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Are all Central Bank interventions created equal? An empirical investigation

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Abstract

This study investigates the relationship between Central Bank interventions and technical trading rule profitability in the spot foreign exchange market. Because interventions are not necessarily exogenous events, we analyze the relationships between interventions by the G-3 Central Banks, financial market conditions, changes in monetary policy and technical trading profitability. By considering announced, unannounced, unilateral and coordinated interventions separately, we provide more insight into the interrelationships between these factors than previous studies. We find that the level of technical trading profits and market uncertainty increase preceding and remain high during interventions, especially announced and coordinated, but decrease afterward. A preliminary investigation of the possible role of a time-varying risk premium around interventions cannot be rejected.

JEL classification: F31; G14; E58
Keywords: Foreign exchange; Central Bank intervention; Technical analysis

1. Introduction

Because the foreign exchange market is the largest and arguably most important financial market in the world, it is believed that if any financial market should be efficient it should be this market. Unfortunately tests of even the weakest form of market efficiency are rejected in the foreign exchange market – technical analysis is consistently profitable. This apparent inefficiency has persisted from the first studies (Poole, 1967; Dooley and Shafer, 1976, 1983) to the most recent studies

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(Neely et al., 1997; Gençay, 1999; LeBaron, 1999; Neely, 2002). Researchers have proposed that Central Banks may play a role in this apparent inefficiency because they can influence the supply and demand for currencies at any time. Consequently exchange rates are not always determined by the laws of supply and demand required for market efficiency (Friedman, 1953; Dooley and Shafer, 1983; Corrado and Taylor, 1986; Sweeney, 1986 among others).

Consistent with the hypothesis that Central Banks may be related to this apparent inefficiency, Szakmary and Mathur (1997), Neely (1998) and LeBaron (1999) find that technical trading profits were correlated with periods of Federal Reserve intervention activity during the 1980s and early 1990s. To better understand this relationship Neely (2002) uses higher frequency data and finds that the profitability of technical analysis actually begins before the start of intervention activities. We build on these studies by investigating differences across types of interventions (e.g. announced versus unannounced) and whether interventions and these periods of apparent inefficiency may be related to some other economic factor(s).

We address these issues using a dataset that is longer and more comprehensive than those used in previous studies. We have both a period of extensive intervention activity (the 1980s and early 1990s) as well as a period with little intervention activity (the mid- to late-1990s). This permits us to compare different types of interventions by the Federal Reserve, the Bank of Japan and the Deutsche Bundesbank. We compare announced and unannounced interventions as well as coordinated and unilateral interventions for these Central Banks. [1] The existing empirical literature tends to concentrate on Fed interventions with little consideration for differences between these types of intervention. To understand the relationships between these different types of interventions, technical trading returns and other factors theory suggests may instigate and/or influence the effectiveness of interventions we use a vector autoregression (VAR) technique. We investigate, for example, the relationships between factors such as the volatility of exchange rates and Central Bank interventions – Fed policy states it intervenes "to calm disorderly markets" and "signal" the desired level of the exchange rate to the market (Cross, 1998). We also investigate several relationships between financial markets, interventions and exchange rate movements proposed by theories of exchange rate determination (for a survey see Frankel and Rose, 1995). All of these relationships are analyzed in the context of technical trading profitability to see if they can help explain this apparent inefficiency.

We start our analysis by verifying that technical analysis can generate statistically and economically significant returns in the Deutsche Mark-$ and Japanese Yen-$ markets in our sample. We find an average annualized excess return of about 10% in the DM-$ market, for example, which is statistically significant. Because the set of rules we consider were profitable over both our sample period and an out-of-sample test period, it is unlikely they are the result of an ex-post bias. The economic significance of the returns is suggested by their robustness to market frictions such as

[1] Unilateral and coordinated interventions were classified using official intervention data. Announced and unannounced interventions were determined from newspaper and newswire reports.

transaction costs and their Sharpe Ratio being significantly better than for the S&P500 (despite the exceptional performance of the stock markets over this period). It is noteworthy that the profitability was concentrated in the 1980–1995 period – the period of active intervention.

In our VAR analysis we find that information on Central Bank interventions (especially announced and coordinated interventions by the Fed and Bundesbank), some changes in monetary policy and changes in market uncertainty are related to technical trading profitability. The technical trading returns and measures of foreign exchange market uncertainty increase preceding interventions, peak on the day(s) of intervention activity and decrease on the last day and afterward. These results suggest that interventions change foreign exchange market expectations and end once they have "calmed disorderly markets". The differences we find across types of interventions provide some insight into the apparently contradictory findings of many previous studies which treated all interventions in the same fashion (see Edison, 1993 or Frankel and Rose, 1995 for a discussion). The relationship between the level of technical trading returns, market uncertainty and interventions suggests that these profits may be the result of a risk premium at these times and not market inefficiency (increasing market uncertainty is frequently, but not necessarily, associated with the presence of a risk premium). Using an international CAPM, we are unable to reject the possible presence of a time-varying risk premium in the technical trading returns correlated with Central Bank intervention activity, especially announced and coordinated.

The paper is organized as follows. A discussion of the data makes up Section 2. In Section 3, we measure and characterize the economic and statistical significance of the technical trading returns. Section 4 discusses the results from the VAR tests. Section 5 characterizes the behavior of foreign exchange and technical trading returns around interventions. A summary of the main results and areas for future research concludes.

2. Data and summary statistics

We consider the daily bid and ask spot exchange rates for the Deutsche Mark and Japanese Yen versus the US dollar over the period from January 1, 1980 to December 31, 1998 from Data Resources Incorporated (DRI). This is a valuable period because it includes a period of active intervention by the G-3 Central Banks, 1980 to the mid-1990s, as well as a period of light intervention activity, the mid- to late-1990s. This contrast allows us to more thoroughly investigate the role of interventions than was possible in previous studies. To determine the potential impact of ex-post bias, we compare our results to the out-of-sample period from January 1, 1975 to December 31, 1979.

For Central Bank interventions, we use the official daily intervention data from the Federal Reserve and the Deutsche Bundesbank. [2] For the Federal Reserve's

[2] The Fed intervention data was obtained from the Federal Reserve and is publicly available with a one-year lag. The intervention data from the Bundesbank was obtained with special permission.

interventions, we only consider the purchases or sales of US dollars made on its own behalf in Japanese Yen or Deutsche Marks. This excludes passive interventions or occasions on which the Fed dealt directly with customers who would otherwise have dealt with market agents (for a discussion see Cross, 1998). Similarly, we only consider interventions by the Bundesbank for which it used its own foreign reserves. This excludes interventions performed on behalf of other Central Banks such as those required by the European Monetary System (for a discussion see Bundesbank, 1992; Hoffman, 1994).

We separate interventions into different categories because it is frequently hypothesized that announced and unannounced interventions as well as coordinated and unilateral interventions influence foreign exchange markets differently (e.g. Bhattacharya and Weller, 1997; Vitale, 1997). Announced interventions were defined based on a search of the Wall Street Journal and the New York Times for newspaper reports and Lexis Nexis for newswire reports of interventions. We do this for the Bank of Japan, Bundesbank and Fed. This provides us with a more accurate picture of the information available to market participants around interventions than is possible using only newspaper reports as in previous studies. [3]

To measure changes in monetary policy we consider the one month Eurocurrency interest rates, and the default premium (BAA less AAA corporate interest rates) for Germany, Japan and the US. [4] We measure market expectations using the forward premium for the DM-$ and Yen-$ currency pairs. We use several measures for market uncertainty: the standard deviation of the spot bid over the past week, the conditional volatility estimated using a GARCH-M model, and more forward-looking measures such as the spot bid-ask spread, and the average implied volatility, [5] open interest and trading volume [6] for the three month at-the-money put and call options in these currency pairs. Due to possible asymmetries in the hedging motive for the trading of puts and calls, especially as market uncertainty increases, we also consider the difference between the implied volatility, open interest and volume for the at-the-money puts and calls. All of the interest rate data was obtained from Datastream, the spot and forward exchange rate data from DRI and the options data from the Chicago Mercantile Exchange (note: the CME data does not start until 1984).

Because we are investigating daily relationships between interventions, economic factors and exchange rate movements, we need to consider the time at which our data was recorded. Due to our focus on interventions, the timing is relative to inter-

[3] Studies such as Dominguez and Frankel (1993), Klein (1993) and Osterberg and Humes (1993, 1995) only used reports appearing in newspapers such as the Wall Street Journal and the New York Times. The addition of newswire sources increased our sample, especially with respect to the smaller interventions.

[4] We also considered factors such as the term structure and quantity of Treasury Bills outstanding but due to their weak statistical significance and space considerations they are not presented.

[5] Jorion (1995) finds the implied volatility from options data outperforms other time-series models at forecasting foreign exchange volatility.

[6] Chaboud and LeBaron (2001) find increased futures trading activity around Fed interventions, especially announced, and suggest it is related to increased uncertainty at these times. As a result we use open interest (quantity of outstanding unexercised option contracts) and trading volume to measure market uncertainty.

ventions. Dominguez (1999) finds that from 1987 to 1995 the Bundesbank intervened at, on average, 11:30 (GMT) and the Fed at 15:00 (GMT). The exchange rates from 1980 to 1986 are the opening prices in New York (14:00 (GMT)) and from 1986 to 1998 they are the last trade in London (about 16:00 (GMT)). Although the exchange rates from 1980 to 1986 may not have followed that day's Federal Reserve interventions, this period was characterized by light Fed intervention activity most of which was coordinated with the Bundesbank. Consequently we assume they occurred before 14:00 (GMT) and thus the exchange rates and our other data were recorded following Bank of Japan, Bundesbank and Fed interventions.

2.1. Descriptive statistics

Technical analysis generates profits by accurately predicting trends in exchange rates and in Fig. 1 we see periods of long upward and downward movements in both currency pairs. The dollar appreciated against the Mark from 1980 to 1985, depreciated from 1985 to 1987, and was relatively stable from 1987 to 1998. Relative to the yen, the dollar was stable from 1980 to 1985, depreciated rapidly from 1985 to 1987 and was stable again from 1987 to 1998. Table 1 presents some descriptive statistics for the log first differences (continuously compounded returns) of the bid for these two currency pairs. The returns display the well-known characteristics of exchange rates – low skewness, large kurtosis, very little autocorrelation, and the presence of conditional heteroskedasticity. Except for the mean, these characteristics were stable over time: the mean is positive or negative reflecting the appreciation or depreciation of the currencies in the different periods. Interestingly the average absolute value of returns was stable over time.

