried out event studies for interventions days, the two days preceding an intervention and two days following an intervention using realized intraday moments to measure the impact of CBI’s. We have looked at the impact of interventions on returns and return volatility. CBI’s appear not to have a significant impact on the returns. Coordinated interventions do have an impact on return volatility. In line with the existing theoretical and empirical literature, this effect appears to be significant. Nevertheless, our analysis allows to document its persistence and show that it is of a temporary nature, at most a few hours. To the extent that CBI’s were aimed at reducing exchange rate volatility (see Almekinders and Eijffinger 1994, for empirical evidence from CB reaction functions) these interventions appear not to have been effective.

Our approach based on realized moments allows to test for the impact on cross-moments of
exchange rate returns as well as on higher moments without having to model these moments. Realized daily covariances are affected by CBI’s as well and the timing of the impact is consistent with the one associated to volatilities. Our results tend to confirm previous findings of the empirical literature based on multivariate GARCH models and document the persistence of these effects. While positive, the impact of coordinated interventions on correlations however has not been found to be substantial. Interestingly, the impact of coordinated CBI’s on realized intraday skewness measures is apparent in the boxplots as well. The impact on the kurtosis could easily be analyzed using the same approach but is left for future work. A striking finding of the paper is that any impact of CBI’s appears to be of a temporary nature, which is line with the findings of Dominguez (2003) for the first two moments. The results for the boxplots are confirmed by those from the analysis of rolling regressions.

Our comprehensive empirical analysis has both implications for policy-making and for empirical modelling of foreign exchange rates. The following conclusions might be relevant for policy making at Central Banks. In the past, even through coordinated interventions Central Banks appear not to have been effective in influencing DEM/USD exchange rate returns. When coordinating their interventions Central Banks have achieved a significant, albeit temporary effect on exchange rate volatility, covariance and to a lesser extent on correlations and skewness. The question whether these effects have been intended and/or have been desired can not be answered on the basis of the statistical information studied.

For a modelling purpose it is important to conclude that the impact of CBI’s does not extend beyond the intervention day. This conclusion implies that in an analysis of daily data, the impact of CBI’s can be accounted for by including dummy variables for the (coordinated) intervention days only in those moments that have been found to be sensitive to CBI’s in the past.

References


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Appendix 1: Data

Exchange Rate Data

Our dataset contains hourly data for two major exchange rates, the Japanese Yen (YEN) and the Deutsche Mark (DEM) (Euro after 1998) against the US Dollar (USD). For these two exchange rates, we have about 12 years of intraday data, from January 1989 to February 2001. The raw data consists of all interbank USD-Euro (DEM) and YEN-USD bid-ask quotes displayed on the Reuters FX screen during this period. Note that intraday FOREX returns computed from quoted bid-ask prices are subject to various market microstructure ‘frictions’, e.g. strategic quote positioning and inventory control. Such features are generally immaterial when analyzing longer horizon returns, but may distort the statistical properties of the underlying ‘fundamental’ high-frequency intraday returns. The sampling frequency for which such considerations become a concern is intimately related to market activity. For our exchange rate series, preliminary analysis based on the methods of Andersen, Bollerslev, Diebold and Labys (2002) suggest that the use of equally-spaced thirty-minute or hourly returns strikes a satisfactory balance between the accuracy of the continuous-record asymptotics underlying the construction of our realized volatility measures on the one hand, and the confounding influences from the market microstructure frictions on the other. As standard in the literature, we compute hourly exchange rate prices from the linearly interpolated average of the logarithms of bid and ask quotes for the two ticks immediately before and after the hourly time stamps throughout the global 24-hour trading day. Next we obtain hourly returns as 100 times the first difference of the equally time-spaced logarithmic prices.

Official CBI’s Data (1989-2001)

The data used in this paper are official data of central bank interventions in the FX market.

