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Richard Payne and Paolo Vitale

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Richard Payne, London School of Economics
Paolo Vitale, London School of Economics and CEPR

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Centre for Economic Policy Research
90–98 Goswell Rd, London EC1V 7RR, UK
Tel: (44 20) 7878 2900, Fax: (44 20) 7878 2999
Email: cepr@cepr.org, Website: www.cepr.org

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ABSTRACT

A Transaction Level Study of the Effects of Central Bank Intervention on Exchange Rates*

We study the effects of sterilized intervention operations executed on behalf of the Swiss National Bank (SNB) using tick-by-tick transaction data between 1986–95. We extend preliminary analysis conducted by Fischer and Zurlinden (1999) by matching these data with intraday indicative exchange rate quotes and with news-wire reports of central banks activity. Via an event study analysis we find that intervention has important short-run effects on exchange rate returns and volatility. In particular, among various results, we find that intervention (i) has a stronger impact when the SNB moves *with the market* and its activity is *concerted* with that of other central banks, (ii) is partially anticipated by the market and (iii) temporarily reduces market liquidity.

JEL Classification: F31, G14 and G15
Keywords: foreign exchange market, market microstructure and sterilized intervention

Richard Payne
Financial Markets Group
London School of Economics
Houghton Street
LONDON
WC2A 2AE
Tel: (44 20) 7955 7893
Fax: (44 20) 7955 7420
Email: r.payne@lse.ac.uk

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Paolo Vitale
Accounting and Finance Department
London School of Economics
Houghton Street
LONDON
WC2A 2AE
Tel: (44 20) 7955 7230
Fax: (44 20) 7955 7420
Email: p.vitale@lse.ac.uk

For further Discussion Papers by this author see:
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NON-TECHNICAL SUMMARY

An open issue in international finance is whether sterilized central bank intervention is effective in changing foreign exchange rates. While we can theoretically show that sterilized purchases and sales of foreign currencies on the part of the monetary authorities can influence exchange rates through a portfolio-balance effect or via a signaling channel, empirical analysis of this issue has so far been inconclusive.

The main obstacle to a proper empirical analysis of the effectiveness of foreign exchange intervention has been a lack of adequate data on central bank intervention. Recently, however, the Swiss National Bank (SNB) has released a novel data set containing tick-by-tick observations of its intervention operations in foreign exchange markets between 1986-95.

We extend preliminary analysis of this transaction data conducted by Fischer and Zurlinden (1999), by combining the information it contains with indicative exchange rate quotes recorded by Olsen and Associates and with Reuters news-wire reports of central banks' activity. Using the event study approach we are able to test the empirical relevance of the signaling hypothesis, according to which intervention operations are employed by monetary authorities to convey information to foreign exchange markets and hence alter market expectations and prices. Specifically, if central bank operations contain information we should be able to see in the data that: (i) signed intervention possesses a significant and permanent impact on exchange rates; (ii) dealers widen their spreads around intervention events; and (iii) exchange rate volatility falls in the aftermath of an intervention event as heterogeneity in market opinions is reduced.

The results of our empirical investigation are generally supportive of the signaling hypothesis. In particular, we find that intervention events have a positive effect on exchange rates, in that when the SNB purchases (sells) US dollars, the American currency strengthens (weakens). This impact is immediate and persistent. We also observe a degree of anticipation in the market, in that the exchange rate moves in the direction of the intervention before the event occurs.

These conclusions hold under several regression specifications for the exchange rate return, i.e.: (i) when we simply consider the direction of intervention as an explanatory variable; (ii) when we employ the signed intervention size; (iii) even when we account for the effects of the intervention activity of other central banks, notably the Federal Reserve and the Bundesbank. In addition, unlike intervention operations, non-intervention trades carried out by the SNB on the Swiss government's behalf do not have any significant or permanent impact on the exchange rate return.

We also find that the SNB activity has a larger and more persistent impact: (i) when operations are concerted with those of the Bundesbank and the Federal Reserve and (ii) when intervention follows the current exchange rate trend. Thus, an important policy implication that we derive is that foreign exchange intervention is not well suited to reversing prior changes in exchange rates. It can, however, supplement more powerful instruments of policymaking in conditioning market sentiment and currency values. Likewise, our findings confirm common opinion that coordinated operations should be preferred to unilateral ones if a large and long-lived impact on exchange rates is sought.

Besides the effects on the first moment of the exchange rate return, we find that central bank intervention also alters market liquidity and exchange rate volatility. In particular, we find that FX dealers react to the intervention activity of the SNB by widening the spread between the bid and ask prices they quote to their clients. In quantitative terms, we find that in response to a typical intervention operation of $30 million, the average dealer will increase the width of the spread by 40 basis points. This is in contrast to the common presumption that foreign exchange dealers do not change the size of their spreads (instead moving quotes in order to manage their inventories), but is in line with the signaling hypothesis. Likewise, we obtain results consistent with this hypothesis when we turn to the analysis of market uncertainty. Indeed, we find that (i) our measure of market uncertainty, the absolute residual exchange rate return, increases during the period of intervention and (ii) as the information conveyed by the operation is diffused among market participants, the uncertainty subsides.

1 Introduction

Scholars have long debated whether central bank intervention operations in the markets for foreign exchange have important effects on exchange rate levels and volatility and on market conditions. While it can be theoretically established that sterilised intervention affects the value of currencies and level of activity in foreign exchange markets,[1] either through a portfolio-balance effect or via a signalling channel, the effectiveness of sterilised intervention remains an unresolved issue from an empirical point of view.

A contributory factor to the unresolved nature of this issue has been a lack of adequate data on central bank intervention transactions. Indeed, until recently, researchers only had access to data sets in which intervention operations were aggregated to daily or lower frequencies.[2] This has proved a serious impediment to empirical analysis of the effects of intervention on exchange rates as, with coarsely sampled data, it is difficult/impossible to overcome simultaneity problems and to characterise the high-frequency effects of intervention on market conditions.

However, recently the SNB has made an innovative data set available to researchers, containing tick-by-tick observations on its intervention operations in FX markets between 1986 and 1995. We extend a preliminary analysis of this data set by Fischer and Zurlinden (1999), by combining the information it contains with indicative exchange rate quotes recorded by Olsen and Associates and with Reuters news-wire reports of central banks' activity.

These data allow us to conduct a high-frequency analysis of the effects of signed intervention operations on exchange returns and the liquidity of foreign exchange markets. We construct time-series for the USD/CHF exchange rate and signed intervention quantities sampled once every 15 minutes and use these data to analyse the high-frequency and longer-run effects of intervention via an event study.

Several recent studies also focus on the intra-day effects of intervention on exchange rates although none of these use actual intra-day intervention data. Peiers (1997) and Dominguez (1999) examine the effects of Reuters news-wire reports of intervention (by the Bundesbank and Federal Reserve respectively) on the USD/DEM. Also, Evans and Lyons (2000) conduct some indirect inference on the liquidity effects of foreign exchange intervention, using a data set of inter-dealer transactions in the USD/DEM market which does not contain direct observations of any central bank operations.

The particular focus of our study is the empirical relevance of the *signalling hypothesis*. This hypothesis suggests that intervention operations are used by monetary authorities to convey information to foreign exchange markets and hence alter market expectations and exchange rates. Thus, if central bank operations are informative: i) signed intervention should have a significant and permanent effect on the value of currencies, ii) dealers' should widen their spreads around intervention events, iii) exchange rate volatility should fall subsequent to intervention as heterogeneity in private beliefs is reduced.

Other important issues we can analyse using the event study methodology include: i) the speed with which intervention influences markets, ii) the impact of intervention size and iii) the effects of market conditions on the effectiveness of intervention. With respect to the first issue, it is usually presumed that foreign exchange markets are very resilient and process information very quickly. The current analysis gives us an opportunity to test this assertion. Analysis of the impact of intervention size is also important, in that the signalling hypothesis suggests that intervention is effective because it is potentially expensive. Hence larger trades should have a bigger impact on exchange rates and market characteristics. Finally, we investigate whether interventions that seek to reinforce prior exchange rate movements have different effects than those which seek to reverse such movements.

The main findings from our analysis are the following.

1. Intervention events have a positive effect on exchange rates: when the SNB purchases (sells) US dollars, the American currency appreciates (depreciates). The impact of intervention is immediate, as the exchange rate moves within the 15 minute interval during which an intervention event is reported, and persistent, as the cumulative effect is still significant after few hours. We also observe market anticipation of intervention information, as the exchange rate moves (significantly) in the direction of the operation in the 15 minute interval that precedes that in which the event occurs. Likewise, we detect partial reversal of the intervention effect in the 15 minute period immediately after the event interval.

2. These conclusions hold: i) when we simply consider the direction of intervention as an explanatory variable, ii) when we employ the signed intervention size in the regression analysis of the exchange rate return and iii) even when we account for the effects of the intervention activity of other central banks, notably the Fed and the Buba. On the contrary these conclusions are not valid when we use *customer trades* instead of intervention operations.