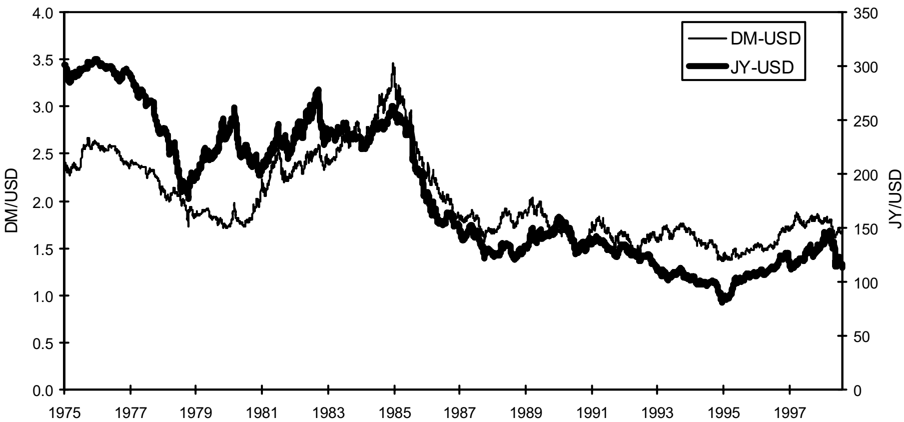


Fig. 1. Exchange Rates from 1975 to 1998. Graph of the daily bid exchange rate for the DM-$, and Yen-$ over the period from January 1, 1975 to December 31, 1998. The data was obtained from DRI and is the New York opening from Bank America (San Francisco) until 1986 and the London close from NatWest (London) afterward.

Table 1
Summary statistics for exchange rate returns

	1975–1980	1980–1985	1985–1990	1990–1995	1995–1998
(a) Deutsche Mark – US dollar					
Mean × 1000	−0.270	0.492	−0.50	−0.074	0.071
Std. Dev. × 1000	4.87	7.02	7.56	7.11	6.05
Mean pos × 1000	3.20	5.43	5.03	5.01	4.14
Mean neg × 1000	−3.45	−5.29	−6.01	−5.44	−4.64
Mean absolute × 1000	3.33	5.37	5.52	5.22	4.37
Skewness	1.06	−0.31	−0.21	0.19	−0.26
Kurtosis	12.46	4.25	5.73	4.77	5.48
(b) Japanese Yen – US Dollar					
Mean × 1000	−0.190	0.045	−0.450	−0.300	0.125
Std. Dev. × 1000	4.96	6.55	6.89	6.26	8.47
Mean pos × 1000	2.73	4.16	4.11	3.87	5.40
Mean neg × 1000	−3.40	−5.99	−5.69	−5.30	−6.36
Mean absolute × 1000	3.05	4.91	4.85	4.52	5.83
Skewness	0.39	−0.40	−0.33	−0.53	−0.82
Kurtosis	15.09	4.17	7.14	5.49	8.36

Summary statistics for the continuously compounded (or log returns) of the daily bid DM-$, and Yen-$ spot exchange rates from January 1, 1975 to December 31, 1998. The data was obtained from DRI and is the New York opening from Bank America (San Francisco) until October 8, 1986 and the London close from NatWest (London) afterward.

Fig. 2 illustrates the changing nature of intervention activity over the period from 1980 to 1998. In Fig. 2(a) and (b) we see that the Fed was fairly active in both the DM-$ and Yen-$ markets from 1980 to mid-1981, inactive from mid-1981 to 1987 (except for some selling of dollars in late-1985), it returned between 1987 and 1995 and was absent from mid-1995 until the end of our sample. On the other hand Fig. 2(c) and (d) show the Bundesbank was very active in both the DM-$ and the DM-European currency markets from 1980 until it ceased intervention activities in mid-1995. These interventions were clustered with the Bundesbank intervening in the DM-$ market almost twice as often as the Fed: the Fed or the Bundesbank intervened on 8% and 17% of trading days respectively, yet if there was an intervention on the previous day these percentages increased to 57% and 60% (the average duration of intervention episodes was 2.6 and 2.8 days respectively).

The average size of interventions increased over the sample and both Central Banks' interventions remained similar in size in each sub-period. As a result of the Bundesbank being more active early in the sample, the overall average size of Bundesbank interventions was smaller than Fed interventions ($77M versus $124M). Comparing types of interventions, announced interventions were, on average, almost twice as large as the unannounced [7] (in the DM-$ market $197M for the Fed and

[7] This is consistent with the results of Klein (1993) who found Fed interventions announced in newspapers were larger than the unannounced. Further we find the interventions announced in both the newspaper and the newswire were slightly larger than those that were only announced on the newswire.

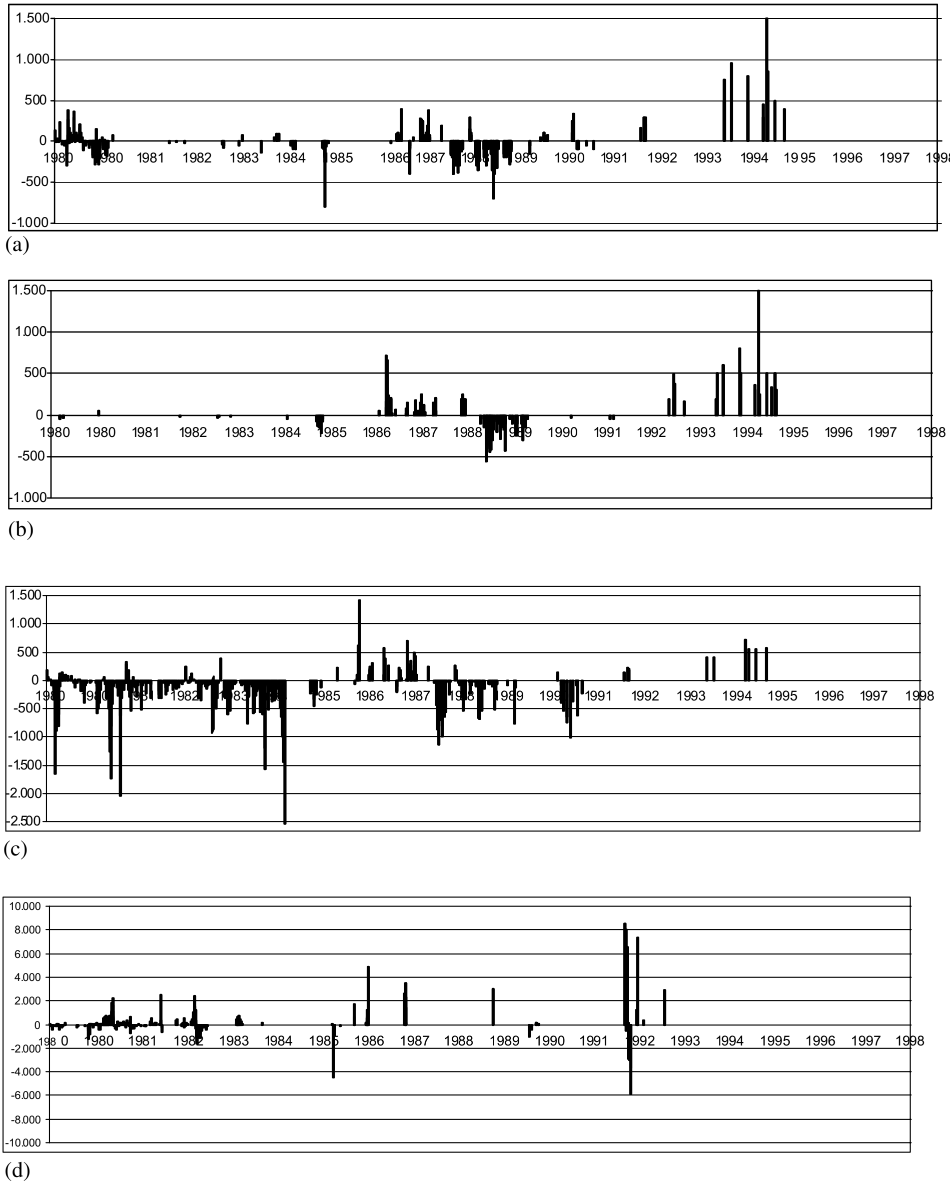


Fig. 2. Timing and Quantity of Federal Reserve and Deutsche Bundesbank Interventions 1980–1998. Graph of the daily quantity of official Central Bank intervention by the Federal Reserve and the Deutsche Bundesbank over the period from January 1, 1980 to December 31, 1998. The quantities are in millions of US dollars and millions of Deutsche Marks respectively. (a) Interventions by the Federal Reserve in the DM-$ market: (b) Interventions by the Federal Reserve in the Yen-$ market: (c) Interventions by the Deutsche Bundesbank in the DM-$ market: (d) Interventions by the Deutsche Bundesbank in the DM-ERM market (interventions in the European currencies):

$105M for the Bundesbank versus $98M and $55M respectively) but coordinated were only slightly larger than unilateral interventions. The frequency also varied: about 65% of interventions were unannounced, less than 25% of all interventions were coordinated, but coordinated interventions were over twice as likely to be announced than unilateral. As a result it does not appear that all interventions are created equal, but it is not clear what impact this has on technical trading returns.

3. Technical trading rules

This section discusses the technical trading strategies we consider. Because implementing technical trading strategies generally requires skill, judgment and other characteristics that are difficult to mimic, we consider one of the simplest and most objective trading strategies: moving average trading rules. [8] This rule generates a buy or sell signal by comparing the current exchange rate to a moving average of past exchange rates: buy when the current spot price is above the moving average and sell when it is below. For example, at time t the T-day moving average of the spot exchange rate (s_t) is defined to be:

$$\mathrm{MA}(T)_t = \frac{1}{T}\sum_{i=0}^{T-1} s_{t-i}. \tag{1}$$

With the current spot price defined in DM/US$, for example, this means the trader wants to be long dollars when $s_t \geqslant \mathrm{MA}(T)_t$.