- For the Fed, all data have been transmitted by the Federal reserve;
- For the Bundesbank, all data have been transmitted by the Bundesbank; the data after 1998 are reported interventions of the ECB, which nevertheless confirmed the 4 interventions carried out in September and November 2000 (but did not release the amounts);
- For the BoJ, the data after April 1 1991 are official data released by the BoJ (http://www.mof.go.jp/english/e1c021.htm). Official interventions before April 1991 are proxied by reported interventions in the Financial press (Wall Street Journal and Financial Times) (see Beine et al. 2002 for more details).

Table A1 presents the number of occurrences of each kind of interventions carried out by the Fed, the Bundesbank (ECB) and the BoJ in the two exchange rate markets. All interventions (except those of the Bank of Japan since 2002) have been sterilized according to the statements of the CB’s.
Table A1: Number of CBI days

<table>
<thead>
<tr>
<th></th>
<th>DEM-USD</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>USD purchases</td>
<td>USD sales</td>
<td>USD purchases</td>
<td>USD sales</td>
</tr>
<tr>
<td>Unilateral FED</td>
<td>26</td>
<td>38</td>
<td>0</td>
<td>33</td>
</tr>
<tr>
<td>Unilateral BB</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coordinated</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: the figures report the number of days of interventions of a given type over the period ranging from January 1 1989 to February 28 2001.

Appendix 2: ARFIMA Estimation of Exchange Rate Realized Volatility

This appendix reports examples of rolling regression estimation results for the parameters $\beta_i$ reported in Figures 4 and 5. Measures of the fit of the ARFIMA models for realized FX volatility are given as well. Table A2 reports estimation results of model (2) with fixed $i$ ($i = 0$) for the intervention variables specific to the YEN/USD market ($FEDU_{t-i}$, $BoJU_{t-i}$, $COORDY_{t-i}$). In other words, only contemporaneous interventions on the YEN/USD are introduced as control variables.

$$(1 - \phi L)(1 - L)^d [\log(\sigma^2_{t,\theta}) - \mu] = \epsilon_t + \mu_t,$$

where

$$\mu_t = \beta_0 MONDAY_t + \beta_1 FEDU_{t-i} + \beta_2 BBU_{t-i} + \beta_3 COORD_{t-i}$$

$$+ \beta_4 FEDU_{t} + \beta_5 BoJU_{t} + \beta_6 COORDY_{t}.$$

Estimates reported in Table A2 confirm that the model reproduces some of the main features of FX realized volatility:

- Long memory: the $d$ parameter lies between 0 and 1, with a value of approximately 0.3, suggesting persistence of volatility shocks and a covariance stationary process; notice that the value of $d$ is consistent with values obtained for the fractional integration parameter estimated in FIGARCH models of FX data.

- Day-of-the-week effect: the $\alpha$ parameter is significantly positive, confirming previous findings (Hsieh 1989) of a positive Monday effect on volatility.
Table A2: Sample of rolling estimations

\[ (1 - \phi L)(1 - L)^d \left[ \ln(\sigma_t^2) - \mu \right] = \beta_0 \text{MONDAY}_t + \beta_1 \text{BBU}_{t-i} + \beta_2 \text{FEDU}_{t-i} + \beta_3 \text{COORD}_{t-i} + \beta_4 \text{FEDUY}_t + \beta_5 \text{BoJU}_t + \beta_6 \text{COORDY}_t + \epsilon_t. \]

\( i \) refers to the lagging or leading procedure of the regressors. For each lagging procedure, \( \theta \) refers to the time quotation of the exchange rate (in GMT+1 physical time). Ljung-Box \( (q) \) and ARCH \( (q) \) are respectively the usual Ljung-Box and ARCH-LM statistics with \( q \) lags applied on the estimated residuals \( \hat{\epsilon}_t \).