3. The impact of SNB activity is larger and more persistent: i) when operations are concerted with those of the Buba and the Fed than when they are conducted unilaterally and ii) when intervention follows the current trend rather than opposing it.

4. Central bank intervention also alters market liquidity, in that FX dealers' spreads widen significantly during the 15 minute interval of intervention.
5. We find that absolute residual exchange rate returns (our measure of market uncertainty) are significantly larger in the 15 minute interval preceding interventions and larger still in the intervention interval itself. Moreover, we see that 30 minutes after an intervention operation absolute residuals are (insignificantly) lower than normal. This indicates that market uncertainty increases before and during intervention, as the anticipation and realisation of an information event augments the dispersion of beliefs among market participants. Further, one might expect that after the intervention, when the information conveyed by the operation is diffused among market participants, exchange rate volatility subsides. Our results bear this out.

The rest of the paper is organised as follows. In Section 2 we briefly describe our data set and the statistical properties of the exchange rate and intervention series. In Section 3 we present our results. Section 4 concludes.

2 Data

As noted in the introduction, the main innovation of the current study is the use of a transactions-level data set on central bank spot purchases and sales of US dollars, time stamped to the minute. These transactions were conducted by the SNB in the USD/CHF market and are recorded for the period covering 1986 to 1995.

The deals that comprise our data are of two types: *interventions* and *customer transactions*. The former are operations conducted on the part of the SNB with the intention of conditioning the market for foreign exchange, while the latter are triggered by the need of the Swiss government for foreign currencies. In the period these data cover the SNB dealing desk would first negotiate a buy or sell order with a foreign exchange dealer. After completion, it would *notify* the counterparty if the transaction was part of an intervention operation or not. Given the different nature of the two types of transactions, our work will focus mainly on the interventions although we provide some analysis of customer trades for comparison.[3]

The transactions information forms the first component of our data set. The second component of the data set consists of tick-by-tick indicative exchange rate quotes on the USD/CHF provided to us by Olsen and Associates (Zurich). These exchange rate data cover the period from March 1986 to November 1999. Simultaneous examination of the exchange rate data and the SNB transactions will allow us to provide very accurate, high-frequency characterisations of the manner in which intervention operations affect FX rates.

The final segment of the data we employ is a set of Reuters news-wire reports of central bank activity in FX markets. We have, for the period from August 1989 to the end of 1995, Reuters news headline data, timestamped to the second, for every day upon which the Federal Reserve intervened in FX markets. As such, we can retrieve all reports of Fed intervention activity for this period and a significant number of intervention reports for the Buba and the SNB given the correlation between the timings of Fed interventions and interventions by the other two banks. Clearly, though, we do not have news headline data for those interventions undertaken by the SNB and the Buba on days upon which the Fed did not intervene. Also, it should be noted that the sample period for our news headline data is shorter than that for the transaction-level SNB data in that it does not cover 1986-1988.

A prior analysis of the transactions data is contained in Fischer and Zurlinden (1999). These authors provide an analysis of the signalling hypothesis but using the actual intervention data from the SNB only. Hence, the only price data used in their study are the actual transactions prices at which SNB interventions were completed. This necessitates the use of an empirical model which accounts for the fact that interventions (and hence price observations) are irregularly spaced in time. Their results imply that, given that the SNB was in the market on a given day, purchases of dollars lead to dollar appreciations and sales lead to dollar depreciation. This effect is only significant for the *first intervention on a given day.*

Plots of intervention activity and the exchange rate over our sample period are given in Figures 1 and 2. In Figure 1 we have aggregated intervention activity up to a daily level so that the figure shows the daily net dollar purchases of the SNB (measured in millions of US dollars) versus time. During this time the SNB intervened in the USD/CHF market on 102 days (with over 70% of these days being in or before 1989.) On an intra-day level, the vast majority of interventions occurred either between 9 and 11am or between 3 and 5pm Swiss local time.[4]

Table 1 gives basic statistical information on the frequency, size and direction of individual intervention transactions. The table shows that there were almost twice as many interventions to sell dollars than interventions to buy. Hence, the mean intervention quantity is significantly negative and median intervention size is -$5m. Also, intervention quantity has negative skew and is leptokurtic. The final two rows of the table show that positive and negative interventions (taken separately) both have median size of $10m. and, further, show that negative interventions (i.e. dollar sales) are more dispersed in magnitude.

Summary statistics for the data series derived from the indicative exchange rate quotes are given in Table 2. As the statistical properties of these indicative quote data are well known (see, for examples, Dacorogna, Müller, Nagler, Olsen, and Pictet (1993) and Andersen and Bollerslev (1997)) we only give a brief analysis of the data here. The statistics in the Table are based on a 15 minute calendar time sampling of the data. We use this sampling frequency in the majority of our analysis and it was chosen so as to allow us to characterise the fine detail of the high-frequency data without distorting the statistical properties of the data by sampling too finely.[5]

Examining the first row of Table 2 we see the standard statistical features of intra-day exchange rate returns i.e. zero mean, little skew and strong leptokurtosis. There is evidence of negative autocorrelation in returns at displacement 1, another common finding. The second row of the Table gives information relevant to USD/CHF quote entry frequency showing, amongst other things, that in the average 15 minute interval there are around 27 quote entries. There is exceedingly strong evidence of positive autocorrelation in the quote frequency data also. Finally we present some information on the features of absolute exchange rate returns, a proxy for return volatility. Again, the dominant feature here is strong positive linear dependence in the series. Such dependence would be generated, for example, by GARCH effects in returns.

One of the main reasons for the strong dependence in the quote frequency and absolute return data is the presence of a repetitive intra-day pattern in FX market activity which generates intra-day seasonal effects in quotes and return volatility. These intra-day patterns are shown in Figure 3. During hours when Far Eastern and Pacific markets are open, activity in the USD/CHF is lower than average. During European and U.S. trading hours the market is much faster, with, on average, around 60 quotes per 15 minute interval in the late GMT afternoon.

The main implications of Table 2 for our event study analysis are the following. First, when studying the effects of interventions on returns we should take account of the low displacement return autocorrelation. In modelling the effects of interventions on volatility and quote frequency we also need to account for the repeated intra-day patterns. This is done using a set of seasonal dummies, one for each hour of the GMT day. We also add autoregressive terms to each of these specifications to account for any residual dependence in these series.

3 High Frequency Effects of Sterilised Intervention

3.1 A simple test of the signalling hypothesis

In Table 3 and Figure 4 we present results from a linear regression of the 15 minute percentage return on the USD/CHF on leads and lags of a signed intervention indicator, I_t (i.e. I_t is +1 in any interval where the SNB purchased dollars, -1 in intervals when the SNB sold dollars and zero otherwise. There was no 15 minute interval where the SNB both bought and sold dollars.) This specification, displayed below, is estimated using the entire sample of 343680 return observations, covering nine years of intervention activity on the part of the SNB between 1986 and 1995:[6]

$$r_t = \alpha + \sum_{j=8}^{-8} \beta_j I_{t+j} + \gamma_1 r_{t-1} + \gamma_2 r_{t-2} + \epsilon_t. \quad (1)$$

We consider 8 leads and lags of the intervention variable so as to capture the effects of sterilised intervention in the 2 hours before and after any intervention event. Two lags of the dependent variable are included to pick up the low displacement return autocorrelation identified in Section 2. We have considered specifications with a larger number of leads and lags and the results from these extended specifications are qualitatively similar to those presented here.

The results from estimation of equation (1) are given in Table 3. The tables shows that only the contemporaneous indicator, I_t, one lead, I_{t+1}, and one lag, I_{t-1}, have significant coefficients. Since the coefficient on I_{t+1} is positive and significant, Table 3 implies that an intervention impacts the return in the 15 minute interval *before* it actually occurs, indicating that market participants tend to anticipate central bank intervention.[7] However, the total impact of an intervention operation is not completely anticipated, as the coefficient on I_t is large, positive and significant. Furthermore, the significant, negative coefficient on I_{t-1} implies that the impact on the USD/CHF is partially reversed in the 15 minute interval that *follows* an intervention event, indicating that market participants over-react in response to the information contained in interventions.

The total effect of an intervention operation is best displayed through a graphical representation of the results reported in Table 3. In Figure 4 we plot, the effect of a dollar purchase by the SNB on the USD/CHF exchange rate (as estimated by partial sums of the coefficients on leads and lags of I_t in Table 3). The dashed lines trace out a 2 standard deviation confidence interval for the total exchange rate impact. The plot of the cumulative intervention effect confirms the conclusions drawn from Table 3, as we observe a large impact, of around 20 basis points, from a purchase of US dollars. Despite the clear mean-reverting behaviour of the cumulative exchange rate impact, we see that after two hours the impact is still positive, roughly equal to 10 basis points.

Hence, interventions appear to have significant and permanent effects on exchange rate levels. Notice that, since during the sample period the SNB sterilised all of its intervention transactions, we cannot attribute this effect to changes in monetary aggregates. Instead, these results suggest that SNB intervention activity "carries" information.