Although many studies ignore transaction costs, we use continuously compounded returns that account for the costs associated with the implementation of these trading strategies. These include buying at the quoted ask and selling at the bid. This provides a conservative estimate of the actual costs (Goodhart et al. (1996) found that quoted prices are 2–3 ticks wider than actual transaction prices). Because we assume investors borrow the currency they sold and invest the currency they are holding at the corresponding overnight interest rates, [9] the strategies are self-financing and the returns are excess returns. Formally the returns are calculated as follows:

when the investor maintains the same position from time t to time $t+1$:

$$\text{long dollars } r_t = \{\ln(s^A_{t+1}/s^A_t) + \ln[(1+i^{A*}_t)/(1+i^B_t)]\}, \tag{2a}$$

$$\text{short dollars } \quad r_t = (-1)\{\ln(s^B_{t+1}/s^B_t) + \ln[(1+i^{B*}_t)/(1+i^A_t)]\}, \tag{2b}$$

when the investor changes position:

[8] Neely et al. (1997) consider more complex trading strategies and find that the optimal technical trading strategies over a similar time period were slight modifications of this trading rule.

[9] The overnight interest rates and the exchange rates are not quoted at exactly the same time, so it may not be possible to obtain the exact returns calculated here. However the interest rates play such a minor role in the trading rule returns that this should not significantly influence our results.

$$\text{long to short} \quad r_t = \{\ln(s^B_{t+1}/s^A_t) + \ln[(1 + i^{A*}_t)/(1 + i^B_t)]\}, \tag{2c}$$

$$\text{short to long} \quad r_t = (-1)\{\ln(s^A_{t+1}/s^B_t) + \ln[(1 + i^{B*}_t)/(1 + i^A_t)]\}, \tag{2d}$$

where $\{s^A_t, s^B_t\}$ are the quoted ask and bid for the spot DM-$ rate at time t, and $\{i^A_t, i^B_t\}$ and $\{i^{A*}_t, i^{B*}_t\}$ are the quoted ask and bid for the overnight US and German interest rates respectively. [10]

3.1. Profitability of technical analysis

Table 2 presents the returns from different moving average trading strategies. Over the entire period, the returns for the DM-$ are generally statistically different from zero – t-statistics of between 1.3 and 2.5. The returns in the Yen-$ market are all statistically significant with t-statistics ranging from 2.7 to 3.7. As a consequence of the moving average trading rules generating statistically significant returns over the out-of-sample 1975–1980 period as well, the concern of ex-post bias in our choice of trading strategies is minimal. In fact it is only in the final sub-period that the statistical significance of the returns in the DM-$ and Yen-$ market vanishes. The concentration of profitability in the 1975–1995 period suggests a possible role for Central Bank intervention in the apparent inefficiency of the foreign exchange market.

Many researchers ignore transaction costs because "buying or selling $1 will cost the trader about $0.00025" (Neely, 1998), so we investigate the sensitivity of our trading rule returns to transaction costs. In Table 3 we start with no transaction costs – the returns are the log first difference of the midpoint of the spot exchange rate. Next we replace the midpoints with the corresponding bid and ask values. Finally we add the cost or benefit from the overnight investment in each currency. The impact of these transaction costs on our returns can be most clearly seen for the MA(10) trading rule which changes position often thus incurring these costs the most frequently. In the simplest case, without any transaction costs, the MA(10) trading rule generates returns with t-statistics of 3.32 in the DM-$ market for 1980–1998. This falls to 1.77 when the bid–ask spread is accounted for and to 1.74 with the inclusion of overnight investing. Other than for the MA(10) trading rule, this table demonstrates that transaction costs do not play a major role in the statistical significance of our technical trading returns. As a consequence it is unlikely that the profitability of our technical trading strategies is the result of market frictions such as transaction costs.

[10] For example, if we assume the trading rule directs the trader to buy DM the trader starts by borrowing dollars at the overnight US interest rate ask. The dollars are converted to DM at the spot bid and invested at the overnight German interest rate bid. The next day the trader either continues to hold DM and rolls over the overnight positions, or reverses them to hold dollars. Consequently the trader earns a dollar return defined as the product of the overnight German interest rate and the appreciation of the DM, less the interest to borrow dollars.

Table 2
Statistical significance of technical trading rule returns

Lags	1980–1998	1975–1980	1980–1985	1985–1990	1990–1995	1995–1998
(a) For the DM-$						
10	1.74	2.13	1.65	2.37	1.10	0.55
25	1.33	3.07	2.70	2.20	2.13	0.26
50	2.18	3.64	2.94	2.55	1.68	1.34
75	1.41	2.47	2.15	2.10	2.02	0.67
100	1.85	2.67	2.23	2.21	2.04	0.54
125	2.23	2.86	2.30	1.60	2.20	0.64
150	1.72	2.36	2.10	1.23	1.85	0.43
200	1.90	2.41	2.11	0.70	1.83	0.42
250	2.52	2.61	1.89	0.65	1.56	−0.05
(b) For the Yen-$						
10	2.73	1.96	1.09	1.44	2.59	−1.00
25	3.12	2.68	1.66	1.22	2.29	−0.56
50	3.06	3.67	2.73	1.62	2.44	0.50
75	3.49	4.33	3.22	0.71	3.09	0.77
100	3.70	4.49	3.27	1.39	2.34	1.00
125	3.47	4.26	3.19	1.54	2.25	1.14
150	3.18	4.00	3.00	1.41	2.05	0.86
200	2.95	3.24	2.34	1.14	1.88	−0.05
250	2.90	2.90	1.91	0.23	1.18	0.01

The *t*-statistics from the DM-$ and Yen-$ returns generated by different moving average trading rules. The returns are calculated using formulas (2a)–(2d). The exchange rates were obtained from DRI and are the New York opening from Bank America (San Francisco) until October 8, 1986 and the London close from NatWest (London) afterward. The German and Japanese overnight interest rates were obtained from DRI and the US interest rates from the Federal Reserve.

3.2. Significance of the trading rule returns

The previous discussion relied upon *t*-statistics to assess the statistical significance of our trading returns. This requires assuming the mean of the trading returns is asymptotically normally distributed. The results in Table 1 suggest this may be a problem. To estimate the impact of this assumption on our results, we use a bootstrap to non-parametrically estimate the statistical significance of our trading rule returns. Our bootstrap methodology is similar to that outlined in Brock et al. (1992). We start by generating bootstrapped exchange rate series under the null hypothesis that the foreign exchange market is efficient and characterized by different random walk processes (for details please see Appendix A). A sample of the bootstrapped *p*-values is presented in Table 4. These values suggest that the *t*-statistics provide reasonable estimates for the statistical significance of our technical trading returns. For example, the *t*-statistic for the returns from the MA(150) trading rule implied a *p*-value of 0.007. This compares very well to the bootstrapped *p*-values of 0.007 and 0.012 obtained under each of the random walk models. Since the *t*-statistics are easily computed and provide a reliable measure of statistical significance, we rely on them in the subsequent analyses.

Table 3
Impact of transaction costs on technical trading rule returns

Lag	1980–1998			1975–1980		
	No trxn costs	Trxn costs no int rates	Trxn costs int rates	No trxn costs	Trxn costs no int rates	Trxn costs int rates
10	3.32	1.77	1.74	3.45	2.11	2.13
25	2.80	1.37	1.33	3.32	2.88	3.07
50	2.29	2.20	2.18	3.75	3.61	3.64
75	1.59	1.43	1.41	2.61	2.38	2.47
100	2.25	1.89	1.85	2.78	2.65	2.67
125	2.27	2.25	2.23	2.95	2.91	2.86
150	1.87	1.74	1.72	2.37	2.32	2.36
200	2.06	1.94	1.89	2.46	2.37	2.41
250	2.51	2.54	2.51	2.56	2.58	2.61

The values in this table for the DM-$ returns using different moving average trading rules from 1975 to 1998. The returns are calculated using formulas (2a)–(2d). The DM-$ exchange rates were obtained from DRI and are the New York opening from Bank America (San Francisco) until October 8, 1986 and the London close from NatWest (London) afterward. The German overnight interest rates were obtained from DRI and the US interest rates from the Federal Reserve. The first column contains the t-statistics for returns using only the midpoint of the exchange rate and no overnight investing (e.g. without any transaction costs), next the returns including the transaction costs based on the quoted bid and ask but no overnight investing and the third column for the returns incorporating both the bid–ask transaction costs and investing overnight.

The statistical significance of technical trading returns does not tell us whether the returns adequately compensate investors for the risk of investing in the foreign exchange market. Ideally we would answer this question by comparing the trading rules' returns to the required return for investing in this market. Because standard asset pricing models perform poorly in the foreign exchange market (see Lewis, 1995 for a discussion), we compare the returns from technical analysis to those from investing in a risk-free asset (one-month US Treasury bills) and in a risky asset (the S&P500). Investing in US T-Bills over this period would have generated an average annualized return of 7.0% and investing in the S&P500 an average annualized return of 18.6%, or an average annualized excess return of 11.6%. To compare the risk-reward trade-off across these investment strategies we use one-year Sharpe Ratios – a higher Sharpe Ratio indicates an investment with a better risk-reward trade-off. [11] Over our sample period, the one-year Sharpe Ratios for investing in the S&P500 and the MA(150) trading rule were 0.49 and 0.65 respectively (from 1980 to mid-1995 they were: 0.34 and 0.76 respectively). This suggests technical trading strategies provide an attractive return for their risk.

In summary, technical trading strategies generate both statistically and economically significant profits. The decrease in their significance after 1995 is consistent with

[11] The one-year Sharpe ratios are estimated using: $\sqrt{N}(\mu_{\text{return}}/\sigma_{\text{return}})$ where μ_{return} is the average continuously compounded daily excess return from each investment; σ_{return}, the standard deviation; and N, the number of trading periods in one year.