<table>
<thead>
<tr>
<th>parameters</th>
<th>( i = 1 )</th>
<th>( i = 0 )</th>
<th>( i = -1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta = 6 )</td>
<td>( \theta = 15 )</td>
<td>( \theta = 6 )</td>
<td>( \theta = 15 )</td>
</tr>
<tr>
<td>( d )</td>
<td>0.378</td>
<td>0.372</td>
<td>0.377</td>
</tr>
<tr>
<td>( [0.019] )</td>
<td>( [0.019] )</td>
<td>( [0.019] )</td>
<td>( [0.019] )</td>
</tr>
<tr>
<td>( \mu )</td>
<td>-1.101</td>
<td>-1.088</td>
<td>-1.099</td>
</tr>
<tr>
<td>( [0.291] )</td>
<td>( [0.274] )</td>
<td>( [0.289] )</td>
<td>( [0.277] )</td>
</tr>
<tr>
<td>( \phi )</td>
<td>-0.101</td>
<td>-0.091</td>
<td>-0.099</td>
</tr>
<tr>
<td>( [0.026] )</td>
<td>( [0.026] )</td>
<td>( [0.026] )</td>
<td>( [0.026] )</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>0.320</td>
<td>0.195</td>
<td>0.320</td>
</tr>
<tr>
<td>( [0.027] )</td>
<td>( [0.027] )</td>
<td>( [0.027] )</td>
<td>( [0.027] )</td>
</tr>
<tr>
<td>( \beta_1 [\text{BBU}, t-i] )</td>
<td>0.088</td>
<td>0.117</td>
<td>0.196</td>
</tr>
<tr>
<td>( [0.116] )</td>
<td>( [0.116] )</td>
<td>( [0.116] )</td>
<td>( [0.115] )</td>
</tr>
<tr>
<td>( \beta_2 [\text{FEDU}, t-i] )</td>
<td>0.068</td>
<td>-0.040</td>
<td>-0.124</td>
</tr>
<tr>
<td>( [0.098] )</td>
<td>( [0.097] )</td>
<td>( [0.103] )</td>
<td>( [0.103] )</td>
</tr>
<tr>
<td>( \beta_3 [\text{COORD}, t-i] )</td>
<td>-0.032</td>
<td>-0.161</td>
<td>-0.165</td>
</tr>
<tr>
<td>( [0.097] )</td>
<td>( [0.096] )</td>
<td>( [0.104] )</td>
<td>( [0.103] )</td>
</tr>
<tr>
<td>( \beta_4 [\text{FEDUY}, t] )</td>
<td>0.066</td>
<td>0.074</td>
<td>0.129</td>
</tr>
<tr>
<td>( [0.127] )</td>
<td>( [0.127] )</td>
<td>( [0.133] )</td>
<td>( [0.132] )</td>
</tr>
<tr>
<td>( \beta_5 [\text{BoJU}, t] )</td>
<td>0.249</td>
<td>0.379</td>
<td>0.242</td>
</tr>
<tr>
<td>( [0.059] )</td>
<td>( [0.059] )</td>
<td>( [0.059] )</td>
<td>( [0.059] )</td>
</tr>
<tr>
<td>( \beta_6 [\text{COORDY}, t] )</td>
<td>0.076</td>
<td>0.258</td>
<td>0.141</td>
</tr>
<tr>
<td>( [0.093] )</td>
<td>( [0.093] )</td>
<td>( [0.100] )</td>
<td>( [0.100] )</td>
</tr>
<tr>
<td>Ljung-Box (50)</td>
<td>59.97</td>
<td>65.37</td>
<td>60.66</td>
</tr>
<tr>
<td>Ljung-Box (100)</td>
<td>102.59</td>
<td>123.34</td>
<td>104.35</td>
</tr>
<tr>
<td>ARCH(20)</td>
<td>1.41</td>
<td>1.75</td>
<td>1.41</td>
</tr>
</tbody>
</table>

Note: The estimated model is \((1 - \phi L)(1 - L)^d \left[ \ln(\sigma_t^2) - \mu \right] = \beta_0 \text{MONDAY}_t + \beta_1 \text{BBU}_{t-i} + \beta_2 \text{FEDU}_{t-i} + \beta_3 \text{COORD}_{t-i} + \beta_4 \text{FEDUY}_t + \beta_5 \text{BoJU}_t + \beta_6 \text{COORDY}_t + \epsilon_t. \)
Appendix 3: Assumptions and properties of realized moments

When computing the realized moments for closing prices (24h GMT), daily returns are defined as: \( r_t = \sum_{i=1}^{K} r_{i,t} \), where \( K \) is the number of intervals per day (e.g. 24) and \( r_{i,t} \) is the \( i \)th intraday return of day \( t \).