To further investigate this thesis, in Table 4 we report the results from estimation of two new specifications for the USD/CHF return. In the first we regress r_t on leads and lags of the signed intervention indicator, I_t, alongside those of the signed intervention *quantity*, X_t. In the second, we substitute the leads and lags of the signed indicator with corresponding leads and lags of *signed, squared quantity.* These specifications are displayed below:

$$r_t = \alpha + \sum_{j=8}^{-8} \beta_j I_{t+j} + \sum_{j=8}^{-8} \delta_j X_{t+j} + \sum_{j=1}^{2} \gamma_j r_{t-j} + \epsilon_t, \tag{2}$$

$$r_t = \alpha + \sum_{j=8}^{-8} \delta_j X_{t+j} + \sum_{j=8}^{-8} \theta_j X^2_{t+j} + \sum_{j=1}^{2} \gamma_j r_{t-j} + \epsilon_t. \tag{3}$$

Equation (2) allows us to assess the relevance of the *size* of intervention, while equation (3) indicates whether the relationship between intervention size and the exchange rate change is non-linear.

Table 4 shows that the introduction of the signed quantity variables does not really alter the size or sign of the coefficients on leads and lags of the indicator. However, the size of the intervention operation is important as the coefficient on current intervention, δ_0, is significantly positive, suggesting that the larger the magnitude of intervention, the larger its immediate impact on the exchange rate. The relationship between intervention size and the exchange rate is shown in the left panel of Figure 5, where we present the cumulative effect of dollar purchases of different sizes. This panel shows that a purchase of just \$50 million by the SNB has a large immediate impact, of nearly 30 basis points, on the exchange rate.

This impact is an order of magnitude larger than the lower bound estimated by Evans and Lyons (2000) for the impact of central bank intervention in the USD/DEM market (5 basis points for operations of \$100 million in size). The difference between the two sets of results may be generated by either the different sizes of the two markets or the absence of actual interventions in their data set, which precludes the direct evaluation of the information content of intervention operations.

The estimation results for equation (3) are presented in the last column of Table 4. They indicate that the relation between the exchange rate and intervention size is *not* linear: the coefficient on the contemporaneous value of signed, squared size is significantly *negative*. Hence the impact of intervention increases with size, but at a less than linear rate. To judge the importance of the concavity, consider the right panel of Figure 5, where we present the contemporaneous impact of US dollar purchases of different sizes: the graphical representation clearly suggests that the non-linearity is not economically significant.

In summary, for this Section, our results seem to confirm the signalling hypothesis. Intervention operations in foreign exchange markets represent an *expensive* instrument of policymaking. Then, because of their potential cost, they can be employed by monetary authorities to credibly convey information to market participants and hence condition market sentiment and currency values. Moreover, since large operations are potentially more expensive they have a bigger impact on exchange rate returns than small ones.[8]

3.2 The impact of customer trades on exchange rates

A further test of the signalling hypothesis compares the effects of SNB interventions on the USD/CHF with those of customer trades. Indeed, if the impact on exchange rates of intervention operations were of comparable magnitude to that of customer orders, one might argue that there is nothing "special" about interventions and the results reported in Section 3.1 could be explained as due to a liquidity effect rather than an information-based one — see, for example, the model of Evans and Lyons (2000). Unfortunately, a direct test is not possible, in that we do not possess any data on order flow for the USD/CHF market. However, we have information on transactions carried out by the SNB on behalf of the Swiss government. As they are the consequence of its liquidity needs, these operations are totally analogous to any purchase or sale of US dollars in the USD/CHF market by private operators.

To test whether intervention operations have a stronger exchange rate impact than other trading activity, we construct the variable CT_t which is a signed SNB customer trading activity indicator: CT_t takes a value of +1 (-1) for those intervals in which the SNB purchases (sells) US dollars as a consequence of the Swiss government's needs. Our data contains 366 intervals in which a customer trade took place, with 326 buys and 40 sells. The average size of a customer trade is close to \$20m. In Table 5 we report results from estimation of equation (4), which is entirely analogous to the specification we used to asses the effects of interventions:

$$r_t \;=\; \alpha \;+\sum_{j=8}^{-8} \beta_j \, CT_{t+j} \;+\; \sum_{j=1}^{2} \gamma_j \, r_{t-j} \;+ \epsilon_t. \qquad (4)$$

Similar to the results of Fischer and Zurlinden (1999), we find that the coefficients of the leads and lags of SNB customer trades often have the *wrong* sign and are, in general, *not* significantly different from zero. More tellingly, in Figure 6 we present the cumulative exchange rate impact of a customer purchase of dollars. In stark contrast to Figure 1, there is no clear pattern in this picture and at no point is the cumulative effect significantly different from zero.

Since their effects are neither significant nor persistent, we conclude that SNB customer trades are qualitatively different to SNB intervention activity. The latter has a significant and persistent effect on the USD/CHF in the expected direction while the former does not even temporarily affect prices. This lends credence to the notion that interventions carry information.

3.3 Intervention and market momentum

Dominguez and Frankel (1993b) list a number of reasons that might induce monetary authorities to intervene in foreign exchange markets. Primary within this group is the desire to calm disorderly markets. In practice, this often translates to central banks purchasing or selling currency in order to reverse a recent change in price. We are therefore interested in establishing if there are significant differences in the impact of intervention which *is with the wind* and intervention which *leans against the wind*.

To test for differences, we use the following definition of intervention *with/against-the-trend*. We define an intervention operation as with-the-trend if its sign is the same as that of the change in the exchange rate over the previous 24 hours.[9] Against-the-trend observations are defined in the corresponding fashion. We then run separate regressions of USD/CHF returns on leads and lags of with/against-the-trend regressions, identical in structure to equation (1).

The results from these regressions are reported in Table 6.[10] In Figure 7 we present plots of the corresponding cumulative intervention effects.

In Table 6 we observe the usual patterns in the sign and significance of the regression coefficients. In particular, in both regressions the coefficient on the current intervention indicator is positive and significant. However, inspection of Figure 7 suggests an important distinction between with and against-the-trend interventions. The impact of a purchase of US dollars by the SNB is more pronounced, persistent and significant when intervention is with-the-trend. We see that, for with-the-trend intervention, the initial increase in the USD/CHF is of the order of 35 basis points and that after two hours the total impact is still significant and around 25 basis points. On the contrary, for against-the trend intervention we observe a much smaller impact at the time of the intervention operation. Moreover, the increase in the cumulative abnormal return is almost completely reversed in the space of a couple of hours.[11]

Thus, it appears that intervention operations are most successful when they occur so as to *reinforce prior market movements*. Indeed, our analysis implies that interventions seeking to reverse recent prices movements are almost entirely ineffective.

3.4 Coordination, anticipation and news-wire reports

An important issue that deserves our attention is that of coordination among central banks. As noted by Fischer and Zurlinden (1999) practically all SNB intervention operations occurring within our sample period were "coordinated" with either the Fed or the Buba, meaning that they would take place on those days in which at least one of these two central banks was also present in the market. Common wisdom suggests that intervention should be more effective when it is coordinated, as then market participants observe a clear consensus among monetary authorities over the desired direction of change for the exchange rate. We wish to test whether this intuition is valid in our data — whether coordinated intervention activity has a larger exchange rate impact than unilateral SNB intervention.

Moreover, one might argue that coordinated intervention activity explains the finding of Section 3.3, that interventions have greater exchange rate effects when they are with-the-trend. If the activity of the SNB follows the lead of the Fed and Buba (and Fed and Buba intervention is effective) then we will see SNB interventions with large effects which appear to be with-the-trend. Of course, the prior trend is caused by the actions of other central banks. This could also explain the finding, displayed in Table 3, that exchange rates move in the direction of SNB intervention in the period *before* the intervention actually takes place.

To test the differential effects of coordinated and non-coordinated intervention accurately we would require full transaction data on Fed and Buba interventions for our sample period. Since these data are not available, we use the news-wire reports of Fed and Buba interventions discussed in Section 2. Note that, given the partial overlap between the headline and intervention data, this means we must work with a smaller data sample for this analysis covering the period from August 1989 and December 1995.[12]

Based on the news headline data we define *concerted* intervention activity as follows. An SNB intervention is said to be concerted if the Fed and Buba were both reported to be in the market up to 1 hour beforehand or 45 minutes afterwards.[13] All other SNB interventions are classed as non-concerted. Using this split of the SNB interventions we can estimate extended versions of equation (1) that separate the effects of concerted/non-concerted activity. Specifically, if C_t denotes the concerted intervention indicator (i.e. a variable that is unity only for those periods in which a concerted intervention took place) we estimated the following regressions:

$$r_t = \alpha + \sum_{j=8}^{-8} \beta_j I_{t+j} + \sum_{j=1}^{-1} \kappa_j C_{t+j} I_{t+j} + \sum_{j=1}^{2} \gamma_j r_{t-j} + \epsilon_t, \quad (5)$$

$$r_t = \alpha + \sum_{j=8}^{-8} \delta_j X_{t+j} + \sum_{j=1}^{-1} \nu_j C_{t+j} X_{t+j} + \sum_{j=1}^{2} \gamma_j r_{t-j} + \epsilon_t. \quad (6)$$

where I_t is a signed SNB intervention indicator and X_t is signed SNB intervention size as before. In Table 7 we report the results of the estimation of equations (5) and (6) for the 1989 to 1995 subsample.

