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Monetary Policy, Model Uncertainty and Exchange Rate Volatility

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Abstract

This paper proposes an explanation for shifts in the volatility of exchange rate returns. We show how uncertainty about the exchange rate model may lead private agents to focus excessively on only a subset of fundamental variables. As a result, exchange rate volatility is mainly determined by the dynamics of this subset of fundamentals. We investigate empirically the relevance of this result within the Taylor-rule based model applied to the British Pound/US Dollar exchange rate. Our results suggest that the agents change the model after the Bank of England introduced an inflation targeting strategy. Reduced uncertainty about interest rates implied by inflation targeting strategy made interest rate a more useful variable for predicting the exchange rate movements. As a result, in addition to the price differential variable, agents focus on the interest rate differential. Econometric analysis suggests that this shift of the model triggered a substantial instantaneous decrease in the volatility of exchange rate returns. Accordingly, we observe a shift from a high to a low volatility exchange rate regime.

Keywords: Exchange rate economics, monetary policy, model uncertainty

JEL Codes: F31, F41, E44

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1 Introduction

One of the well known and much documented facts in international economics are shifts in the volatility of exchange rates. In particular, fixed exchange rates are less volatile than floating rates. Floating exchange rates also display low and high volatility regimes, as documented by Engel and Hamilton (1990). Numerous researchers attempted to link these volatility shifts to the dynamics of macroeconomic fundamental variables. Mussa (1986), Gerlach (1988), Baxter and Stockman (1989), Flood and Rose (1995), among the others, observed that, in low inflation countries, variability of most of aggregate variables is unaffected by the exchange rate regime. As a result, the consensus emerged that there is remarkably little evidence of a systematic relationship between the volatilities of exchange rates and macroeconomic variables. This stylized fact is inconsistent with theories that model the exchange rate as a variable reflecting underlying economic shocks.

The poor performance of these exchange rate models may be due to the stability of fundamental variable parameters that they assume. Schinasi and Swami (1989) find that time-varying parameter exchange rate models outperform the random walk in out of sample forecasting. More recently, Cheung and Chinn (2001) point out that currency traders shift the importance attached to macroeconomic variables over time. Cheung, Chinn and Pascual (2005) and Rossi (2006) find that predictive power of different fundamental exchange rate models depends on the considered currency and horizon. Thus, as Frydman and Goldberg (2007) note, 'the empirical exchange rate studies suggest that macroeconomic fundamentals matter, but in a way that is not stable over time'.

The contribution of this paper is twofold. First, we propose a theoretical framework which implies the time-varying link between exchange rates and the underlying macroeconomic variables. We show that uncertainty about the model of the exchange rate may lead private agents to focus excessively on a subset of fundamental variables at different points in time. As a result, exchange rate volatility is mainly determined by the dynamics of this subset of fundamentals. Second, we provide an empirical illustration of this theoretical result. We study the implications of model uncertainty on the link between the exchange rate and the underlying macroeconomic variables. The macroeconomic variables are implied by the Taylor-rule and this framework is applied to a successful inflation targeting economy, the UK. Our results suggest that the agents focus on a new set of fundamentals after the Bank of England introduced an inflation targeting strategy. Reduced uncertainty about interest rates implied by inflation targeting strategy made interest rate a more useful variable for predicting the exchange rate movements. As a result, in addition to the price differential variable, agents focus on the interest rate differential. Econometric analysis shows that interest rate differential is less volatile after the adoption of inflation strategy by the Bank of England. At the same time, there is a substantial instantaneous decrease in the volatility of the British Pound/US Dollar returns so that we observe a shift from a high to a low volatility exchange rate regime. Since the break in the volatility of interest rate differential was triggered by the one in the UK interest rate volatility, we think that the inflation targeting strategy adopted by the Bank of England in October 1992 largely contributed to this result.

Theoretical framework assumes that private agents face model uncertainty and make inference on the model, that is, they form expectations about the future exchange rate using the best model according to a model selection criterion. Accordingly, their expectations may shift if the best model changes, for example due to other fundamentals being included. Because the expectations dominate the exchange rate process, the statistical properties of the latter change, jointly with the set of fundamental variables.