Table 4
Non-parametric estimations of the significance of technical trading rule returns

		Parametric estimate of the p-values from	Non-parametric estimates of the p-values from	
		t-Statistic	H_0: random walk process 1	H_0: random walk process 2
Trading rule	MA(10)	0.001	0.000	0.000
	MA(50)	0.002	0.004	0.007
	MA(150)	0.007	0.007	0.012
	MA(250)	0.088	0.088	0.093
Removing these interventions from MA(150)	Fed DM	0.169	0.247	0.253
	Fed JY	0.053	0.063	0.088
	all Fed (DM/JY)	0.206	0.216	0.242
	Buba in USD	0.363	0.421	0.413
	Buba in ERM	0.052	0.052	0.069
	all Buba (US/ERM)	0.500	0.516	0.524
	Both US-DM	0.106	0.122	0.141

The values in this table are for the p-values of the different trading rule returns over the period from 1980 to 1998. These are implied from the parametrically determined t-statistics in the first column of values and from a non-parametric bootstrap in the second and third columns (see Appendix A for a discussion and the definitions of the two random walk processes). They were calculated using formulas (2a)–(2d). The exchange rates were obtained from DRI and are the New York opening from Bank America (San Francisco) until October 8, 1986 and the London close from NatWest (London) afterward. The German overnight interest rates were obtained from DRI and the US interest rates from the Federal Reserve. The bottom portion of the table verifies the measures of statistical significance of trading rule returns used in the replication of LeBaron's (1999) analysis performed in Section 5. The replication of LeBaron (1999) involves the calculation of returns for the trading rules after removing days on which the specified central bank intervention activities occurred.

the hypothesis that this apparent inefficiency could be related to Central Bank intervention activities – a decrease in intervention activity is one of the main differences between these periods.

4. Vector autoregression analysis

To estimate the relationships between exchange rate movements and different economic factors, especially interventions, we use a VAR model to determine whether past values of one variable, v, are linearly informative about the current value of another variable, x:

$$x_t = \beta_0 + \sum_{i=1}^{p} \beta_{1i} x_{t-i} + \sum_{i=1}^{p} \beta_{2i} v_{t-i} + \varepsilon_t \tag{3}$$

This is a form of Granger causality test (see Hamilton, 1994 for a discussion) where the null hypothesis is that the past values of v do not help explain the present value of

x or formally H_0: $\beta_{21} = \beta_{22} = \beta_{23} = \beta_{24} = \beta_{25} = 0$. The number of lags, p, was chosen using the Akaike information criteria (AIC). The test statistic for our null hypothesis is obtained by comparing the sum of squared errors from the unconstrained regression in Eq. (3) (called SSE_u) to the sum of squared errors from a regression using only the lagged values of x (called SSE_c). Both of these models can be estimated by ordinary least squares. The test statistic is defined as:

$$G_t = \frac{(\text{SSE}_\text{c} - \text{SSE}_\text{u})}{\text{SSE}_\text{u}/(T - (2p) - 1)} \tag{4}$$

This follows an F-distribution under the assumption that SSE_c and SSE_u are asymptotically normally distributed. [12] If G_t is greater than the critical value we reject the null hypothesis that past values of v do not provide information relevant to the current value of x. Cooley and LeRoy (1985) suggest this technique for determining whether changes in one variable systematically precede changes in another.

We use this technique to investigate the possible correlations between technical trading profits, Central Bank interventions, market uncertainty and monetary policy. We consider measures of market uncertainty because increased market uncertainty could lead to central bank intervention (Cross, 1998) or possibly indicate the presence of a risk premium. We consider monetary policy because many models suggest that it may influence exchange rates (see Frankel and Rose, 1995) or be influenced by exchange rate movements (e.g. Kaminsky and Lewis, 1996). As a result the main hypotheses we investigate are: How is uncertainty related to trading rule profitability? Interventions? Do changes in monetary policy precede trading rule profitability? Do changes in monetary policy precede or follow interventions?

4.1. Interventions, exchange rates and trading rule returns

In the first and fourth columns of Table 5a we see the relationships between the continuously compounded returns for the DM-$ and Yen-$ exchange rates and different economic factors. [13] We start with the G_t-statistics for the DM-$ exchange rate. The only measures of market uncertainty that appear to have predictive power for changes in the exchange rate are the average volume and the differences in the volume and open interest between the at-the-money put and call options. Moving to our intervention variables, we find interventions by the Federal Reserve in the DM and Yen had predictive ability for movements in the daily DM-$ exchange rate G_t-statistic values of 3.04 and 2.33 respectively). Because interventions are clustered

[12] Because this is an asymptotic F-test, Geweke et al. (1983) and Guilkey and Salemi (1982) investigate the finite sample properties of this statistic. They find that it is robust to changes in the number of lagged values, the presence of serial correlation in the variables and other deviations from normality (even if the chosen parameterization was not correct).

[13] The results in Table 5 use a lag length of five days. Although the optimal lag lengths obtained using the AIC varied from 2 to 20, the most common value was 5 and the significance of the results was consistent using the optimal lag length or 5. Consequently, to aid in interpretation of the results we use five lags throughout.

Table 5
Results from the VAR analysis

Variable	DM-$			JY-$		
	FX return	Abs(FX returns)	Trading rule	FX return	Abs(FX returns)	Trading rule
Panel (a)						
Spread in DM-$	1.16	0.96	1.01	1.94	1.55	2.29**
Spread in JY-$	0.81	2.04*	1.42	0.58	1.29	0.86
Forward premium DM-$	1.63	1.00	0.81	0.38	0.78	0.62
Forward premium JY-$	1.25	0.11	1.19	2.38**	1.90	2.52**
Volatility (previous week)	1.23	10.65**	1.11	1.92	4.55**	1.71
Implied volatility	1.55	3.77**	1.56	0.96	1.75	0.96
Open interest	1.34	0.98	1.29	0.32	1.61	0.29
Volume	2.34**	1.79	2.36**	1.05	1.58	1.08
Put–call volume	4.60**	2.44**	1.39	2.62**	1.80	0.46
P–C open int	2.26**	0.52	0.68	0.97	2.10*	0.40
P–C implied volatility	1.34	1.76	1.44	0.68	1.07	0.58
Fed interventions in DM	3.04**	3.99**	0.84	0.82	1.93	1.08
Announced Fed in DM	2.18*	1.65	0.81	0.77	0.72	1.34
Fed interventions in Yen	2.33**	0.76	0.76	0.75	1.18	2.52
Announced Fed in Yen	1.69	0.47	1.15	0.77	1.22	2.31**
Bundesbank interventions in $	1.06	2.16*	2.28**	0.22	1.23	0.84
Announced Bundesbank in $	1.11	1.32	1.16	0.59	0.77	0.42
Fed–Bundesbank in DM-$	1.31	2.11*	2.35**	0.94	2.65**	0.96
Announced Fed–Buba in DM-$	0.90	0.81	0.46	0.87	0.31	0.92
Announced Bank of Japan	0.79	1.41	0.79	1.09	0.51	0.87
US short-term rates	0.55	1.04	0.51	0.04	0.79	0.05
German short-term rates	0.71	1.31	0.71	0.68	0.97	0.69

Japanese short-term rates	0.83	1.13	0.77	2.85**	3.65**	2.84**
Beginning Fed in DM	2.66**	1.27	0.98	2.04*	0.45	1.34
Beginning Fed in JY	1.32	0.91	1.42	1.30	0.84	2.18*
Beginning Buba in USD	1.13	0.50	0.69	1.37	0.69	0.46
Beginning Fed–Buba	2.60**	2.53**	1.37	2.28**	2.23**	1.05
End Fed in DM	0.94	2.03*	1.60	0.92	2.36**	0.71
End Fed in JY	1.15	0.63	1.37	1.55	0.76	0.99
End Buba in USD	0.45	0.57	0.28	0.85	0.66	0.32
End Fed–Buba in USD	0.73	0.47	2.71**	1.32	0.86	0.52

Panel (b)

	Fed DM	Fed JY	Bundes-bank USD	Both USD	Announced Fed DM	Announced Fed JY	Announced Bundes-bank USD	Announced both USD	Announced Bk of Japan USD
FX Return	4.36**	6.06**	9.23**	5.00**	5.03**	5.70**	6.59**	1.72	1.70
Abs(Return)	1.24	1.05	1.30	1.86	2.51**	2.64**	2.72**	1.51	2.25*
Trading rule	2.48**	2.08*	5.93**	2.34**	2.00*	2.89**	3.52**	1.81	1.15
Spread in DM-$	2.93**	1.38	8.79**	4.33**	1.32	0.87	3.32**	1.37	2.12*
Spread in JY-$	3.34**	1.61	6.26**	3.79**	1.95	0.83	3.39**	1.45	3.04**
Forward premium DM-$	2.75**	0.63	9.37**	4.21**	0.32	0.16	1.86	0.11	0.14
Forward premium JY-$	0.43	0.13	2.97**	1.49	0.21	0.46	0.62	0.34	0.47
Volatility (previous week)	0.49	0.68	0.37	0.53	0.85	1.79	2.84**	1.04	0.68
Open interest	7.40**	8.03**	2.09*	7.47**	9.11**	7.47**	3.83**	3.84**	4.40**
Volume	2.89**	2.27**	2.27**	2.31**	4.69**	2.38**	1.14	1.62	1.26
Implied volatility	1.56	1.32	3.48**	2.34**	1.14	0.57	1.58	1.69	1.67
P–C open interest	10.01**	2.81**	2.11*	6.35**	8.74**	2.70**	1.86	2.10*	0.30
P–C volume	2.36**	0.61	0.98	1.53	2.24**	0.51	1.05	0.95	1.11
P–C implied volatility	1.51	1.34	3.70**	2.96**	1.08	0.84	1.83	1.77	2.32**
US short-term rates	0.47	0.09	0.87	0.55	0.14	0.23	0.53	1.07	1.20
German short-term rates	1.24	1.17	0.77	0.26	1.26	0.94	1.40	0.99	0.55
Japanese short-term rates	0.55	0.75	1.41	0.81	1.00	1.28	0.09	0.43	0.61

Table 5 (*continued*)

Panel (c)