The estimated coefficients in Table 7 (and the cumulative exchange rate impact presented in Figure 8) suggest that the effect of the intervention activity of the SNB is more pronounced when it is concerted with that of the Buba and the Fed. In particular, the coefficients of the first lead and the contemporaneous value of the product of the concerted intervention indicator, C_t, with the signed intervention indicator, I_t, and the signed intervention quantity, X_t, are positive (although in most cases only marginally significant). However, it should be noted that the first lead of SNB intervention indicator retains significance at the 1% level indicating that it is not simply coordinated intervention activity that explains the "anticipation effect" we uncovered previously.

We proceed to directly and separately evaluate the effects of Fed and Buba activity on the USD/CHF using the newswire data. Rather than combining them with the SNB interventions to create a concerted intervention dummy we now create separate signed intervention indicators for the Fed and Buba from the news headlines.[14] We then estimate the following specification for USD/CHF returns:

$$r_t = \alpha + \sum_{j=8}^{-8} \beta_j I_{t+j} + \sum_{j=4}^{-4} \phi_j I^F_{t+j} + \sum_{j=4}^{-4} \psi_j I^B_{t+j} + \sum_{j=1}^{2} \gamma_j r_{t-j} + \epsilon_t. \quad (7)$$

where I^F_t is the signed Fed intervention indicator and I^B_t is the signed Buba intervention indicator. Estimated coefficients from this specification are presented in Table 8. The coefficients demonstrate that reports of Fed and Buba intervention activity have a significant effect on the USD/CHF return. As expected, purchases (sales) of the US currency on the part of the Fed or the Buba tend to appreciate (depreciate) the US dollar. Consistent with prior results in Dominguez (1999), we also see that the effect of these intervention reports is felt well before the reporting interval: the third lead of Fed intervention, I^F_{t+3}, and the second and third leads of Buba intervention, I^B_{t+2} and I^B_{t+3}, are positive and significantly so at the 1% level. Hence, exchange rates react up to 45 minutes ahead of Reuters intervention reports, due to the delay in these reports.

More importantly, in Table 8 we see that the coefficients on the first lead of the SNB intervention indicator and its contemporaneous value are still positive and significant at the 1% level. Hence, we conclude that even when accounting for the reports of other central bank activity: (i) purchases and sales of US dollars on the part of the SNB have an important impact on USD/CHF returns and (ii) the impact of these SNB operations is in part felt before their completion. We conjecture that such anticipation might be the consequence of the time required to negotiate a deal. Indeed, news of SNB intervention might spread in the market before its transactions are finalised, during the period in which the SNB dealing desk negotiates its deals with FX dealers.

3.5 Intervention, liquidity and uncertainty

A basic assumption of the signalling hypothesis is that market participants are uncertain about the fundamental factors which affect the value of foreign currencies. Monetary authorities are presumed to exploit the superior information they possess on these fundamental factors to condition market sentiment and exchange rates. This implies that intervention operations are likely to affect the dispersion of opinions among market participants. Moreover, both when intervention operations possess an information content and when they simply perturb the optimal inventory of individual dealers, they are likely to affect the terms upon which dealers are prepared to trade. In particular, we might expect intervention activity to induce dealers to widen the spreads they charge.

Investigation of the relationship between intervention activity and spreads is straightforward as the exchange rate quote data we use gives direct measures of spreads. In order to investigate the relation between sterilised intervention and market uncertainty, though, we need to find ways to measure the latter. The best way to measure such uncertainty is through examination of the dispersion of the distribution of exchange rate expectations among FX dealers.

However, we do not know of any survey data that contains observations of agents' expectations at the relevant high frequency and therefore we are forced to use a crude measure of such uncertainty. As market microstructure theory suggests, agents uncertainty (alongside other factors) affects the volatility of prices in securities markets. To measure volatility we use the absolute value of the residuals, $\hat{\epsilon}_t$, from the linear regression of returns on leads and lags of intervention quantity (plus two lags of the dependent variable.) This gives us a proxy for the level of market uncertainty.

Using the intervention indicator and size data and our volatility proxy ($\hat{\epsilon}_t$) we estimate the following two specifications:

$$|\hat{\epsilon}_t| \;=\; \alpha \;+\sum_{i=1}^{23} \omega_i\, D_{i,t} \;+\; \sum_{j=8}^{-8} \beta_j\, |I_{t+j}| \;+\; \sum_{j=1}^{10} \gamma_j\, |\hat{\epsilon}_{t-j}| \;+\; \eta_t, \tag{8}$$

$$|\hat{\epsilon}_t| \;=\; \alpha \;+\; \sum_{i=1}^{23} \omega_i\, D_{i,t} \;+\; \sum_{j=8}^{-8} \delta_j\, |X_{t+j}| \;+\; \sum_{j=1}^{10} \gamma_j\, |\hat{\epsilon}_{t-j}| \;+\; \eta_t. \tag{9}$$

where the $D_{i,t}$ variables are a set of 23 hourly dummies employed to model the repetitive intra-day pattern in volatility. We estimate similar specifications for spreads:

$$s_t \;=\; \sum_{i=1}^{24} \omega_i D_{i,t} + \sum_{j=8}^{-8} \beta_j\, |I_{t+j}| \;+\; \sum_{j=1}^{5} \gamma_j\, s_{t-j} \;+ \epsilon_t, \tag{10}$$

$$s_t \;=\; \sum_{i=1}^{24} \omega_i D_{i,t} + \sum_{j=8}^{-8} \delta_j\, |X_{t+j}| \;+\; \sum_{j=1}^{5} \gamma_j\, s_{t-j} \;+ \epsilon_t. \tag{11}$$

Table 9 displays the results from our spread estimations and Table 10 displays those from the volatility estimations. In Table 9 we see that the coefficients of several leads and lags for both regressions are positive. Moreover, the coefficients of the first lag of the absolute intervention indicator and the contemporaneous absolute quantity are significantly larger than zero. These results are interesting, as it is commonly believed that FX dealers rarely change the width of their spreads, but rather move quotes in order to manage inventory. Our regressions indicate that, in line with the signalling hypothesis, FX dealers react to SNB intervention operations by widening the spread between their bid and ask quotes. In quantitative terms, given that the coefficient on the contemporaneous intervention size regressor is 0.0131 and median intervention size is $30 million, we conclude that the average dealer augments the width of the spread by nearly 40 basis points in reaction to a purchase or sale of dollars on the part of the Swiss monetary authorities. This is consistent with the magnitudes reported in Table 4 and once again suggests an impact of central bank operations that is an order of magnitude larger than those in Evans and Lyons (2000).

In Table 10 we report the results of the volatility estimations.[15] Inspection of the results shows a similar pattern in the coefficients of the leads and lags of the intervention variables,

$|I_t|$ and $|X_t|$: i) the coefficients of most leads, the contemporaneous value and the first lag are positive, ii) most of the coefficients of the remaining lags are negative, iii) the coefficients on the contemporaneous values of the intervention variables are significant.

These results suggest that sterilised intervention affects exchange rate volatility and market uncertainty. Indeed we notice that: i) the volatility of the USD/CHF rate of return is generally increased before an intervention event, with a rise that is significantly above zero in the 15 minute interval that precedes intervention; ii) this increase is amplified in the interval during which intervention occurs and iii) volatility declines starting in the interval immediately after intervention.

This evidence seems in line with the information based interpretation we gave to the results reported in Table 3: as market participants' assessments of the likelihood of upcoming intervention are increased, the dispersion of their beliefs rises and hence so does the volatility of the USD/CHF return. On the other hand, the operation *per se* reveals fundamental information and hence reduces the heterogeneity of expectations and the volatility of the exchange rate subsides post-intervention.

3.6 Intervention effects under aggregation

Our final piece of analysis evaluates the longer-run importance of SNB interventions in the USD/CHF market. Whilst, earlier in the paper, we have argued that the very-high frequency response of exchange rates to interventions indicates that these operations "carry" information, we have not documented the persistence of the intervention effects beyond a couple of hours. One would have thought that, if interventions were truly important events for exchange rate determination, one should also be able to track their exchange rate effects over days.

Hence, to tackle this issue, we examine the results from regressions of *temporally aggregated exchange rate return* data on *aggregated intervention activity.* We begin by aggregating our 15 minute returns to give hourly, 2 hourly, 4 hourly, 12 hourly and daily returns. We then construct 2 aggregated intervention variables. The first is a signed aggregated intervention indicator (equal to 1 if there was a dollar purchase over the aggregate period, -1 if there was a dollar sale and 0 otherwise.) The second variable is signed, aggregate intervention quantity over the relevant interval (e.g. signed, daily intervention quantity.) We then run two sets of linear regressions. The first regresses aggregated returns on a constant, two lags of aggregated returns and the contemporaneous aggregated intervention indicator only i.e:

$$r_t^k \;=\; \lambda_0 + \sum_{j=1}^{2} \lambda_j r_{t-j}^k \;+\; \beta_0 I_t^k \;+\; \epsilon_t, \tag{12}$$

where r_t^k is the return aggregate across k observations and I_t^k is the corresponding aggregated intervention indicator. The second set of regressions have aggregated returns on the left hand side and a constant, two lags of aggregated returns and contemporaneous aggregate intervention quantity on the right hand side:

$$r_t^k \;=\; \lambda_0 + \sum_{j=1}^{2} \lambda_j r_{t-j}^k \;+\; \delta_0 X_t^k \;+\; \epsilon_t, \tag{13}$$

where X_t^k is aggregate quantity. The intervention coefficients and t-statistics from these regressions, for various k, are given in 11.