### 3.1: Realized volatility

Consider two measures of the daily volatility \( V(r_t) \): \( V_{1,t} \equiv r^2_t \), i.e. daily squared returns, and \( V_{2,t} \equiv \sum_{i=1}^{K} r^2_{i,t} \), i.e. the so-called realized volatility.

**Assumption A1:** \( r_{i,t} \) is a martingale difference sequence (MDS), i.e. \( E(r_{i,t} | \Omega_{i-1,t}) = 0 \), where \( \Omega_{i-1,t} \) denotes a filtration (information set) including past information on \( r \) up to (and including) the point in time \( i - 1 \) on day \( t \).

**Implications of Assumption A1:**

1. \( E(r_{i,t}) = 0 \);
2. \( \text{Cov}(r_{i,t}, r_{j,t'}) |_{\Omega_{\max(i-1,j-1),\max(t,t')}} = 0 \), which implies \( \text{Cov}(r_{i,t}, r_{j,t'}) = 0 \);
3. \( E(r_{i,t} r_{j,t'}^k | \Omega_{i-1,t}) = 0 \) if \( i > j \) and \( t \geq t' \), \( k \in \{1, 2, \ldots\} \).

The implications follow immediately when we use the law of iterated expectations. Note that Assumption A1 does not imply that \( E(r_{i,t} r_{j,t'}^k | \Omega_{j-1,t'}) = 0 \) if \( i \leq j \), \( t < t' \).

**Proposition 1:** Under A1, \( V_{1,t} \) and \( V_{2,t} \) are unbiased estimators of \( V(r_t) \).

**Proof:**

\[
E(V_{1,t}) = E(r^2_t) = V(r_t) \\
V(r_t) \underbrace{=}_{A1} E(r^2_t) \\
\quad = E \left( \left( \sum_{i=1}^{K} r_{i,t} \right)^2 \right) \\
\quad = E \left( \sum_{i=1}^{K} r^2_{i,t} + 2 \sum_{i=1}^{K} \sum_{j=1}^{K-1} r_{i,t} r_{j,t} \right) \\
\quad \underbrace{=}_{A1} E \left( \sum_{i=1}^{K} r^2_{i,t} \right) \\
\quad = E(V_{2,t}).
\]
Assumption $A_2$: $E(r_{i,t}r_{j,t}^3|\Omega_{j-1,t}) = 0 \forall i < j$.

$\Rightarrow$ Assumption of zero skewness of some conditional distribution / symmetry of the conditional distributions.

**Proposition 2:** Under $A_1 - A_2$, $V_{2,t}$ is a more efficient estimate of $V(r_t)$ than $V_{1,t}$.

**Proof:** for simplicity let us consider the case where $K = 2$.

\[
E(V_{1,t}^2) = E\left( (r_{1,t} + r_{2,t})^4 \right) = E\left( r_{1,t}^4 + r_{2,t}^4 + 4r_{1,t}^3r_{2,t} + 4r_{1,t}r_{2,t}^3 + 6r_{1,t}^2r_{2,t}^2 \right) \\
\geq_{A_1-A_2} E\left( r_{1,t}^4 + r_{2,t}^4 + 6r_{1,t}r_{2,t}^2 \right)
\]

More generally, it follows that:

\[
E(V_{1,t}^2) = E\left( \sum_{i=1}^{K} r_{i,t}^4 + 3 \sum_{i=1}^{K} \sum_{j \neq i} r_{i,t}^2r_{j,t}^2 \right)
\]