A similar approach is recently taken by Bacchetta and Van Wincoop (2004). They present a theoretical framework where heterogeneous information in the foreign exchange market can lead investors to attach excessive weight to an observed fundamental. They argue that this scapegoat, as they call it, can change over time. Their results crucially depend on the assumption of the heterogeneity of information in the foreign exchange market. In this paper, we explain why shifts between the fundamentals may occur and generate volatility switches without needing to resort to the assumption of heterogeneous agents.

We introduce model uncertainty into the Taylor-rule model of the exchange rate. This is a simple, empirical model derived from the Taylor rule of the monetary authorities of two countries, assuming that one (or both) of them includes the exchange rate variable in its reaction function. Several recent studies show that indeed some of the central banks include the exchange rate in their interest rules (see for instance Lubik and Schorfheide 2007). Since some of the central banks use the exchange rate as an information variable to conduct their monetary policy, we might expect a link between the Taylor-rule variables and the exchange rate. Engel and West (2006) find that the Taylor rule exchange rate model supports German data. Similarly, Mark (2006) shows that adaptive learning of the Taylor-rule fundamental variables provides a possible framework for understanding real USD/DM exchange rate dynamics. Molodsova and Papell (2007) generalize these results. They provide evidence that exchange rate predictability of the Taylor-rule fundamentals is much stronger than of other models. Using different measures of potential output, they find that the model outperforms the random walk in terms of short-run predictability, for 5 out of 12 countries. Finally, Clarida and Waldman (2007) find a positive correlation between the announcement of higher inflation and a currency appreciation in countries where the central banks have an inflation target implemented within a Taylor Rule.

The calibration of the Taylor-rule model for the British Pound/US Dollar exchange rate points to a shift in the model used by agents which occurs after the Bank of England introduced an inflation targeting strategy. In particular, at this point in time, in addition to the price level variable, the agents focus on the interest rate differential. We use a set of structural break tests to assess whether the calibrated change date corresponds to the break dates in the realized volatility of the exchange rate returns and underlying macroeconomic variables. We find that there is a significant instantaneous decrease in the volatilities of British Pound/US Dollar returns and interest rate differential after the Bank of England implemented the inflation targeting strategy. However, we find no evidence for significant decrease in price differential volatility at that time. These results suggest that the change in the volatility of the exchange rate was triggered by the shift of the model.

The remainder of the paper is organized as follows. In the second section, we present the general asset pricing model of the exchange rate. The third section introduces the agent-econometrician framework and describes the way the expectations are formed. In the fourth section we derive the resulting equilibrium and study its characteristics. Section five introduces the Taylor-rule model of the exchange rate. The sixth section calibrates the Taylor-rule model for British Pound/US Dollar exchange rate and in the seventh section, we empirically test for the structural breaks in the exchange rate, the interest rate and the price volatilities. Finally, the eighth section concludes.

2 General model of the exchange rate

As proposed by Mussa (1979), we model the exchange rate as an asset price which is a forward-looking and expectations-determined variable. The exchange rate s_t is a convex combination of the log fundamental variables $f_t = (f_{1,t}, f_{2,t}, ..., f_{n,t})'$ and the expected future exchange rate

$$s_t = (1-\theta)\phi f_t + \theta \hat{E}_t s_{t+1} \tag{1}$$

where θ is a discount factor, $\hat{E}_t$ denotes not necessarily rational expectation conditional on information up to time t, ϕ is a $(1 \times n)$ vector of fundamental variables' coefficients. Assuming rational expectations $\hat{E} = E$ and solving model (1) forward yields

$$s_t = (1-\theta)\phi \sum_{l=0}^{T} \theta^l E_t f_{t+l} + \theta^T E_t s_{t+T}.$$

Letting $T \to \infty$ and imposing the no-bubbles condition, $\theta < 1$, such that $\lim_{T\to\infty} \theta^T E_t s_{t+T} = 0$, we find the present value representation:

$$s_t = (1-\theta)\phi \sum_{l=0}^{\infty} \theta^l E_t f_{t+l}$$

We further assume that the fundamental variables in f_t follow an AR(1) process, i.e.

$$f_{i,t} = \rho_i f_{i,t-1} + \varepsilon_{i,t} \tag{2}$$

where ρ_i is an AR(1) parameter and $\varepsilon_{i,t} \sim N\left(0,_{\varepsilon_i}\right)$. The rational expectations solution to this model is

$$\begin{aligned} s_t &= (1-\theta)\phi \sum_{j=0}^{\infty} \theta^l E_t f_{t+l} \\ &= (1-\theta)\phi \left(I - \theta\rho\right)^{-1} f_t \end{aligned} \tag{3}$$

where ρ is a diagonal matrix $(n \times n)$ with ρ_i elements on the diagonal with $i = 1, ..., n$.