The Table demonstrates a number of facts. First, in line with earlier results, aggregated intervention quantity is almost always more significant than the intervention indicator (for a given degree of aggregation.) Second, intervention quantity has a significant effect on exchange rate returns even when both are measured at the daily level (and for all smaller degrees of aggregation.) This is not true for the intervention indicator variable. Lastly, though, we should consider the actual magnitude of these intervention effects on exchange rates. Consider, for example, the daily results for intervention quantities. The median (unsigned) size of a (non-zero) daily intervention is \$50m. Hence, the impact of such an intervention on the exchange rate is $50 \times 0.0019 < 0.1$ i.e. on a daily level, an SNB intervention of median size will change exchange rates by less than 0.1%. Hence, whilst we have documented the significance and persistence of intervention effects on the USD/CHF, it should be noted that their quantitative impact is small. Given the pace of FX markets and the small sizes of these interventions relative to daily volumes, this is probably not too surprising.

4 Concluding Remarks

We have conducted an investigation of the effects of sterilised intervention in the USD/CHF market. The novelty of this study lies in the use of a transaction based data set of SNB activity between 1986 and 1995, whose information is combined with indicative exchange rate quotes recorded by Olsen and Associates and Reuters news-wire reports. With such a rich data set we have been able to identify a clear and significant link between sterilised intervention and exchange rate returns and volatility. In particular, using an event study, we have exactly quantified the effects of single intervention operations on the USD/CHF rate at a 15 minute sampling frequency.

However, the effect of intervention events on the exchange rate is fairly small and becomes relatively difficult to identify in more coarsely sampled data. It also appears that central banks are more effective in conditioning exchange rates when they coordinate their intervention operations. This suggests an important policy implication: monetary authorities can confidently employ foreign exchange intervention to affect market sentiment and currency values over very short intervals of time, especially when they can act in unison. Longer term objectives should instead fall under the jurisdiction of other more powerful policy instruments. This policy prescription is in line with common practice, as there is anecdotal evidence that when monetary authorities intend to reverse long-term trends they accompany fundamental shifts in monetary policies with some activity in foreign exchange markets.[16]

A further policy implication can be drawn from another result: we find in our sample that intervention operations which are against-the-wind have longer-run effects which are insignificantly different from zero. On the other hand, interventions which are with-the-trend have strong and persistent exchange rate impacts. This result suggests that foreign exchange intervention is not well suited to reversing prior changes in exchange rates but it can be effectively employed to reinforce existing trends.

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Notes

[1]See among others Mussa (1981), Bhattacharya and Weller (1997) and Vitale (1999).

[2]See in particular Dominguez and Frankel (1993b), Dominguez and Frankel (1993a). Edison (1993) and Sarno and Taylor (2000) contain extensive reviews of this literature.

[3]Importantly, as a standard practice the SNB would immediately sterilise the effects of both customer transactions and interventions on monetary aggregates through compensatory open market operations.

[4]See Fischer and Zurlinden (1999) for a more complete description of the intra-day frequency of these interventions.

[5]Danielsson and Payne (2000), comparing indicative data on the USD/DEM with firm quotes drawn from an electronic broking system, show that the statistical properties of indicative and firm returns are essentially identical at sampling frequencies of 10 minutes and greater.

[6]Given the conditional heteroskedasticity and serial dependence usually found in high frequency financial time series, we estimate the standard errors of the regression coefficients using the Newey-West method.

[7]A possible explanation for this "anticipation effect" is the presence of small reporting lags in the intervention data set. In the mid 1980s and the early 1990s intervention operations were completed on the phone and subsequently registered on report slips. We have investigated this possibility by examining the effects of interventions occurring in the first 5 minutes of any 15 minute interval separately from all others. If there was a reporting lag we would expect to see such interventions strongly affecting returns in the interval prior to that in which the intervention was reported whilst the remaining intervention observations would not. This is not the case in the data.

[8]For a formal discussion see Bhattacharya and Weller (1997) and Vitale (1999).

[9]This definition implies that 72 (105) events are classified as with- (against-) the-trend. Note that this 24 hour "trend" period is measured so as to end two hours before any intervention such that it does not overlap with any of the leads of I_t in the regression specification.

[10]Similar estimates are obtained using other definitions of with- (against-) the-trend intervention e.g. defining trends using weekly exchange rate changes.

[11] An interpretation of these results could be based on a learning mechanism. In particular, if market participants are in the process of learning a shift in policy or in the fundamentals, the monetary authorities are able to accelerate such a process with coherent intervention operations.

[12]As a check of the quality of such data we cross the information contained in the news-wire reports with that for the SNB intervention. We find that 74% of all SNB intervention operations were reported by Reuters. Moreover, of those intervention operations which were concerted with the Buba and the Fed 84% were reported. Finally, of the intervention operations which were reported, the median of the time lag between the actual operation and the corresponding report is 11 minutes and 30 seconds for all operations and 11 minutes for the concerted ones. While we do not have means to prove it, we conjecture that the news-wire reports for the operations of the Fed and the Buba are more accurate.

[13]Of the 62 interventions in the August 1989 to December 1995 sub-sample, 22 are classified as concerted. We have experimented with alternative definitions for concerted intervention, for example defining concerted interventions as those when the SNB, Buba and Fed were all in the market on the same day. The results derived are qualitatively similar to those presented here.

[14]The indicators can be signed as the news headlines always include an indication of the direction of the intervention.

[15]The usual strong persistence in absolute returns dictates the use 10 lags of the dependent variable in the linear regression. GARCH models were tested and ruled out due to instability in their estimation.

[16]In particular, the G-5 coordinated their monetary and foreign intervention to manage the US dollar in the mid 1980s, as extensively discussed by Funabashi (1988).

Table 1: Summary statistics for intervention transactions

Variable	Obs.	Mean	s.d.	Median	Skew	Kurt
I_t	709	-3.29*	10.41	-5	-1.40*	11.54*
Variable	Obs.	Mean	s.d.	Median	Min	Max
I_t^+	243	8.39*	3.23	10	5	35
I_t^-	466	-9.39*	7.14	-10	-100	-5

Notes: Statistics are calculated from the tick-by-tick transaction series. A * indicates that the given statistic is significantly different from zero at the 5% level. I_t is signed intervention quantity (positive for dollar purchases.) I_t^+ and I_t^- are the subsamples of positive and negative interventions respectively. *s.d.* is the standard deviation of the given variable, *Skew* is the coefficient of skewness and *Kurt* is excess kurtosis.

Table 2: Summary statistics for exchange rate data

Variable	Mean	s.d.	Skew	Kurtosis	$\hat{\rho}_1$	$Q(10)$
r_t	-2.8 $\times 10^{-5}$	0.086	0.054	28.472	-0.112	4383.875
q_t	27.333	742.561	1.477	5.491	0.893	1734989.700
$\|r_t\|$	0.052	0.068	4.544	53.490	0.292	98366.779

Notes: statistics are based on 343680 observations with a 15 minute sampling frequency. This sample omits exchange rate data from weekends. The variable r_t is the percentage return on the USD/CHF and q_t is the count of the number of quote entries in a given 15 minute period. The final variable $|r_t|$ is the absolute exchange rate return. *s.d.*, *Skew* and *Kurt* are as defined in the notes to Table Table 1. $\hat{\rho}_1$ is the first estimated autocorrelation and $Q(10)$ is the tenth order Box-Ljung statistic.

Table 3: Effects of signed intervention on percentage return

Regressor	Coefficient	Regressor	Coefficient
α	0.0000		
β_8	-0.0120	β_7	0.0117
β_6	0.0077	β_5	-0.0207
β_4	-0.0023	β_3	0.0261
β_2	0.0080	β_1	0.0467**
β_0	0.1241**		
β_{-1}	-0.0338**	β_{-2}	-0.0069
β_{-3}	-0.0174	β_{-4}	-0.0162
β_{-5}	0.0120	β_{-6}	-0.0032
β_{-7}	-0.0069	β_{-8}	-0.0103
γ_1	-0.1146^{**}	γ_2	-0.0167^{**}
$\bar{R}^2$	0.014	$Q(5)$	30.32**

Notes: the table contains results from estimation of equation (1). Regression coefficients are estimated using the OLS method with Newey-West standard errors and 2 lags in the dependent variable. I_t is signed intervention (+1 for dollar purchases, -1 for dollar sales) and r_t is the percentage return on the USD/CHF. A * (**) indicates that the given statistic is significantly different from zero at the 5% (1%) level. $Q[5]$ is the fifth order Box-Ljung statistic for serial correlation.