	German S-T Rate	German Def Prem	DM-USD spread	DM-USD historic volatility	DM-USD implied volatility	Japanese S-T rate	Japanese Def Prem	JY-USD spread	JY-USD historic volatility	JY-USD implied volatility
Spot rate	1.21	0.43	3.85**	1.46	4.02**	1.23	0.12	0.34	8.20**	0.62
Abs(spot)	1.04	0.72	1.24	350.52**	2.52**	2.92**	0.23	0.65	342.80**	0.43
Trading rule	0.56	0.44	4.05**	1.17	4.09**	1.16	0.88	0.44	10.90**	0.82
Fed DM	0.85	0.15	0.68	3.24**	0.93	0.69	0.08	1.75	2.35**	3.04**
Fed JY	0.85	0.00	0.52	1.69	1.65	1.05	0.00	1.58	2.39**	0.02
Buba USD	2.53**	3.87**	5.78**	4.62**	0.30	0.40	2.04*	3.98**	1.43	0.14
Both DM-USD	2.98**	6.20**	0.83	8.48**	0.53	0.37	3.15**	0.89	2.55**	1.19
Ann Fed DM	0.62	0.00	1.53	2.62	1.15	0.49	0.00	0.53	1.00	5.03**
Ann Fed JY	0.61	0.00	1.66	2.04	1.73	0.69	0.00	1.18	2.56**	0.02
Ann Buba USD	2.11*	0.01	1.49	2.86**	0.25	0.35	0.00	0.59	1.16	0.14
Ann both USD	0.98	0.00	1.74	1.87	0.38	0.29	0.00	0.81	0.37	4.11**
Ann B of J	0.65	0.04	1.10	1.05	0.97	0.28	0.00	0.63	1.57	2.57**
Start Fed DM	0.84	0.23	2.21*	1.22	0.94	1.04	0.11	1.65	0.49	0.53
Start Fed JY	0.91	0.00	0.53	1.64	2.01*	1.23	0.00	1.27	0.70	0.01
Start Buba USD	1.52	0.02	3.43**	6.06**	0.19	0.61	0.00	3.78**	1.00	0.27
Start both	2.63**	8.70**	0.84	8.58**	0.78	0.45	4.42**	0.67	1.63	1.68
End Fed DM	0.50	0.24	1.30	0.69	1.04	1.07	0.13	1.81	0.61	0.13
End Fed JY	0.44	0.00	0.83	1.30	2.41**	1.11	0.00	2.00*	0.99	0.01
End Buba USD	2.37**	0.06	3.21**	2.10*	0.23	0.35	0.00	3.25**	2.17*	0.48
End both USD	1.91	9.43**	0.73	1.59	0.60	0.50	4.78**	0.83	1.60	1.75

Panel (a): The values in this table are for the G_t-statistics (Eq. (4)) from the tests of Eq. (3) over the period from 1980 to 1998. The values are for the log first differences (continuously compounded returns), the absolute value of these returns and the returns from the 50 day moving average trading rules. The data sources are discussed in Section 2. (*Note:* * indicates statistical significance at the 10% level or better and ** indicates statistical significance at the 5% level or better.)

Panel (b): The values in this table are for the G_t-statistics (Eq. (4)) from the tests of Eq. (3) over the period from 1980 to 1998. The values are for the absolute value of the official interventions by the Federal Reserve and Deutsche Bundesbank. The exchange rates are from DRI (the New York opening from Bank America (San Francisco) until October 8, 1986 and the London close from NatWest (London) afterward. (*Note:* * indicates statistical significance at the 10% level or better and ** indicates statistical significance at the 5% level or better.)

Panel (c): The values in this table are for the G_t-statistics (Eq. (4)) from the tests of Eq. (3) over the period from 1980 to 1998. The values are for our measures of market uncertainty: the bid–ask spread and the standard deviation of the exchange rates over the past week and past month with exchange rates from DRI (the New York opening from Bank America (San Francisco) until October 8, 1986 and the London close from NatWest (London) afterward). (*Note:* * indicates statistical significance at the 10% level or better and ** indicates statistical significance at the 5% level or better.)

and it is possible that the market reaction to the beginning of intervention activity is different from other days, especially the end, we consider the first and last days of intervention activity separately. In the bottom part of the table, we present the results for only the first and last days of interventions. We find that the significance of Fed interventions in DM are concentrated on the first day of intervention activity in the DM and the first day of coordinated Fed–Bundesbank intervention activity (values of 2.66 and 2.60 respectively). This suggests that it is the beginning of the intervention episode that provides the most statistically significant information to predict future exchange rate movements. Analyzing the announced interventions, we find the announced Fed interventions in DM were correlated with DM-$ returns (value of 2.18). This suggests the market reacts to the signal contained in the announcement. [14] For the Yen, the statistically significant relationships with changes in monetary policy (changes in the forward premium and short-term interest rates) differences in the trading volume of put and call options and the first days of Federal Reserve intervention in the DM-$ market.

The second and fifth columns consider how the absolute value of the foreign exchange returns are related to our set of economic factors including the absolute value of interventions. We use the absolute value of interventions because this allows us to analyze the relationship between changes in returns and interventions without having to consider the direction (e.g. returns are larger around interventions, whether or not it is an upward or downward movement or an intervention to support or weaken the dollar). For the DM-$, we see that changes in market uncertainty consistently precede movements in the exchange rates (value of over 10 on our historical measure of exchange rate volatility and 3.77 on the average implied volatility). The relationships are also significant for the Fed and Bundesbank interventions in the DM-$ market. For the Yen we find similar relationships except that for the Yen the value of the Japanese Short-term interest rates also plays a significant role.

The final part of Table 5a investigates the technical trading returns in both currencies (columns three and six). The returns are for the MA(50) trading rules against our set of economic factors and the absolute value of interventions. [15] Overall these results indicate that interventions have the most significant predictive power for technical trading returns. For the DM-$ trading rules, it was unilateral interventions by the Bundesbank and coordinated Fed–Bundesbank interventions that were the most significant but for the Yen it was Fed interventions in Yen. Although the last day of an episode of intervention activity had the most predictive power for technical trading returns in the DM-$ it was the first day for Yen. Across trading rules (results not presented) changes in market uncertainty had more significant predictive ability for the returns of the shorter trading rules, but for the longer moving average trading rules it was the Central Bank intervention activities. For the Yen-$ trading rules,

[14] Another argument is that the announcement was based on rumors related to other factors that generated the movements in exchange rates. This is highlighted in results not presented that demonstrate the effect of announced Fed interventions in DM was largest on days of incorrectly announced interventions.

[15] The results for the other trading rules are very similar so they are not presented.

changes in monetary policy (both the forward premium and the short-term interest rates) also preceded trading rule profits.

Economic theory provides us with guidance on how these factors should influence exchange rate movements, so we use the estimated coefficients to determine if the directions of the relationships are consistent with our theory. Using GMM standard errors to compensate for both the heteroskedasticity and serial correlation present in the data (see Cochrane, 2001 for a nice discussion), the signs on the statistically significant coefficients suggest that the DM-$ and Yen-$ rate decreased following increases in the difference in put-call trading volume and open interest, interventions to decrease the value of the dollar as well as following changes in monetary policy that decreased the interest rate differential with the US. These results are consistent with our intuition and monetary theory: exchange rate movements are related to market uncertainty, Central Bank interventions and monetary policy. The most consistent relationships, however, were with interventions. The actual type of intervention and part of an intervention episode depended on the return series under consideration.

4.2. Monetary policy and market conditions

Because interventions, market uncertainty and monetary policy are not necessarily independent we investigate the predictive power of market uncertainty and monetary policy for Central Bank interventions. In Table 5b we see that movements in exchange rates and our measures of market uncertainty have significant predictive power for interventions. The most important measures of market uncertainty are the level of open interest and the difference in the open interest for puts and calls. The predictive power of these factors is stronger for the Bundesbank interventions than for the Fed interventions. The predictive power of our measures of market uncertainty are even larger for the announced than for the unannounced interventions. In most cases, the changes in market uncertainty were concentrated on the days of correctly announced interventions suggesting a role for the information in announcements.

Since we hypothesized different relationships for interventions and market uncertainty, we look at the individual coefficients to more clearly see what is happening. We find that increasing market uncertainty and larger movements in exchange rates are related to an increased probability of future Central Bank intervention. [16] These results are consistent with Central Banks intervening to calm disorderly markets and Neely (2002) who finds that interventions follow the start of technical trading rule profitability. As a result, we find that the well-documented correlation between interventions and trading rule returns may be related to another factor – market uncertainty.

[16] This is consistent with the results in Chaboud and LeBaron (2001) who find an increase in the trading volume of foreign exchange futures preceding interventions and they attribute this to increasing uncertainty at this time.

To complete our investigation, we determine whether interventions have any predictive power for our measures of market uncertainty and monetary policy – whether there is two way causality. Table 5c considers the relationship between changes in our measures of monetary policy (one month Eurocurrency interest rates and the default premium), our measures of market uncertainty and the absolute value of interventions. In the German market we find Bundesbank and coordinated Fed–Bundesbank interventions precede our changes in monetary policy and some changes in market uncertainty (the bid–ask spread and historic volatility). Considering interventions as episodes of intervention activity, we find that this relationship is principally because of the first day of an episode of intervention activity – these measures of market uncertainty decrease following the start of intervention activity. In Japan the interventions, especially announced, preceded changes in the default premium and some measures of market uncertainty. However, the results were less significant for the Yen market than for the Deutsche Mark.

Looking at the direction in the relationships, we see that the default premium decreased following the interventions to decrease the value of the domestic currency (DM and Yen for Germany and Japan respectively). This is consistent with the idea that risk for companies in the country would increase if the Central Banks were required to intervene to support the currency. The measures of market uncertainty for which interventions were significant were the more historical measures which increased after the start of interventions. The more forward looking measures such as the implied volatility were harder to predict using past information on interventions.

In summary we find that large movements in exchange rates were the most common factor preceding interventions. Increasing forward premiums and increasing market uncertainty (particularly options market activity) were found to precede various interventions. This suggests that interventions were at least somewhat anticipated by the market. We do not, however, find that the other factors we investigated systematically preceded movements in exchange rates. Taken together these results suggest that technical trading rule profitability may be related to increased foreign exchange risk around Central Bank intervention activity.