3 Expectations of agents

Sargent (1993) notes that rational expectations impose two requirements on economic models: individual rationality, and mutual consistency of perceptions about the environment. Thus, rational expectations models imply agents within the model possess much more knowledge than an econometrician - who faces estimation and inference problems. Therefore, it seems more adequate to assume that agents, modeled by economists, have at most the same knowledge and capacities as these economists-themselves. For this reason, Bray (1982), Bray and Savin (1986), Sargent (1993) and Evans and Honkapohja (2001), among others, assume that agents behave as econometricians and estimate the model of the economy. When this model is correctly specified, their estimates converge to the Rational Expectations (RE) solution. However, if agents are assumed to behave as econometricians, they do not know the model of the economy with certainty.

A prominent example of economists' ignorance about the economic environment is the field of exchange rate economics. Since the early seventies, economists have looked for a 'correct' model, which could identify a relationship between the exchange rate and macroeconomic fundamentals (see Meese and Rogoff 1983). Although Mark (1995) found that some fundamental variables matter in the long run, a consensus has emerged that we do not know the model that determines the exchange rate dynamics in the short run. At the same time, survey evidence indicates that traders often shift the importance attached to different fundamental variables. In particular, they regularly focus on one fundamental to forecast the future exchange rate[1].

In line with this observation, experimental evidence collected by Adam (2007) indicates that agents use very simple forecasts conditioned only on one explanatory variable, even if information on other relevant variables is available to them. This underparametrization may occur because, as Branch and Evans (2007) argue, forecasters limit the number of variables and the number of lags because of the degree of freedom restrictions and additional computational costs involved in using large models.

We model this behavior by assuming that agents choose the best model according to the Bayesian Information Criterion (BIC). This assumption allows us to preserve the internal consistency of the agent-econometrician framework and to pick up the particularity of the traders' practices at the same time. Furthermore, it favours parsimony which is a key feature of agents' forecasting practices as observed by Adam (2007).

This mechanism is as follows. Using standard OLS techniques, agents estimate all the possible combinations of the fundamental variables of the model and choose the combination that minimizes BIC. Thus, they use both parameter and model learning.

3.1 Parameter learning

Suppose the model of the exchange rate in (1) includes n fundamental variables. Then we have $j = 1, ..., m$ linear combinations of n fundamental variables, where $m = 2^n$. M_j and β_j are the vectors (or scalars) of regressors and corresponding coefficients. For each possible combination of regressors (corresponding to distinct forecasting models) M_j with $j = 1, ..., m$ the coefficients β_j are estimated

[1]For detailed analysis of the forex traders' techniques see Cheung and Chinn (2001).

and evaluated (according to BIC; Schwarz 1978) by agents at every period t. The exact timing assumption of the model is as follows. At $t-1$, the agents regress the current market exchange rate s_{t-1} on the set of current fundamental variables incorporated in the model $M_{j,t-1}$. This gives the estimates of the parameters of the models $\beta_{j,t-1}$. At t, these estimates are used to form expectations in the next period on the future exchange rate: $\hat{E}_t s_{t+1}$. At t, agents calculate the sum of squared errors (SSE) of all the models and choose the one that minimizes BIC. First, we describe parameter learning at $t-1$.

Agents' Perceived Law of Motion (PLM) includes each possible combination of fundamental variables so that it can be formulated as

$$s_t = M_{j,t-1} + \eta_{j,t-1} \tag{4}$$

where $\eta_{j,t-1}$ are the *iid* shocks. Agents estimate the coefficients by OLS. Given initial values of the model parameters $\beta_{j,0}$, we can write the OLS procedure as a recursive algorithm as shown in Evans and Honkapohja (2001):

$$\begin{aligned} \beta_{j,t-1} &= \beta_{j,t-2} + t^{-1} R_{j,t-1} f_{j,t-1} \left(s_{t-1} - \beta'_{j,t-2} f_{j,t-1} \right) \\ R_{j,t-1} &= R_{j,t-2} + t^{-1} \left(f'_{j,t-1} f_{j,t-1} - R_{j,t-2} \right) \end{aligned} \tag{5}$$

where $\beta_{j,t-1}$are the parameters estimated at $t-1$ and $R_{j,t-1} = t^{-1} \sum_{l=1}^{t} f_{j,t-2} f'_{j,t-2}$ is a moment matrix.