Table 4: Effects of intervention size on returns

Equation (2)		Equation (3)	
Regression	Coefficient	Regression	Coefficient
α	-0.00002**	α	-0.00002
β_4	-0.00906	δ_4	0.00004
β_3	0.03121	δ_3	0.0009
β_2	0.00549	δ_2	0.00062
β_1	0.04614**	δ_1	0.00164*
β_0	0.06687**	δ_0	0.00371**
β_{-1}	-0.03858*	δ_{-1}	-0.00106*
β_{-2}	-0.01035	δ_{-2}	-0.00018
β_{-3}	-0.01056	δ_{-3}	-0.00071*
β_{-4}	-0.02174	δ_{-4}	-0.00043
δ_4	0.00019	θ_4	0.000000
δ_3	-0.00015	θ_3	-0.000004
δ_2	0.00004	θ_2	-0.000003
δ_1	0.00004	θ_1	-0.000006
δ_0	0.00159**	θ_0	-0.000008**
δ_{-1}	0.00003	θ_{-1}	0.000004
δ_{-2}	0.00005	θ_{-2}	0.000001
δ_{-3}	-0.00017	θ_{-3}	0.000002
δ_{-4}	0.00018	θ_{-4}	0.000002
γ_1	-0.11455**	γ_1	-0.11459**
γ_2	-0.01676**	γ_2	-0.01684**
$\bar{R}^2$	0.015	$\bar{R}^2$	0.015
$Q(5)$	30.16**	$Q(5)$	29.8**

Notes: regression coefficients are estimated using the OLS method with Newey-West standard errors and 2 lags in the dependent variable. I_t is signed intervention (+1 for dollar purchases, -1 for dollar sales), X_t is signed intervention *magnitude* (in millions of US dollars) and r_t is the percentage return on the USD/CHF. A * (**) indicates that the given statistic is significantly different from zero at the 5% (1%) level. $Q[5]$ is the fifth order Box-Ljung statistic for serial correlation. The coefficient values which are not reported for reason of space are not significant.

Table 5: Regression of returns on SNB customer trades

Regressor	Coefficient	Regression	Coefficient
α	1.29×10^{-5}		
β_8	-0.0047	β_7	-0.0008
β_6	-0.0117**	β_5	-0.0018
β_4	-0.0056	β_3	-0.0072
β_2	-0.0036	β_1	-0.0229**
β_0	-0.0095		
β_{-1}	0.0048	β_{-2}	0.0006
β_{-3}	0.0029	β_{-4}	0.0061
β_{-5}	-0.0058	β_{-6}	0.0009
β_{-7}	-0.0041	β_{-8}	0.0072
γ_1	-0.1142**	γ_2	-0.0175**
$\bar{R}^2$	0.013	$Q(5)$	3.97

Notes: regression coefficients are estimated using the OLS method with Newey-West standard errors. CT_t is signed SNB customer trading activity (+1 for dollar purchases, -1 for dollar sales). A * (**) indicates that the given statistic is significantly different from zero at the 5% (1%) level. $Q[5]$ is the fifth order Box-Ljung statistic for serial correlation.

Table 6: Effects of prior exchange rate trend on intervention effect

Regressor	With Trend	Against Trend
α	0.0000	0.0000
β_8	-0.0131	-0.0109
β_7	0.0139	0.0107
β_6	0.0301	-0.0065
β_5	-0.0145	-0.0253
β_4	0.0374	-0.0293
β_3	0.0646*	0.0005
β_2	0.0100	0.0043
β_1	0.0661*	0.0333
β_0	0.1866**	0.0820**
β_{-1}	-0.0350	-0.0325*
β_{-2}	0.0026	-0.0130
β_{-3}	-0.0278*	-0.0091
β_{-4}	-0.0230	-0.0113
β_{-5}	0.0070	0.0178
β_{-6}	-0.0023	-0.0014
β_{-7}	-0.00237	0.0048
β_{-8}	-0.0153	-0.0070
γ_1	-0.1147**	-0.1142**
γ_2	-0.0170**	-0.0165**
$\bar{R}^2$	0.014	0.013
$Q(5)$	27.90**	29.33**

Notes: the table presents results from estimations of the with/against the trend regressions and the concerted/non-concerted specifications. Coefficients are estimated using the OLS method with Newey-West standard errors and 2 lags in the dependent variable. I_t is signed intervention (+1 for dollar purchases, -1 for dollar sales) and r_t is the percentage return on the USD/CHF. A * (**) indicates that the given statistic is significantly different from zero at the 5% (1%) level. $Q[5]$ is the fifth order Box-Ljung statistic for serial correlation.

Table 7: Concerted intervention regressions

Equation (5)				Equation (6)			
Regr.	Coeff.	Regr.	Coeff.	Regr.	Coeff.	Regr.	Coeff.
α	1.93×10^{-6}	κ_1	0.1153	α	2.35×10^{-5}	ν_1	0.0059**
β_8	-0.0056	κ_0	0.1230	δ_8	-9.94×10^{-5}	ν_0	0.0040
β_7	-0.0101	κ_{-1}	-0.0685	δ_7	-9.56×10^{-5}	ν_{-1}	-0.0027**
β_6	0.0054	γ_1	-0.1416**	δ_6	-5.72×10^{-5}	γ_1	-0.1417**
β_5	-0.0437**	γ_2	-0.0220**	δ_5	-0.0004	γ_2	-0.0222**
β_4	0.0011			δ_4	0.0003		
β_3	0.0575			δ_3	0.0002		
β_2	0.0238			δ_2	0.0002		
β_1	0.0485**			δ_1	0.0003		
β_0	0.1576**			δ_0	0.0019**		
β_{-1}	-0.0089			δ_{-1}	0.0000		
β_{-2}	-0.0063			δ_{-2}	-0.0001		
β_{-3}	-0.0199			δ_{-3}	-0.0002		
β_{-4}	0.0243			δ_{-4}	0.0004		
β_{-5}	0.0040			δ_{-5}	-0.0001		
β_{-6}	-0.0144			δ_{-6}	-0.0003		
β_{-7}	0.0096			δ_{-7}	0.0003		
β_{-8}	-0.0034			δ_{-8}	0.0001		
$\bar{R}^2$	0.014			$\bar{R}^2$	0.022		
$Q(5)$	30.60**			$Q(5)$	28.55**		

Notes: regression coefficients are estimated using the OLS method with Newey-West standard errors. I_t is signed intervention (+1 for dollar purchases, -1 for dollar sales), X_t is signed intervention quantity (positive for dollar purchases, negative for dollar sales), C_t is a concerted intervention indicator, which is unity for intervals in which the SNB intervened *and* the Fed and Buba were both reported to be in the market up to 1 hour beforehand or 45 minutes afterwards. A * (**) indicates that the given statistic is significantly different from zero at the 5% (1%) level. $Q[5]$ is the fifth order Box-Ljung statistic for serial correlation.

Table 8: Regression of returns on separate signed SNB, Fed and Buba intervention indicators

Regressor	Coefficient	Regressor	Coefficient
α	-0.0002	ϕ_4	0.0153
β_8	-0.0057	ϕ_3	0.0617**
β_7	-0.0084	ϕ_2	-0.0003
β_6	0.0071	ϕ_1	-0.0142
β_5	-0.0442**	ϕ_0	-0.0112
β_4	-0.0015	ϕ_{-1}	-0.0082
β_3	0.0474	ϕ_{-2}	-0.0224**
β_2	0.0210	ϕ_{-3}	-0.0220**
β_1	0.0674**	ϕ_{-4}	0.0013
β_0	0.1670**	ψ_4	-0.0008
β_{-1}	-0.0491	ψ_3	0.0511**
β_{-2}	-0.0056	ψ_2	0.0659**
β_{-3}	-0.0165	ψ_1	0.0039
β_{-4}	0.0184	ψ_0	-0.0128
β_{-5}	0.0045	ψ_{-1}	-0.0183
β_{-6}	-0.0016	ψ_{-2}	0.0109
β_{-7}	0.0193	ψ_{-3}	0.0014
β_{-8}	0.0025	ψ_{-4}	-0.0396**
γ_1	-0.1308**	γ_2	-0.0219**
$\bar{R}^2$	0.020	$Q(5)$	43.51**

Notes: regression coefficients are estimated using the OLS method with Newey-West standard errors. I_t is signed intervention (+1 for dollar purchases, -1 for dollar sales), I_t^F is a signed indicator of Reuters reports of Fed intervention and I_t^B is a signed indicator of Reuters reports of Buba intervention. A * (**) indicates that the given statistic is significantly different from zero at the 5% (1%) level. $Q[5]$ is the fifth order Box-Ljung statistic for serial correlation.