5. Periods of Central Bank intervention activity

To better understand the relationship between interventions and the level and volatility of exchange rates, this section characterizes many factors around different types of interventions. Fig. 3(a) and (b) present the *t*-statistics for the average DM-$ returns from the MA(150) trading rules in the periods around Fed, Bundesbank and coordinated Fed–Bundesbank intervention activities. Because of the clustering of interventions, the days before and after interventions are defined as the days before and after an episode. Comparing these figures we see that the significance of the trading rules' profits is generally larger for coordinated than unilateral interventions and for announced rather than unannounced interventions. However it is only

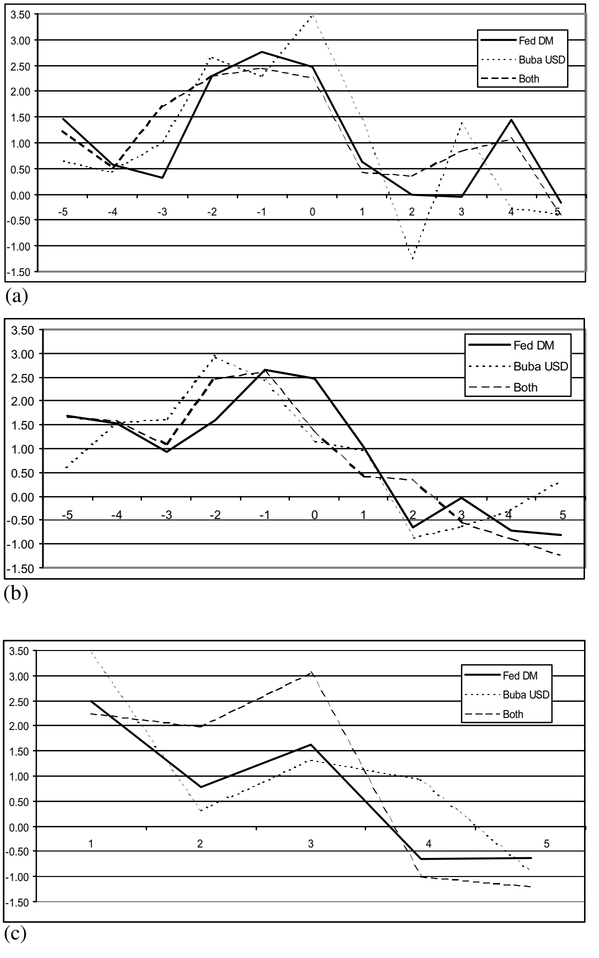
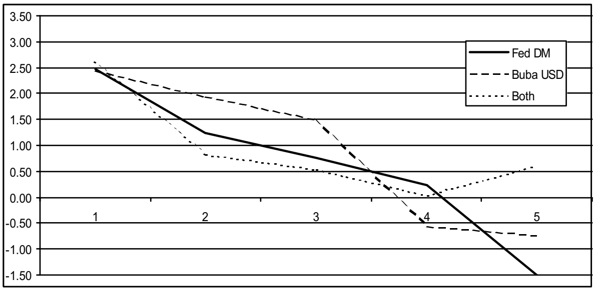


Fig. 3. Technical Trading Rule Returns Around Central Bank Interventions. Graph of the *t*-statistics for the daily DM-$ returns from the 150 day moving average trading rules in the DM-$ market over the period from January 1, 1980 to December 31, 1998. The returns are calculated using formulas (2a)–(2d) and are presented in the periods surrounding the Federal Reserve, Bundesbank and coordinated interventions (interventions are at time 0). The exchange rates were obtained from DRI and are the New York opening from Bank America (San Francisco) until October 8, 1986 and the London close from NatWest (London) afterward. The German overnight interest rates were obtained from DRI and the US interest rates from the Federal Reserve. (a) For all interventions before and after interventions (time zero is the days of intervention activity): (b) for announced interventions before and after interventions (time zero is the days of intervention activity): (c) for all days with intervention activity during successive interventions (time 1 is the first day of intervention activity): (d) for announced successive interventions (time 1 is the first day of intervention activity).

the returns on the days of intervention activity that were statistically different from zero. Since our previous analysis suggests that interventions are clustered, Fig. 3(c) and (d) illustrate how the significance of the returns changes as the number of days of



(d)

Fig. 3 (*continued*)

successive intervention increases especially for the announced interventions. This suggests interventions continue until the movement in exchange rates has been slowed or reversed. Intervention announcements may increase credibility and thus do this more rapidly.

Table 6 demonstrates that different trading rules earned an average annualized excess return of about 5% in the five days preceding interventions, 18% on the days of intervention activity and −7% in the five days following interventions. The largest returns were found on the days of coordinated intervention activity (an average annualized excess return of 25% versus about 16% for the unilateral interventions). Across all types of intervention, we find that the excess returns decrease in the following order: coordinated, announced, unilateral and unannounced interventions.

Table 6
Technical trading rule returns around Central Bank interventions

Intervention	Trading rule	Five periods before an intervention	Periods of intervention	Five periods after an intervention	Number of interventions
Fed in DM	MA(10)	7.26%	15.72%	1.22%	383
	MA(150)	8.40%	12.61%	2.97%	
Buba in US$	MA(10)	4.52%	12.43%	10.31%	819
	MA(150)	7.24%	24.40%	−3.00%	
Both the Fed and Buba in DM-$	MA(10)	10.43%	25.84%	−3.10%	177
	MA(150)	12.70%	26.75%	−5.88%	

The average annualized DM-$ returns for different moving average trading rules around and during Central Bank interventions over the period from 1980 to 1998. The returns are calculated using formulas (2a)–(2d) in the periods surrounding different Central Bank interventions (intervention is defined as time 0). The exchange rates were obtained from DRI and are the New York opening from Bank America (San Francisco) until October 8, 1986 and the London close from NatWest (London) afterward. The German overnight interest rates were obtained from DRI and the US interest rates from the Federal Reserve.

Although the average annualized excess return on the days during which a Central Bank was actively intervening was 18% it was −3% on the last day of intervention activity. This provides further evidence that interventions were not immediately successful and they ceased once the Central Banks had succeeded at either slowing or reversing the current trend. The timing of the trading rule profits indicates that they started before and continued throughout the period of intervention activity (as in Neely, 2002). Our results go further than Neely (2002) by showing how this depends on the type of intervention.

Since interventions play such an important role in the trading rule profitability, we ask the question: What if we only traded during the periods of Central Bank intervention activity? Doing this we are able to generate impressive returns with Sharpe Ratios well over one. The Sharpe Ratios are largest for the coordinated and announced interventions. The longer moving average trading rules generate larger returns in the periods preceding interventions and incur lower losses afterward. In general the magnitude of the returns from the different trading rules in the DM-$ market around interventions is as follows (in order of decreasing magnitude): coordinated interventions, announced Fed and Bundesbank interventions, unannounced interventions by the Fed and Bundesbank, announced interventions by the Bank of Japan, and announcements of changes in exchange rates or monetary policy. Even though the shorter trading rules' ability to change position frequently could be expected to allow them to generate larger returns by better reacting to exchange rate movements, we find their average returns were smaller around interventions. This suggests that the trends motivating intervention are longer term and better picked up by the longer trading rules.

Looking at our measures of market uncertainty around interventions we find similar results: market uncertainty increases preceding interventions, peaks on the days of intervention and decreases afterward (see Fig. 4(a)–(c) for the conditional volatility, implied volatility and open interest measures, respectively). In results not presented we find a slight decrease in uncertainty during interventions with a decrease in uncertainty on the last day or the day after the end of the intervention activity. This is somewhat different from the results of previous studies (e.g. Bonser-Neal and Tanner, 1996; Dominguez, 1998). By considering the periods before, during and after the intervention separately, we are able to distinguish the differences over the periods of intervention activity where other studies consider all days of intervention similarly making it difficult to distinguish this effect.

5.1. Role of interventions in previous results

The preceding results suggest that the well-documented correlation between technical trading rule profitability and Fed intervention activity (Szakmary and Mathur, 1997; LeBaron, 1999; Neely, 2002) was related to coordinated Central Bank interventions. To verify this we replicate LeBaron's study. Neely (2002) extends LeBaron's results to include interventions by other Central Banks. We further extend it by including different types of interventions. LeBaron (1999) compared the profitability of a MA(150) trading rule to the profitability of the same trading rule on a

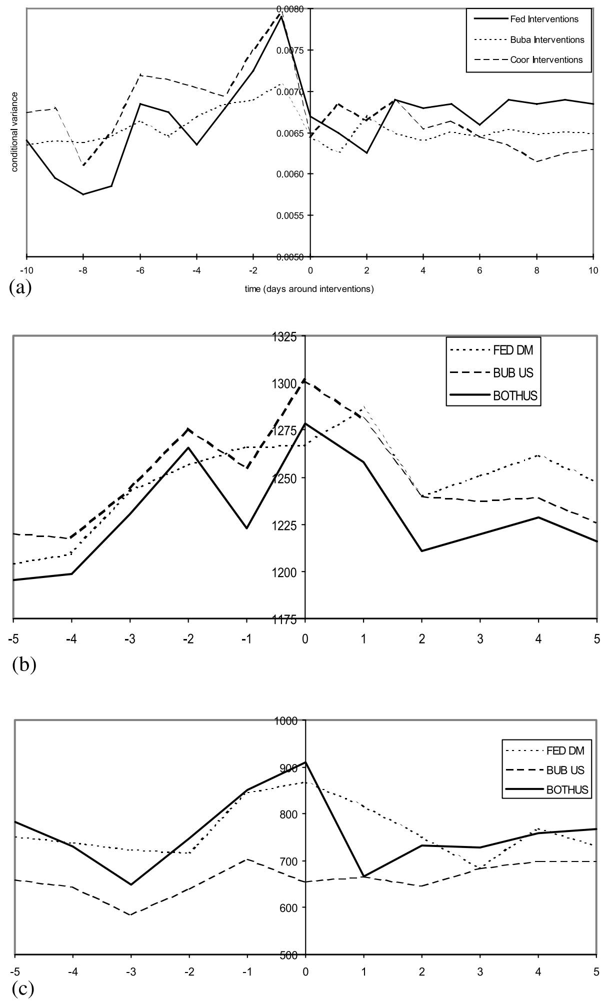


Fig. 4. Foreign Exchange Market Uncertainty Around Central Bank Interventions. Graph of the conditional volatility estimated using a GARCH-M process, the implied volatility and open interest from the 3 month DM-$ at-the-money options around interventions over the period from January 1, 1980 to December 31, 1998. These are in the periods surrounding the Federal Reserve, Bundesbank and coordinated interventions (interventions are at time 0). The values were obtained from data from the Chicago Mercantile Exchange. (a) Conditional volatility from a GARCH-M process; (b) implied volatility from the DM-$ at-the-money three month options; (c) open interest from the DM-$ at-the-money three month options.

data series from which the days of Fed intervention activity were removed. He found that the statistical significance of the trading returns decreased dramatically after the removal of the periods of Fed intervention activity.