3.2 Model selection

BIC is an asymptotically consistent model selection criterion. This means that, given a family of models including the true model, the probability that BIC will select the correct one approaches 1 as the sample size becomes large. Thus, asymptotically, the 'correct' model of the exchange rate should be chosen by agents. However, Hansen and Sargent (2000) argue that historical times series are not long enough to recognize data generating model. More precisely, when the sample size is finite, BIC will select an incorrect model with a positive probability. In this paper, we focus on this case, where, misspecified models can govern the short term exchange rate dynamics.

Given the models $M_{j,t}$, which are the combinations of fundamental variables f_j and the vector of corresponding coefficients β_j, the agents' forecast of the future exchange rate is the following

$$\hat{E}_t s_{t+1} = M_t^{BIC} \tag{6}$$

where

$$M_t^{BIC} = \arg \min_{M_{j,t-1}} BIC, \text{ for } j = 1, ..., m \tag{7}$$

with BIC defined for each model as

$$BIC_{j,t} = \log\left(\frac{SSE_{j,t-1}}{t}\right) + \frac{n \log t}{t}, \text{ for } j = 1, ..., m \tag{8}$$

where

$$SSE_{j,t-1} = \left(s - f_j\beta_j\right)' \left(s - f_j\beta_j\right) \tag{9}$$

In the forecast in (6), agents use estimated parameters $\beta_{j,t-1}$to form their expectations at t and the set of current fundamental variables in question $f_{j,t}$. This is to avoid the simultaneity problem in the model of the exchange rate. If parameters $\beta_{j,t}$, which are the estimates from the regression of s_t on $f_{j,t}$, are used to make the forecast $\hat{E}_t s_{t+1}$, this forecast is jointly determined with the exchange rate s_t (see (1)). The equilibrium stochastic process followed by the exchange rate (actual law of motion, ALM) is obtained by substituting the market forecast, equation (6), into the model (1).

$$s_t = (1 - \theta)\,\phi f_t + \theta M_t^{BIC} \tag{10}$$

We assumed that agents in the foreign exchange market act as econometricians and thus they use adaptive learning to update the model parameters. When a perceived law of motion (PLM) has the structure of the Rational Expectations Equilibrium (REE) the LS estimates will asymptotically converge to the RE values[2]. Thus, when the agents know that the exchange rate is a linear combination of the fundamentals in f_t, they learn the RE solution in (3). However,

[2] In addition to the REE structure, the E-stability condition needs to be met. We define this concept after Evans and Honkapohja (2001) in the following section.

if they are assumed to form their forecasts according to BIC, and the sample size is finite, underparametrization might occur. Such underparametrization means that the equation estimated by the econometrician omits relevant variables. In this case, the REE cannot be reached. Since agents' forecasts feed back into the model of the economy, the exchange rate departs from the value that would prevail if they knew all the states of the model.

4 Underparametrization and resulting equilibrium

In order to keep the agent-econometrician framework coherent, we need to impose some additional constraints on agents' behavior. First, we suppose that model uncertainty under the BIC framework may lead to underparametrization of the model of the exchange rate. Second, as in Lucas' (1972) definition of RE, we assume that the agents use all available information optimally in forming expectations. By optimal use of information we mean that the agents cannot detect the mistakes they are making while using an underparametrized model of the economy. This is obtained by applying the orthogonality conditions between forecast errors and forecast models to the underparametrized model. The equilibrium in such an environment is obtained when both, the optimally formed expectations about the exchange rate and the exchange rate process itself converge. Since the agents' information set is limited relative to the RE case, the resulting solution will be called Restricted Perceptions Equilibrium (RPE)[3].

4.1 Restricted Perception Equilibrium

Suppose that the model of the exchange rate includes two fundamental variables $n = 2$

$$s_t = (1-\theta)\phi f_t + \theta \hat{E}_t s_{t+1} \tag{11}$$

[3]Restricted Perceptions Equilibrium was first mentioned by Evans and Honkapohja (2001).