Table 9: Spread regressions

Equation (10)		Equation (11)	
Regressor	Coefficient	Regressor	Coefficient
β_8	-0.15	δ_8	-0.0007
β_7	-0.07	δ_7	0.0045**
β_6	0.10	δ_6	0.0007
β_5	0.08	δ_5	0.0018
β_4	-0.13	δ_4	-0.0006
β_3	-0.08	δ_3	-0.0023
β_2	0.14	δ_2	0.0038
β_1	0.23	δ_1	0.0015
β_0	0.30	δ_0	0.0131**
β_{-1}	0.40**	δ_{-1}	0.0053
β_{-2}	-0.18	δ_{-2}	-0.0027
β_{-3}	-0.01	δ_{-3}	0.0011
β_{-4}	-0.13	δ_{-4}	0.0001
β_{-5}	0.19	δ_{-5}	0.0015
β_{-6}	-0.03	δ_{-6}	-0.0018
β_{-7}	0.44	δ_{-7}	0.0050
β_{-8}	-0.20	δ_{-8}	-0.0038
$\bar{R}^2$	0.927	$\bar{R}^2$	0.917
$Q(5)$	2524.92	$Q(5)$	2525.29

Notes: regression coefficients are estimated using the OLS method with Newey-West standard errors. $D_{i,t}$ is a dummy variable for the ith hour of the day. I_t is signed intervention (+1 for dollar purchases, -1 for dollar sales) and X_t is signed intervention size. s_t is the percentage bid-ask spread. A * (**) indicates that the given statistic is significantly different from zero at the 5% (1%) level. $Q[5]$ is the fifth order Box-Ljung statistic for serial correlation. The coefficients on the hourly dummies and the lagged dependent variables are not reported for reasons of space.

Table 10: Volatility regressions

Equation (8)		Equation (9)	
Regression	Coefficient	Regression	Coefficient
α	0.0131**	α	0.01314**
β_8	0.0001	δ_8	0.00008
β_7	0.0020	δ_7	0.00002
β_6	0.0023	δ_6	0.00004
β_5	0.0132	δ_5	0.00011
β_4	0.0173	δ_4	0.00045
β_3	0.0260*	δ_3	0.00019
β_2	0.0051	δ_2	0.00020
β_1	0.04307**	δ_1	0.00068
β_0	0.0535**	δ_0	0.00087**
β_{-1}	0.0091	δ_{-1}	0.00018
β_{-2}	-0.0087	δ_{-2}	-0.00007
β_{-3}	-0.0005	δ_{-3}	0.00004
β_{-4}	-0.0029	δ_{-4}	0.00005
β_{-5}	0.0026	δ_{-5}	0.00002
β_{-6}	-0.0118	δ_{-6}	-0.00025*
β_{-7}	-0.0007	δ_{-7}	0.00005
β_{-8}	-0.0118^*	δ_{-8}	-0.00005
$\bar{R}^2$	0.464	$\bar{R}^2$	0.463
$Q(5)$	14.12*	$Q(5)$	14.09*

Notes: regression coefficients are estimated using the OLS method with Newey-West standard errors, 23 dummies for the time of the day and 10 lags in the dependent variable. Now $|I_t|$ and $|X_t|$ are unsigned intervention variables, i.e. $|I_t|$ is a dummy variable which takes value 1 when an intervention operation takes place and 0 otherwise, while $|X_t|$ is equal to $|I_t|$ time the absolute size (in million of dollars) of intervention. Finally, $D_{i,t}$ is the dummy variable for the hour of the day. A * (**) indicates that the given statistic is significantly different from zero at the 5% (1%) level. $Q[5]$ is the fifth order Box-Ljung statistic for serial correlation. For reason of space the estimates of the coefficients of the dummy variables and the lags of the dependent variable are not reported.

Table 11: Intervention effects and aggregation

Aggregation (k)	Equation (12)		Equation (13)	
	Coeff. On I_t	t-value	Coeff. On X_t	t-value
4	0.1435	4.12	0.0027	5.84
8	0.1895	3.77	0.0027	3.10
16	0.1273	2.29	0.0020	3.09
48	0.1523	1.90	0.0025	3.02
96	0.1159	0.98	0.0019	2.06

Notes: this Table presents coefficients from regressions of temporally aggregated returns on aggregated intervention data. The basic 15 minute return data is aggregated to give 1 hour, 2 hour, 4 hour, 12 hour and 1 day returns. Similarly we aggregate the intervention data to give a signed intervention indicator and aggregated intervention quantity (for the various levels of aggregation). We then regress aggregated returns on a constant, 2 lags of aggregated returns and the contemporaneous aggregated intervention indicator. The coefficient and t-statistic on the indicator are given in columns 2 and 3 for various levels of aggregation. We also regress aggregated returns on a constant, 2 lags of aggregated returns and contemporaneous aggregated intervention quantity. Results from this regression, for various degrees of aggregation, are given in columns 4 and 5.

Figure 1: SNB purchases of U.S. dollars: 1986-1999.

Figure 2: USD/CHF exchange rate: 3/3/86-19/11/99.

Figure 3: Intra-day activity patterns in indicative USD/CHF data.

Figure 4: Basic effects of intervention on the USD/CHF. Results are based on exchange rates and intervention events defined using a 15 minutes sampling frequency. Time is measured in 15 minute intervals relative to intervention. The dashed lines indicate the 95% confidence interval for the cumulative intervention effect.

Figure 5: Size effects of intervention on the USD/CHF. Results are based on exchange rates and intervention events defined using a 15 minutes sampling frequency. The x-axis for panel (a) gives the (15 minute) interval relative to the intervention. In panel (a), the three selected values for the intervention size correspond to the 25th percentile, median, and 75th percentile of the distribution of intervention size.

Figure 6: Basic effects of SNB customer trades on the USD/CHF. Results are based on exchange rates and intervention events defined using a 15 minutes sampling frequency. Time is measured in 15 minute intervals relative to intervention. The dashed lines indicate the 95% confidence interval for the cumulative effect of non-intervention operations.

Figure 7: Effects of trend on intervention impact. Results are based on exchange rates and intervention events defined using a 15 minutes sampling frequency. An intervention event is defined to be with the trend if its sign is the same as that of the change in the rate of the prior 24 hours. Time is measured in 15 minute intervals relative to the intervention. The dashed lines indicate the 95% confidence interval for the cumulative intervention effect.

Figure 8: Effects of concerted and non-concerted intervention on the USD/CHF. Results are based on exchange rates and intervention events defined using a 15 minutes sampling frequency. Time is measured in 15 minute intervals relative to intervention. In both panels the intervention size employed is the median intervention size. The dashed lines indicate the 95% confidence interval for the cumulative intervention effect.