Table 7 presents our findings. Consistent with LeBaron (1999) and Neely (2002), we find that removing the days on which the Fed and Bundesbank intervened in the

Table 7
Extension of LeBaron (1999)

Intervention removed	1980–1998	1980–1984	1985–1989	1990–1994	1995–1998
None/full data	2.46	1.09	2.24	1.26	−0.24
Fed DM	0.96	0.29	0.87	0.63	−0.27
Fed JY	1.61	0.96	0.91	0.94	−0.24
All Fed (DM/JY)	0.82	0.27	0.14	0.74	−0.24
Buba in USD	0.35	−1.16	0.91	0.604	−0.27
Buba in ERM	1.55	0.21	1.42	1.01	−0.24
All Buba (US/ ERM)	−0.01	−2.08	0.22	0.79	−0.24
Both US-DM	1.26	0.15	1.48	0.73	−0.27
Fed only DM	1.79	1.01	1.57	0.72	−0.24
Buba only $	1.51	0.30	1.79	0.71	−0.24
Ann Fed or Buba	1.46	1.23	1.68	0.80	−0.27
Unann Fed or Buba	0.06	1.25	1.24	0.66	−0.24
Ann Bank of Japan	2.31	1.37	1.87	1.04	−0.25
News Announcements	2.42	1.36	2.36	0.55	−0.32

This table presents the *t*-statistics for the DM-$ returns from a MA(150) trading rule relying on past DM-$ rates over the period from 1980 to 1998. The returns are calculated using formulas (2a)–(2d). The data sources are discussed in Section 2. Each row presents the *t*-statistics for the returns using a data set in which the days on which the corresponding event occurred are removed (this is a replication of LeBaron (1999) expanded to consider more than interventions by the Fed).

DM-$ eliminated the statistical significance of the technical trading returns (the *t*-statistics fell from 2.46 to 0.96 and 2.46 to 0.35 respectively). Looking at the other types of interventions we find that there is more to the story. Although removing just the coordinated Fed–Bundesbank interventions only caused the *t*-statistic to drop from 2.46 to 1.26, this is noteworthy because the coordinated interventions occurred relatively infrequently (they accounted for less than one-third of the Fed interventions and even less of the Bundesbank interventions). In fact, removing just the unilateral interventions by the Fed or the Bundesbank results in *t*-statistics of 1.78 and 1.50 respectively, so it is the coordinated interventions that are driving much of this result. We also find a considerable impact after removing the announced interventions, despite their small number. Consequently our findings are consistent with those of the previous studies and illustrate the importance of coordinated and announced interventions.

5.2. Technical trading returns and a time-varying risk premium

A possible explanation for the previous finding that technical trading returns and market uncertainty increase preceding interventions and remain fairly high during the episodes of intervention is the presence of a time-varying risk premium. Even though increasing market uncertainty does not necessarily imply an increase in the risk for which investors need to be compensated, these relationships suggest that it is a hypothesis worth investigating. Time-varying risk premia have been studied in equity markets (for surveys see Campbell, 2000; Karolyi and Stulz, forthcoming) and the foreign exchange futures market (e.g. McCurdy and Morgan, 1992;

Kho, 1996) but relatively little work has been done in the spot foreign exchange market. [17]

To test for time-varying risk premia in the spot foreign exchange market, we estimate conditional and unconditional versions of the simplest international asset pricing model – the single beta CAPM of Grauer et al. (1976). This model values international assets under the assumption that capital markets are integrated and purchasing power parity holds. [18] Building on the Sharpe (1964) and Lintner (1965) CAPM this model assumes the conditional expected return on an international asset i is proportional to the investors' expected compensation for a unit of covariance risk with the global market portfolio:

$$E[r^{e}_{i,t+1}|\Omega_t] = E[r^{e}_{m,t+1}|\Omega_t]\,\mathrm{cov}(r^{e}_{i,t+1}, r^{e}_{m,t+1}|\Omega_t)/\mathrm{var}(r^{e}_{m,t+1}|\Omega_t) \tag{5}$$

where $r^{e}_{i,t+1}$ is the return on asset i from time t to $t+1$ in excess of a risk-free return, $r^{e}_{m,t+1}$ is the excess return on a world market portfolio and Ω_t is the information set that investors use to set prices. We take the view of a global investor whose returns are calculated in US dollars so we use the MSCI world index denominated in US dollars as our market and the risk-free rate is the nominal return on the 30 day US Treasury Bill. [19]

We start with the unconditional model which assumes the beta and risk premium are constant:

$$r^{e}_{i,t+1} = \alpha + \beta r^{e}_{m,t+1} + \varepsilon_{i,t+1} \tag{6}$$

where the return on the asset we are trying to price, $r^{e}_{i,t+1}$, is the return from our technical trading strategies. Results not shown indicate that an unconditional international CAPM does a poor job of explaining the average returns from our technical trading strategies. The estimated value of beta is not statistically significant for any of the market indices. Further, the estimated intercepts are highly statistically significant, so the Gibbons et al. (1989) F-test that the model is correct and thus the true intercepts are zero is rejected with a high degree of confidence (greater than 1% in all cases). Our rejection of this model is not surprising given the highly significant time variation in the profitability of the technical trading rules.

To try to capture time variation in the risk premium in the spot foreign exchange market, we estimate a conditional version of Eq. (6). We model the expected changes

[17] Most work on technical trading returns in the spot foreign exchange market does not explicitly adjust for risk, rather it compares the returns to a buy and hold strategy or uses a mean adjustment for risk (e.g. Sweeney, 1986; Levich and Thomas, 1993).

[18] Although deviations from purchasing power parity have been documented in the short run, the evidence suggests that it does hold in the longer run (for a survey see Froot and Rogoff, 1995). Consequently this international version of the CAPM has been used as the starting point in many studies (e.g. Fama and French, 1998; Zhang, 2002). For a formal discussion see Karolyi and Stulz (forthcoming).

[19] Because the choice of index and currency of denomination are critical for any international asset pricing model, we consider a range of indices (e.g. Stambaugh, 1982) and currencies (e.g. Sjoo and Sweeney, 2001). We start with the index denominated in US dollars because of the dominant role of the US in world financial markets. For robustness we also consider the MSCI world index in British Pounds and a linear combination of the domestic indices for Germany, Japan and the US each denominated in their local currency.

in the values of the parameters in our model over time as a linear function of current period information as in Cochrane (1996, 2001) and Ferson and Harvey (1999). This dependence is specified by scaling the market risk premium with instruments that are believed to be important for summarizing variation in conditional moments based on our earlier analyses. Clearly our set of information, z_t, is, at best, a subset of the information available to investors ($z_t \in \Omega_t$). The conditional model is therefore:

$$r^{e}_{i,t+1} = \alpha_t(z_t) + \beta_t(z_t) r^{e}_{m,t+1} + \varepsilon_{i,t+1} \tag{7}$$

Assuming a linear relationship between beta and our conditioning information, we estimate this model with both the conditioning information and our market premium as follows:

$$r^{e}_{i,t+1} = \alpha(1 + \delta_\alpha z_t) + \beta(1 + \delta_\beta z_t) r^{e}_{m,t+1} + \varepsilon_{i,t+1} \tag{7'}$$

For this model we cannot reject the GRS F-test. To determine whether allowing for a time-varying risk premium in the conditional model significantly improves the fit of the model over the unconditional model we use a likelihood ratio test. [20] The statistical significance of many of the likelihood ratio test statistics in Table 8 suggests that our conditional versions of the international CAPM perform significantly better than the unconditional form but the results depend on the market index. For the MSCI world index denominated in US dollars we find evidence of the risk premium increasing around interventions – it is only the presence of an intervention that is important. When we change to the MSCI world index denominated in British Pounds and domestic indices, we find the significance of interventions depends on the direction of the intervention, not just the occurrence of an intervention. Studying the periods around interventions we find that the MSCI world (USD) index decreases around all types of interventions but the movements in the other indices depend on the direction of the intervention thus influencing the correlation with technical trading returns. [21]

Despite the preliminary nature of this analysis, it suggests that we are unable to reject the hypothesis that there is a time-varying risk premium in the foreign exchange market and it is correlated with central bank interventions, especially coordinated and announced interventions. Only a minor role appeared to be played by factors related to monetary policy and market uncertainty.

[20] We use a likelihood ratio test to measure the significance of the improvement in pricing errors since conditional models may simply perform better due to the extra degree of freedom.

[21] For example, interventions to decrease the value of the US dollar are related to a decrease in the value of the dollar and non-US stock market indices as well as a slight increase in the US market. This results in (1) a decrease in the US dollar denominated world index (the slight upward pressure from the increase in the US market offset by the large decreases in the non-US markets) and (2) a decrease in the non-US dollar denominated world index (the increase in the US market would be decreased through currency conversion and the other markets fell). Around interventions to increase the value of the US dollar the US market decreases slightly and the foreign markets decrease. Aggregating leads to a decrease in the value of the US dollar denominated index, again, and an increase in the non-US dollar denominated world index. Thus the US dollar denominated world index moves in the same direction around all interventions. Whereas the direction of the other indices depends on the type of intervention.