The REE is

$$s_t = (1-\theta)\phi\,(I-\theta\rho)^{-1}\,f_t$$

or

$$s_t = \begin{pmatrix} f_{1,t} & f_{2,t} \end{pmatrix} \begin{pmatrix} \frac{1-\theta}{1-\theta\rho_1}\phi_1 \\ \frac{1-\theta}{1-\theta\rho_2}\phi_2 \end{pmatrix} \tag{12}$$

where $f_t = (f_{1t}, f_{2t})^{'}$ and ϕ is a (1×2) fundamentals coefficients vector.

In order to see the results of potential underparametrization on the exchange rate process, here we study a simple case. Suppose that the selection criterion in (8) leads the agents to choose a model with only one fundamental variable f_1: $M_t^{BIC} = \beta_1 f_{1,t}$. Thus, their PLM is

$$s_t = \beta_1 f_{1,t} \tag{13}$$

This gives the following forecast:

$$E_t s_{t+1} = \beta_1 \rho_1 f_{1,t} \tag{14}$$

where β_1 is a LS estimate of the belief parameter. Note that we also used the fact that the fundamental follows an $AR(1)$ and thus the forecast for the next period $t+1$ also incorporates the autoregressive coefficient ρ_1. It is equivalent to assume that the agents know that the fundamental f_1 follows an $AR(1)$. The equilibrium stochastic process followed by the exchange rate (actual law of motion, ALM) is obtained by substituting the market forecast, equation (14), into the model (11)

$$s_t = \chi_1 f_{1,t} + \chi_2 f_{2,t} \tag{15}$$

$$\chi_1 = (1-\theta)\phi_1 + \theta\rho_1\beta_1 \tag{16}$$

$$\chi_2 = (1-\theta)\phi_2 \tag{17}$$

We assume that agents' beliefs (PLM) are optimal (within their misspecification) so that they satisfy the following orthogonality condition:

$$E\left(f_1\left(s_t - \beta_1 f_1\right)\right) = 0 \tag{18}$$

In the equilibrium process, the parameter β_1 must satisfy this orthogonality condition (18) and be consistent with the ALM of the economy in (11). The fixed points χ_i of such a process describe RPE. Substituting the actual law of motion, equation (11) for s_t and solving for the belief parameter β_1 yields

$$\beta_1 = \chi_1 + \chi_2 \frac{Ef_{1,t}f_{2,t}}{Ef_{1,t}^2} = \chi_1 + \chi_2 \Omega_{11}^{-1}\Omega_{12} \tag{19}$$

where $E\begin{pmatrix} f_1 \\ f_2 \end{pmatrix}(f_1\ f_2)' = \begin{pmatrix} \Omega_{11} & \Omega_{12} \\ \Omega_{21} & \Omega_{22} \end{pmatrix}$. Using the belief parameter, given by (19), in equations (16) and (17) and solving for the ALM parameters χ_1 and χ_2, we find

$$\begin{pmatrix} 1-\theta\rho_1 & -\theta\xi\rho_1 \\ 0 & 1 \end{pmatrix} \chi = (1-\theta)\phi \tag{20}$$

where $\chi = (\chi_1, \chi_2)'$ and $\xi = \Omega_{11}^{-1}\Omega_{12}$. Denote the matrix premultiplying χ by B. A RPE exists (and is unique) provided the inverse of B exists. The inverse of B exists if $\theta\rho_1 \neq 1$. This is by definition since θ is a discount factor; $0 < \theta < 1$ and f_1 follows a stationary process so that $|\rho_1| < 1$. The resulting RPE is described by the fixed points in χ

$$\begin{aligned} \chi_1 &= \frac{1-\theta}{1-\theta\rho_1}\phi_1 + \frac{\theta(1-\theta)}{1-\theta\rho_1}\rho_1\Omega_{11}^{-1}\Omega_{12}\phi_2 \\ \chi_2 &= (1-\theta)\phi_2 \end{aligned} \tag{21}$$

and the equilibrium process of the exchange rate follows

$$s_t = \begin{pmatrix} f_{1,t} & f_{2,t} \end{pmatrix} \begin{pmatrix} \frac{1-\theta}{1-\theta\rho_1}\phi_1 + \frac{\theta(1-\theta)}{1-\theta\rho_1}\rho_1\Omega_{11}^{-1}\Omega_{12}\phi_2 \\ (1-\theta)\phi_2 \end{pmatrix} \tag{22}$$

This equilibrium arises between optimally misspecified beliefs and the stochastic process of the exchange rate. These beliefs are optimal because they give the best linear forecast when agents are assumed to know only one explanatory variable. The linear projection of the exchange rate s_t on the fundamental variable f_1 is orthogonal and thus, given the information set, the forecast error is the smallest possible.