Figure 1: SNB purchases of U.S. dollars: 1986-1999

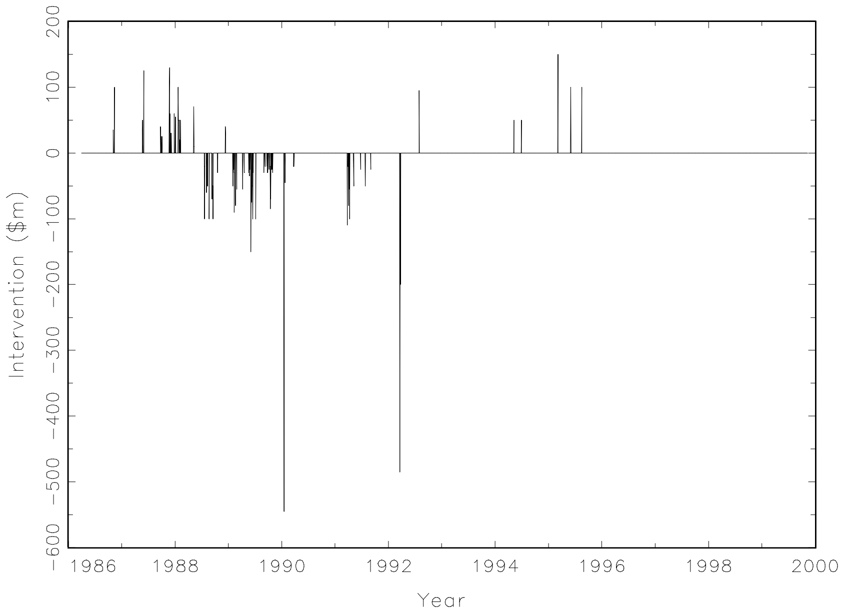


Figure 2: USD/CHF exchange rate: 3/3/86-19/11/99

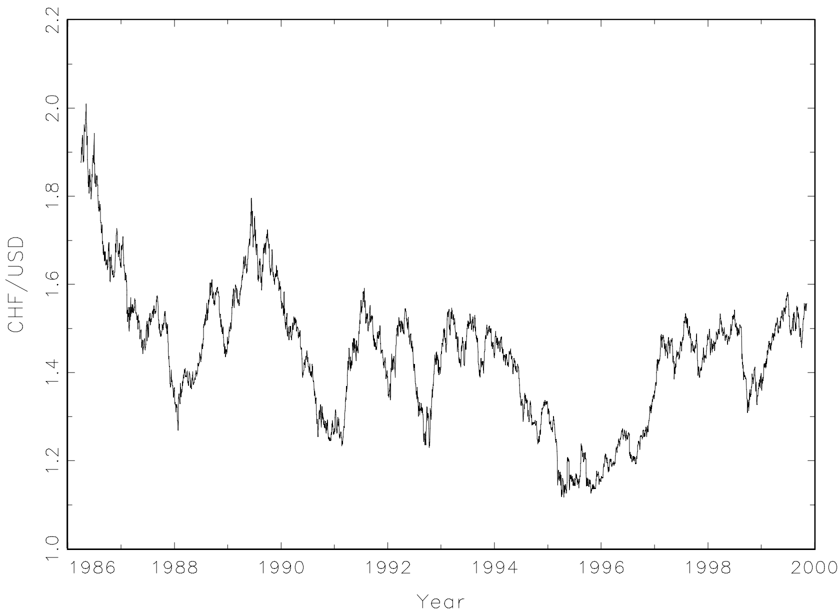
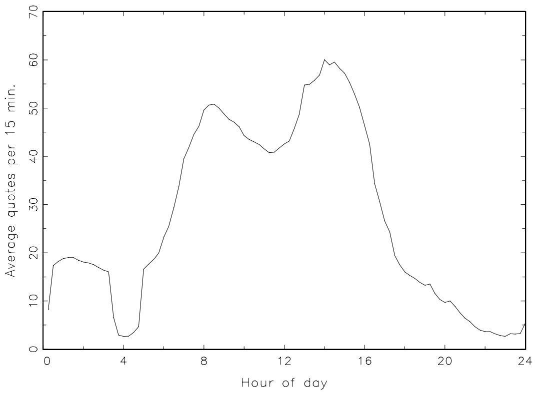
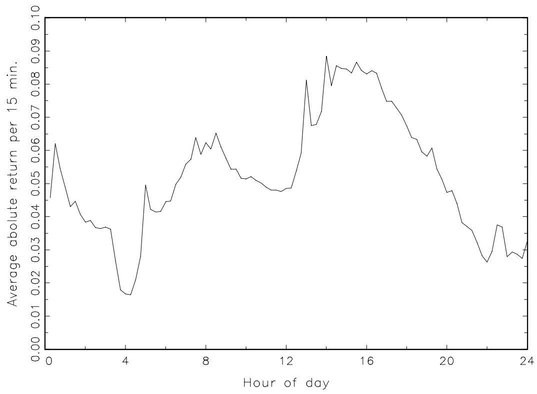


Figure 3: Intra-day activity patterns in indicative USD/CHF data



(a) Quote frequency



(b) Absolute return

Figure 4: Basic effects of intervention on the USD/CHF

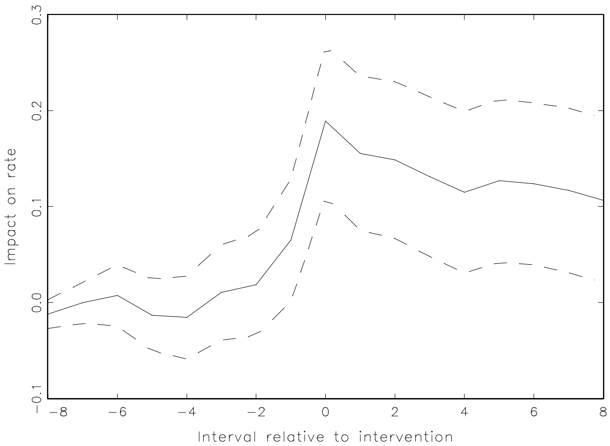
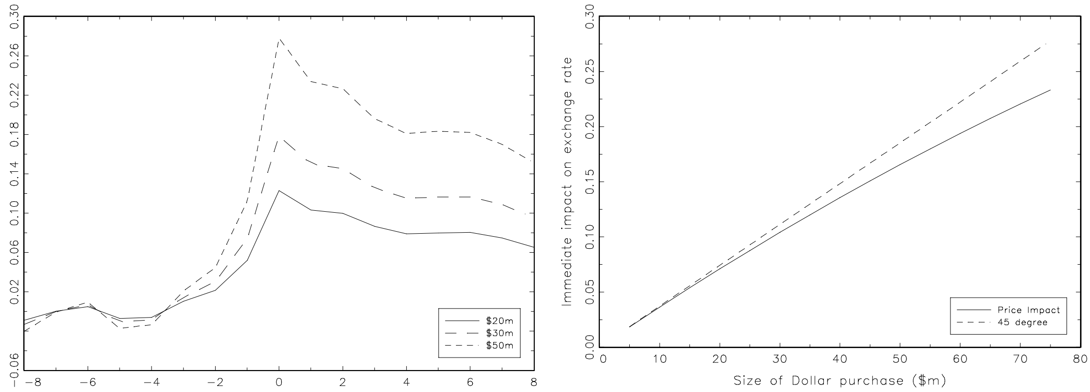


Figure 5: Size effects of intervention on the USD/CHF



(a) Impulse-response function

(b) Non-linearities in immediate impact

Figure 6: Basic effects of SNB customer trades on the USD/CHF

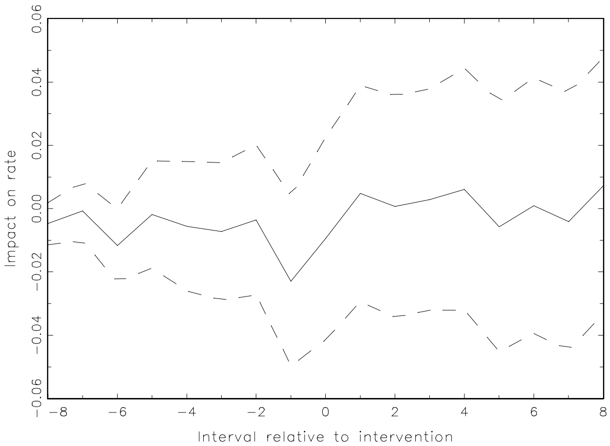
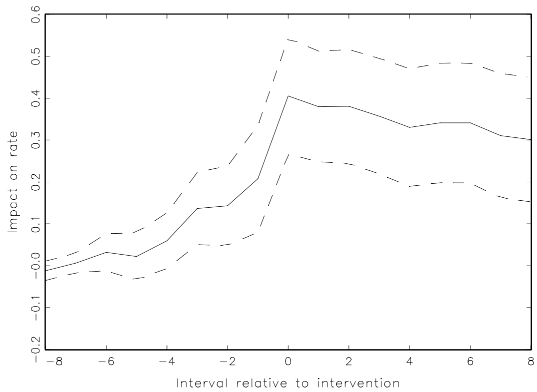
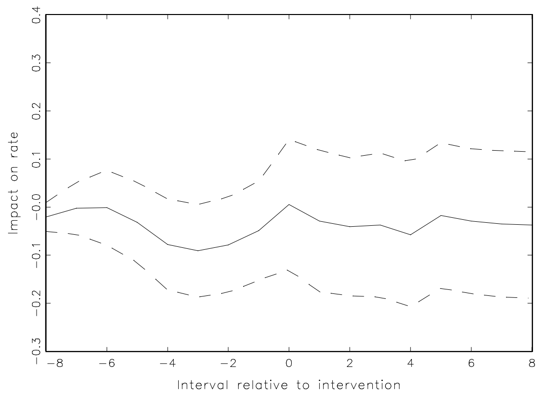


Figure 7: Effects of trend on intervention impact

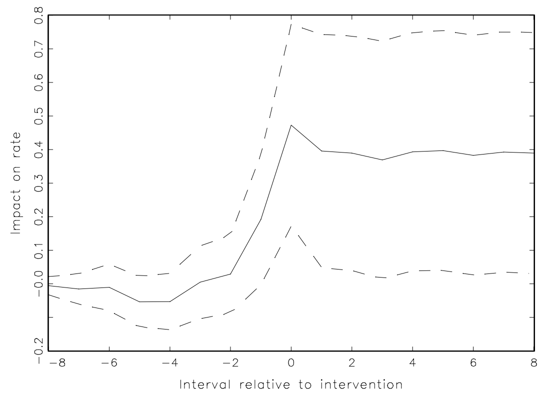


(a) With trend

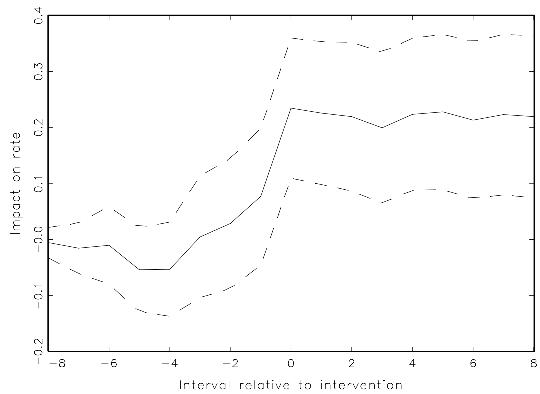


(b) Against trend

Figure 8: Effects of concerted and non-concerted intervention on the USD/CHF



(a) Concerted intervention



(b) Non-concerted intervention