Similarly, for $V_{2,t}$,

\[
E(V_{2,t}^2) = E\left( (r_{2,t}^2 + r_{2,t}^2)^2 \right) = E\left( r_{1,t}^4 + r_{2,t}^4 + 2r_{1,t}^2r_{2,t}^2 \right),
\]

or more generally:

\[
E(V_{2,t}^2) = E\left( \sum_{i=1}^{K} r_{i,t}^4 + \sum_{i=1}^{K} \sum_{j \neq i} r_{i,t}^2r_{j,t}^2 \right)
\]

Since $r_{i,t}^2r_{j,t}^2 \geq 0$, it follows directly that $E(V_{1,t}^2) \geq E(V_{2,t}^2)$ and since $E(V_{1,t}) = E(V_{2,t}) = V(r_t)$, $V(V_{1,t}) > V(V_{2,t})$.

Note that the proof could be done in terms of conditional expected values as well.

**3.2: Realized skewness**

Recall that the skewness is defined as:

\[
\frac{E[(r_t - E(r_t))^3]}{E(r_t)^{3/2}} = \frac{E(r_t^3)}{E(r_t)^{3/2}}.
\]

For this reason a first measure of the daily cube returns is naturally $S_{1,t} \equiv r_{1,t}^3$. Extending the idea of realized volatility to the third moment would suggest the estimator $S_{2,t} \equiv \sum_{i=1}^{K} r_{i,t}^3$.

Is $S_{2,t}$ an unbiased estimator of $E(r_t^3)$?

**Assumption $A_3$:** $E(r_{i,t}^3r_{j,t}^3|\Omega_{j-1,t}) = 0 \forall i > j$.

**Proposition 3:** Under $A_1, A_3$, $S_{2,t}$ is an unbiased estimator of $E(r_t^3)$.  

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Proof: for simplicity let us consider the case where \( K = 2 \).

\[
E(r_t^3) = E \left( (r_{1,t} + r_{2,t})^3 \right) \\
= E \left( r_{1,t}^3 + r_{2,t}^3 + 3r_{1,t}r_{2,t}^2 + 3r_{1,t}r_{2,t} + 3r_{1,t}r_{2,t}^2 \right) \\
\overset{A_1, A_3}{=} E \left( r_{1,t}^3 + r_{2,t}^3 \right) \\
= E(S_{2,t})
\]

Which of the two estimators dominates in terms of efficiency depends on sign and size of higher moments as the simple case when \( K = 2 \) shows.

Proof:

\[
E(S_{1,t}^2) \overset{A_1}{=} E \left( (r_{1,t} + r_{2,t})^6 \right) \\
= E \left( r_{1,t}^6 + r_{2,t}^6 + 6r_{1,t}r_{2,t}^5 + 15r_{1,t}^2r_{2,t}^4 + 20r_{1,t}r_{2,t}^3 + 15r_{1,t}r_{2,t}r_{2,t}^2 \right) \\
E(S_{2,t}^2) \overset{A_1, A_3}{=} E \left( (r_{1,t}^3 + r_{2,t}^3)^2 \right) \\
= E \left( r_{1,t}^6 + r_{2,t}^6 + 2r_{1,t}r_{2,t}^3 \right)
\]

\[
E(S_{1,t}^2) - E(S_{2,t}^2) = E(18r_{1,t}^4r_{2,t}^3) \\
+ E(6r_{1,t}r_{2,t}^5) \\
+ E(15r_{1,t}^2r_{2,t}^4) \\
+ E(15r_{1,t}r_{2,t}^3r_{2,t}^2) \\
> ? 0
\]

Assuming independence over time of the intradaily returns, which implies Assumption A3, and assuming a symmetric distribution around the mean of these returns, we get that \( E(r_{1,t}^3r_{2,t}^3) = 0 \) and \( E(r_{1,t}r_{2,t}^5) = 0 \). In that case, \( E(S_{1,t}^2) - E(S_{2,t}^2) = E(15r_{1,t}^4r_{2,t}^3) + E(15r_{1,t}r_{2,t}^3r_{2,t}^2) > 0 \), which implies that \( S_{2,t} \) is more efficient than \( S_{1,t} \).
Appendix 4: Theoretical Background