Because we assumed that the two fundamental variables are uncorrelated we can write RPE as

$$s_t = \begin{pmatrix} f_{1,t} & f_{2,t} \end{pmatrix} \begin{pmatrix} \frac{1-\theta}{1-\theta\rho_1}\phi_1 \\ (1-\theta)\phi_2 \end{pmatrix} \quad (23)$$

The coefficient β_1 is consistently estimated because the bias $\frac{\theta(1-\theta)}{1-\theta\rho_1}\rho_1\Omega_{11}^{-1}\Omega_{12}\phi_2$ in (23) disappears and, as a result, β_1 converges to the REE value: $\beta_1 = \frac{1-\theta}{1-\theta\rho_1}\phi_1$. The coefficient on the second fundamental variable χ_2 does not converge to the REE value even if the regressors are uncorrelated. Furthermore, its impact on the exchange rate process is smaller than in REE[4]. Assume a special case where $\phi_1 = \phi_2$ and $\rho_1 = \rho_2$[5]. Then the weights given to both fundamental variables in the exchange rate process in (12) will be equal, while in (23) the first fundamental variable f_1 will receive a heavier weight. Since the exchange rate process in (23) is a linear combination of two processes f_1 and f_2, its statistical properties will be described more closely by the one with the heavier weight (f_1 in this case). In a dynamic setup, when agents are allowed to choose the best forecasting model according to BIC, the selected variable (or the model) will receive higher weight than the remaining fundamental variables, and dominate the statistical properties of the exchange rate process. These properties will shift, either if the best forecasting model changes or if the statistical properties of the selected variable (or the model) change.

4.2 Is RPE learnable?

We know that for given parameter values of β_1, θ and ϕ, there is a unique RPE. Can agents learn this equilibrium? In other words the question is whether agents using adaptive learning can find an estimate of $\beta_1$defined by RPE in (19). The E-stability (Expectational Stability) principle determines whether an RPE is learnable. We can write the OLS procedure as a recursive algorithm

[4]Note that $\theta < 1$ and $|\rho_1| < 1$ so that $\frac{1-\theta}{1-\theta\rho_1} > (1-\theta)$.

[5]Obviously, these are special cases which have low probability to occur in the data. They help however in understanding how this underparametrization may generate shifts in statistical regimes of the exchange rate. In the empirical part, we relax these assumptions and rely on the data properties.

$$\beta_{1,t-1} = \beta_{1,t-2} + t^{-1} R_{1,t-1}^{-1} f_{1,t-1} \left(s_{t-1} - \beta'_{1,t-2} f_{1,t-1} \right) \tag{24}$$

$$R_{1,t-1} = R_{1,t-2} + t^{-1} \left(f_{1,t-1} f'_{1,t-1} - R_{1,t-2} \right) \tag{25}$$

where $\beta_{1,t-1}$ is the parameter estimated at $t-1$ and $R_{1,t-1} = t^{-1} \sum_{j=1}^{t} f_{1,t-2} f^{'}_{1,t-2}$ is the second moment matrix. Plugging equation (15) shifted one period back to $t-1$ into (24) we find

$$\beta_{1,t-1} = \beta_{1,t-2} + t^{-1} R_{1,t-1}^{-1} f_{1,t-1} \left(f_{1,t-1} \; f_{2,t-1} \right) \begin{pmatrix} (1-\theta)\phi_1 - (1-\theta\rho_1)\,\beta_{1,t-2} \\ (1-\theta)\phi_2 \end{pmatrix} \tag{26}$$

Following Evans and Honkapohja (2001), we fix the parameters β and R and compute the expectations over state variables.

$$ER^{-1} f_{1,t-1} \left(f_{1,t-1} \; f_{2,t-1} \right) \begin{pmatrix} (1-\theta)\phi_1 - (1-\theta\rho_1)\,\beta_{1,t-2} \\ (1-\theta)\phi_2 \end{pmatrix} \tag{27}$$