Table 8
Test of a time-varying risk premium

Unconditional model	World (USD)	World (GBP)	USA	Germany	Japan
	0	0	0	0	0
Conditioning information					
(a) For the technical trading rule returns in the DM-$ market					
Abs(Fed DM)	7.14**	2.17	0.01	0.01	3.80*
Abs(Fed JY)	1.91	0.05	1.02	0.58	0.81
Abs(Bundesbank USD)	4.50*	1.11	0.17	0.04	3.87*
Abs(Both USD-DM)	7.28**	0.42	0.00	0.00	3.58*
Fed DM	0.11	0.16	6.72**	0.11	1.89
Fed JY	0.25	1.08	5.79**	0.71	0.11
Bundesbank USD	0.75	2.16	2.91	0.04	0.34
Both USD	1.04	3.42*	5.50**	0.08	0.09
Abs(Announced Fed DM)	3.15*	0.78	0.98	0.23	2.80
Abs(Announced Fed JY)	0.79	0.01	3.28*	0.84	0.71
Abs(Ann Bundesbank USD)	4.98**	0.58	0.11	0.00	2.49
Abs(Ann Both USD-DM)	1.08	0.00	0.58	0.01	2.68
Announced Fed DM	0.18	0.21	9.92**	0.43	1.85
Announced Fed JY	0.01	0.33	6.86**	0.13	0.47
Ann Bundesbank USD	1.98	3.99*	4.33*	0.00	0.59
Ann Both USD-DM	1.08	0.00	0.58	0.01	2.68
Announced Bank of Japan	0.23	0.58	1.81	1.40	0.10
US short-term rates	0.14	0.08	0.03	0.13	0.05
German short-term rates	0.56	0.07	0.22	0.81	0.42
Japanese short-term rates	0.01	0.15	0.03	2.68	0.70
US default premium	0.26	0.23	0.78	0.18	0.37
German default premium	0.26	0.29	0.68	0.25	0.49
Japanese default premium	1.46	1.07	0.02	0.03	0.38
Historical volatility (1 week)	0.32	1.18	0.07	0.03	0.08
Spread	0.00	0.00	0.14	1.18	1.50
Implied volatility	0.51	0.32	1.29	0.02	0.22
Open interest	3.44*	0.49	2.25	0.36	0.07
Volume	0.46	0.36	1.53	0.23	0.02
(b) For the technical trading rule returns in the JY-$ market					
Abs(Fed DM)	3.69*	0.00	1.68	0.97	2.31
Abs(Fed JY)	3.70*	1.83	5.87**	2.88	0.01
Abs(Bundesbank USD)	0.01	0.85	0.29	1.02	3.03*
Abs(Both USD-DM)	0.68	0.04	0.08	1.15	2.23
Fed DM	0.26	0.03	0.03	2.36	0.08
Fed JY	1.31	1.15	0.14	3.67*	0.55
Bundesbank USD	1.00	1.10	0.08	3.06*	3.43*
Both USD	0.47	0.01	0.02	4.22*	1.12
Abs(Announced Fed DM)	6.51**	0.02	0.96	1.45	1.09
Abs(Announced Fed JY)	5.63**	2.33	3.03*	4.97**	0.00
Abs(Ann Bundesbank USD)	0.27	0.14	0.01	1.15	0.59
Abs(Ann Both USD-DM)	1.84	0.09	1.17	0.01	0.65
Announced Fed DM	0.04	0.06	0.12	3.07*	0.20
Announced Fed JY	1.94	0.54	0.43	3.91*	0.28
Ann Bundesbank USD	0.36	0.00	0.13	2.76	1.44
Ann Both USD-DM	1.84	0.09	1.17	0.01	0.65

(continued on next page)

Table 8 (*continued*)

Unconditional model	World (USD)	World (GBP)	USA	Germany	Japan
	0	0	0	0	0
Conditioning information					
Announced Bank of Japan	0.98	3.25*	6.99**	1.27	0.00
US short-term rates	0.01	0.51	0.44	2.79	0.04
German short-term rates	1.81	1.08	0.24	0.08	0.07
Japanese short-term rates	0.09	0.36	6.35**	10.32**	0.64
US default premium	3.22*	3.01*	0.79	0.00	0.01
German default premium	3.23*	3.11*	0.68	0.02	0.03
Japanese default premium	0.47	0.85	0.07	0.03	0.00
Historical volatility (1 week)	2.99*	5.67**	6.32**	1.53	0.77
Spread	2.18	2.30	1.88	3.69*	0.74
Implied volatility	2.13	3.97*	1.46	0.09	3.37*
Open interest	0.80	0.37	0.38	0.10	0.00
Volume	2.60	2.65	0.77	0.20	3.60*

This table presents the likelihood ration test statistics for the comparison of the fit for the unconditional and conditional CAPM in Eqs. (6) and (7′). The trading rule returns are for the MA(150) trading rule over the period from 1980 to 1998. The returns are calculated using formulas (2a)–(2d). The exchange rates were obtained from DRI and are the New York opening from Bank America (San Francisco) until October 8, 1986 and the London close from NatWest (London) afterward. The market returns are the MSCI world index in US dollars (USD) and British Pounds (GBP) as well as the MSCI indices for Germany, Japan and the US all in local currency. The risk-free rate is the US Treasury Bill with 30 days to maturity.

6. Summary and topics for further study

The goal of this study was to shed some light on the evidence from previous studies suggesting a role for Federal Reserve interventions in the technical trading rule profitability in the spot foreign exchange market. The analysis of the characteristics of the foreign exchange market in the periods around Central Bank interventions demonstrate that interventions were related to movements in several economic factors at these times, especially market uncertainty. Although there was some evidence of a relationship to certain measures of monetary policy, the impact was not consistent and was only with respect to the Japanese Yen. The most important of these relationships was the increase in technical trading rule returns around interventions (especially announced and coordinated interventions). The trading rule returns and our measures of market uncertainty increased preceding interventions, remained high during and decreased afterward. Because it appears that interventions followed increasing uncertainty in the foreign exchange market and the end of intervention episodes was marked by a decrease in this uncertainty, this suggests that there may be more to the profitability of technical analysis at these times than previously believed. This is further supported by Neely (2002) who finds that the profitability of technical analysis precedes the start of intervention activities.

The second key finding was that the strength of these effects was influenced by the type of intervention. Previous studies did not consider the possible differences across types of intervention, but our results suggest that information and signaling based on the type of intervention may play a role in these results. Both our VAR analysis and our replication of LeBaron (1999) suggest that the results from previous studies may have been most heavily impacted by the coordinated interventions and announced interventions, not all interventions equally. Different moving average trading rules had different abilities to generate profits because of their differing abilities to predict interventions. The longer moving average trading rules performed better at predicting the direction of upcoming interventions. The different profitabilities suggest that Central Bank interventions were related to the persistent movements in exchange rates and not short-term movements that may more strongly influence short moving average trading rules.

One of the possible implications of the concentration of technical trading rule profitability and market uncertainty in the period from 1980 to 1994 (when there was significant intervention activity) and around interventions is that the profitability may be related to a risk premium around interventions. Although we do not investigate this in detail, we use a conditional and unconditional version of an international CAPM to test for a time-varying risk premium. We are not able to reject the possible presence of a risk premium related to interventions. This is consistent with studies such as Kho (1996) and McCurdy and Morgan (1992) who find evidence of a time-varying risk premium in the foreign exchange futures market, but did not consider possible relationships between the risk premia and Central Bank interventions.

As a consequence our study advances our understanding of Central Bank interventions and their role in the apparent inefficiency of the foreign exchange market suggested by the profitability of technical analysis. It appears the much of this relationship is related to an increase in uncertainty at these times, especially around certain types of interventions (announced and coordinated). Because previous studies considered all interventions similarly and did not consider interventions as episodes, many of the relationships we find for different economic factors (especially market uncertainty) around interventions were more difficult to detect.

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Appendix A

In this appendix we describe the bootstrap methodology that we used to determine the robustness of *t*-statistics for the statistical significance of the technical trading rule returns (for a technical treatment see Appendix A in Brock et al. (1992)). This is necessary because the use of the t-statistic is based on the assumption that the mean return is asymptotically normally distributed and it is not clear that this is the case for our data. The bootstrap methodology determines the significance of these returns without the possible influence of deviations from this assumption.

In this procedure we start by assuming that the foreign exchange market is efficient, so the foreign exchange returns follow a random walk. To incorporate different characteristics of the foreign exchange market in our return generating process, we use two common versions of the random walk hypothesis (see Campbell et al., 1997). Each of these models is estimated for our exchange rate data. The estimated residuals are then redrawn with replacement to form a set of random residuals that are combined with our estimated parameters to form a new, simulated series. Using the technical trading rules on the simulated series we are able to estimate the distribution for the trading rules and therefore the p-values.

Formally, the first model we consider is a random walk where the returns are characterized by an autoregressive process of order one (AR(1)). This means we assume that the dynamics for the excess returns from the trading rules, x_t, depend on the return last period, a drift term, α, and independently and identically distributed innovations, ε_t:

$$x_t = \alpha + \rho x_{t-1} + \varepsilon_t \quad \text{where} \quad \varepsilon_t \sim \text{IID}(0, \sigma^2) \quad \text{and} \quad |\rho| < 1.$$

The bootstrap series is created by regressing the current trading rule returns (x_t) on those from the last period (x_{t-1}) and drawing randomly with replacement from the estimated errors ($\hat{\varepsilon}_t$). These values are then resampled with replacement and a new return series is generated using the estimated model.

Because it is unlikely that the variance is constant throughout our example as is assumed in the first model, our second model relaxes the assumption that the errors have to be identically distributed. The second model explicitly accounts for the conditional heteroskedasticity in the returns by assuming that the trading rule returns follow the process:

$$x_t = \alpha + \rho x_{t-1} + \varepsilon_t \quad \text{where} \quad \sigma_t^2 = a_0 + a_1 \varepsilon_{t-1}^2 + a_2 \sigma_{t-1}^2.$$

To create the bootstrap return series in this case, we draw randomly with replacement from the standardized estimated errors defined by: $\varepsilon_t^* = \hat{\sigma}_t^{-1/2} \hat{\varepsilon}_t$ and insert them into the estimated model to create a new series.

To estimate the statistical significance of the trading rule returns, this procedure is repeated 250 times to generate an empirical estimation of the returns distribution. Using this distribution, the statistical significance is determined by the fraction of the simulated series that generated returns larger than those actually observed. [22]

[22] According to Monte Carlo evidence in Efron and Tibshirani (1986) performing the simulation 250 times should be more than adequate for an accurate bootstrap estimation of the return distribution.

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