In this appendix, we sketch out the model developed by Vitale (1999) capturing some of the impacts of CBI’s in the foreign exchange market. The model offers two advantages over alternative frameworks. First, consistent with our interpretation (see section 2.8), it captures the role of central bank order flows in a micro-structure framework that depicts the interactions between the various agents (the central bank, the liquidity traders and the market maker). In turn, this allows to capture the signalling channel of central bank trades in the very short run in the presence of asymmetric information. Second, the motives of interventions are explicitly accounted for, which allows us to address the simultaneity issue. We just extract the main results of the model and refer the interesting reader to Vitale (1999) for further details.

Suppose a central bank choosing its market order \( x_{CB,t} \) at time \( t \) such as minimizing its expected loss function \( L_{CB} \) of the form:

\[
L_{CB,t} = (s_t - f)x_{CB,t} + q(s_t - \bar{s})^2,
\]

in which \( s_t \) is (the log of) the exchange rate level (number of domestic currency unit per unit of foreign currency) observed at time \( t \), \( f \) is the (log) fundamental value of the exchange rate over which the central bank possesses private information (which implies that for market participants, \( f \sim N(s_{t-1}, \sigma_f^2) \) and \( \bar{s} \) is (the log of) the target level of the central bank. \( q \) tackles the degree of commitment to the target. The market maker tries to extract from the observed order flow information about the fundamental value of the exchange rate. His filtering procedure depends on whether the target \( \bar{s} \) is common knowledge or not.

If the target is known, the central bank strategically chooses the value of its order as:

\[
x_{CB,t} = \beta(f - s_{t-1}) + \gamma(s_t - \bar{s}) + \theta(x_{lt}),
\]

where \( \beta \) and \( \gamma \) capture trading intensities. The market maker will filter out the part of the signal not associated to the fundamental value, so that the change in the exchange rate is given by:

\[
s_t - s_{t-1} = \lambda[\beta(f - s_{t-1}) + x_{lt}],
\]

where \( \lambda \) captures the sensitiveness of the exchange rate to the market order (which is inversely proportional to market liquidity) and \( x_{lt} \) is the flow of orders of liquidity traders which are supposed to be distributed as a normal variable with \( x_{lt} \sim N(0, \sigma_l^2) \). Compared to a situation in which the central bank does not intervene, the impact of the intervention on the change of the exchange rate and its volatility are respectively given by \( \lambda[\beta(f - s_{t-1})] \) and \( \lambda^2\beta^2\sigma_f^2 \). The following results are interesting from three different points of view. First, in this context, it shows that there is some dependence between the intervention and the previous level of the exchange rate, not with the past exchange rate returns or the past volatility of the returns. Second, it shows that the impact might be weak on the returns if the degree of misalignment is low. Third, the prediction of such models is that intervention should raise volatility of exchange rate variations.

In the case the target is unknown, the market maker must use an estimate of \( \bar{s} \). Assuming that \( \bar{s} \sim N(s^e, \sigma_{\bar{s}}^2) \), the order of the central bank is:

\[
x_{CB,t} = \beta(f - s_{t-1}) + \gamma(s^e - s_{t-1}) + \theta(\bar{s} - s^e),
\]

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where $\theta$ also captures the trading intensity. The impact on exchange rate return is:

$$s_t - s_{t-1} = \lambda [\beta(f - s_{t-1}) + \theta(\bar{s} - s_e^c) + x_{lt}].$$

This case provides another rationale of the documented weak impact of CBI on exchange rate returns. For instance, if $f > s_{t-1} > s_e^c > \bar{s}$, the central bank sells foreign currency ($x_{CB,t} < 0$) whereas the terms $\beta(f - s_{t-1})$ and $\theta(\bar{s} - s_e^c)$ cancel out. Interestingly, the impact in terms of volatility is given by $\lambda^2 \beta^2 \sigma_f^2 + \lambda^2 \theta^2 \sigma_e^2$ and turns out to be strictly positive.