Letting $Ef_1 f_1^{'} = \lim_{t\to\infty} Ef_{1,t} f_{1,t}^{'}$ we associate the following Ordinary Differential System (ODS)

$$\frac{d\beta_1}{d\tau} = R^{-1}\Omega_{11} \left(T(\beta_1) - \beta_1 \right); \tag{28}$$
$$\frac{dR}{d\tau} = \Omega_{11} - R.$$

where $E \begin{pmatrix} f_1 \\ f_2 \end{pmatrix} (f_1 \; f_2)^{'} = \begin{pmatrix} \Omega_{11} & \Omega_{12} \\ \Omega_{21} & \Omega_{22} \end{pmatrix}$ and $T(\beta_1) = (1-\theta)\phi_1 + \theta\rho_1\beta_1 + \Omega_{11}^{-1}\Omega_{12}(1-\theta)\phi_2$. T-map, $T(\beta_1)$ is a map from the space of beliefs to outcomes. In the equilibrium they need to converge.

Since R converges globally to Ω_{11}, it follows that stability of this ODS is governed by stability of the first equation in (28). The fixed point of the T-map is given by

$$\bar{\beta}_1 = \frac{1-\theta}{1-\theta\rho_1}\phi_1 + \frac{1-\theta}{1-\theta\rho_1}\Omega_{11}^{-1}\Omega_{12}\phi_2 \tag{29}$$

The solution in (29) is E-stable when $\theta\rho_1 < 1$. Note that θ is a discount factor and $\theta < 1$and ρ_1 is an $AR(1)$ coefficient $|\rho_1| < 1$. Therefore, we find that if agents underparametrize the asset pricing model of the exchange rate as in (1), they will learn the Restricted Perception Equilibrium (RPE) under LS.

In what follows, we assume model uncertainty and the BIC framework and introduce it into the Taylor-rule model of the exchange rate.

5 Taylor-rule model of the exchange rate

The central banks may want to react to and smooth exchange rate movements especially in small open economies, where domestic business cycle fluctuations are likely to have a substantial international relative price component. Ball (1999) and Svensson (2000) use an open economy model to show that including the exchange rate into the interest rule of the central bank leads to lower fluctuations of real GDP and inflation.

The simple empirical two-country model builds on the Taylor rules of two countries. The foreign (US) monetary authority sets interest rates according to a simple interest rule proposed by Taylor (1993):

$$i_t^* = \gamma_y y_t^{*g} + \gamma_\pi \pi_t^* + \nu_t^* \tag{30}$$

where the monetary policy instrument i_t is a short term interest rate, y_t^g is the output gap, π_t is inflation and ν_t is a shock to the monetary policy rule. The interest rate rule does not include an intercept as the inflation target is assumed to be zero and the output gap is measured as the percentage deviation of current output from the potential one. We assume $\gamma_y > 0$ and $\gamma_y > 1$, as found in Clarida, Gali and Gertler (1998). The home (UK) central bank also finds the exchange rate to be a relevant information variable and its reaction function is as follows

$$i_t = \gamma_s \left(s_t - \overline{s}_t^*\right) + \gamma_y y_t^g + \gamma_\pi \pi_t + \nu_t \tag{31}$$

For convenience, we suppose that the parameters γ_y and γ_π are identical in the two countries. s_t is the exchange rate measured in British Pounds per unit of foreign currency (US dollars). We assume that $0 < \gamma_s < 1$ so that when the home currency appreciates (s_t decreases) above a certain level given by $\overline{s}_t^*$ the monetary authority relaxes its monetary policy i.e. lowers its interest rate i_t.

We also assume that the home central bank defines the level $\overline{s}_t^*$ according to PPP

$$\overline{s}_t^* = p_t - p_t^*$$

and that the UIP condition is

$$E_t s_{t+1} - s_t = i_t - i_t^* + u_t$$

where u_t is an exogenous risk premium shock. We combine the two Taylor rules to obtain

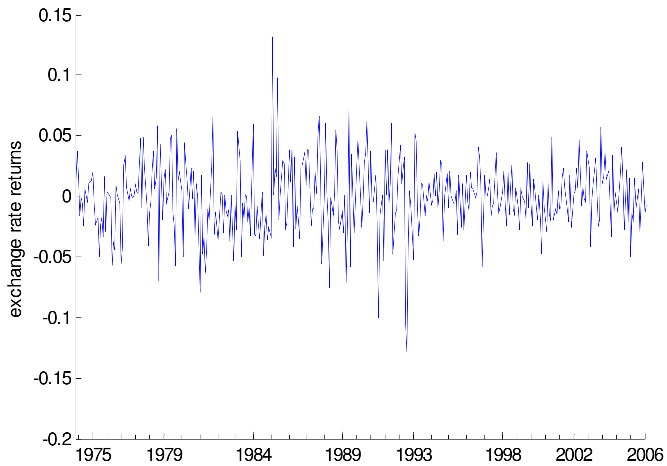
$$s_t = \gamma_s \left[\hat{\imath}_t + \hat{p}_t - \frac{\gamma_y}{\gamma_s} \hat{y}_t^g - \frac{\gamma_\pi}{\gamma_s} \hat{\pi}_t \right] + \widehat{\upsilon}_t + (1 - \gamma_s) E_t s_{t+1} \tag{32}$$

The current exchange rate is a function of four fundamental variables i.e. the interest rate, the price level, output gap and inflation (all variables being differentials of home and foreign values), the expected future exchange rate and home and foreign shocks to monetary policy rules and risk premium u_t, so that $\widehat{\upsilon}_t = \nu_t^* - \nu_t - u_t$. The model can be written as a standard asset pricing equation in (1) where $\theta = (1 - \gamma_s)$ is a discount factor, fundamental variables are $f_t = (\ \hat{\imath}_t, \ \ \hat{p}_t, \ \ \hat{y}_t^g, \ \ \hat{\pi}_t \ )'$ and $\phi' = \left(1, 1, -\frac{\gamma_y}{\gamma_s}, -\frac{\gamma_\pi}{\gamma_s}\right)$ is a (4×1) vector of the Taylor-rule coefficients.

5.1 The Taylor rule framework and the British Pound dynamics

The UK is an interesting case to study the dynamics of the exchange rate within the Taylor rule model for several reasons. First, the British Pound/US Dollar returns became much less volatile in the last 15 years. We document this fact in Figure (1). It clearly shows that the volatility of British Pound/US Dollar returns largely decreased after 1992. Second, since the Bank of England adopted the inflation targeting strategy in October 1992, inflation volatility decreased substantially, as documented by Neumann and von Hagen (2002) and Benati (2003) among others. In addition, recent empirical evidence presented by Lubik and Schorfheide (2007) indicate that the Bank of England takes into account

Figure 1: **GBP/USD returns**



exchange rate movements when setting up its monetary policy within the Taylor rule. Theoretical studies as in Benigno and Benigno (2001), Monacelli (1998) and Gali and Monacelli (2005) find that alternative monetary policy regimes entail different degrees of exchange rate volatility. Empirical evidence such as in Edwards (2006) suggests that the adoption of inflation targeting tends to reduce exchange rate conditional volatility in several countries. We seek to verify whether a similar pattern occurred in the UK economy. More precisely, we test the hypothesis whether the observed decrease in the exchange rate volatility can be due to shifts in fundamental variables the agents focus on.

6 Calibration

We now turn to investigate whether we can find support for the proposed agent-econometrician framework applied to the Taylor-rule model of the exchange rate in the data. In particular, we calibrate the following model for the UK

$$s_t = (1-\theta)\,\phi f_t + \theta M_t^{BIC} \tag{33}$$

where $\theta = (1-\gamma_s)$, and $\phi' = \left(1, 1, -\frac{\gamma_y}{\gamma_s}, -\frac{\gamma_\pi}{\gamma_s}\right)$, the vector of fundamental variables $f_t = (\ \hat{\imath}_t,\ \ \hat{p}_t,\ \ \hat{y}_t^g,\ \ \hat{\pi}_t\ )$' and the agents choose the best forecasting model according to (7).

6.1 Data and basic statistics

The input for equation (33) are the nominal exchange rate, the fundamental variables and the parameter values in θ and ϕ' are given so that the only unknown is the best model chosen in different periods according to BIC. We use post Bretton-Woods demeaned monthly data between $1974M1$ and $2006M5$. The nominal exchange rate is expressed as the number of British Pound per US Dollar. We use the UK economy as a home country and all the fundamentals are constructed as differentials between UK and US variables; data were obtained from the International Financial Statistics (IFS). Output is measured as the log of seasonally adjusted industrial production, prices as the log of the CPI, inflation as the first difference of log prices, interest rates by a money market rate expressed at annual rates, and the exchange rate as the log of the end of the period rate[6]. We construct the output gap series as deviations of actual output from the Hodrick-Prescott (1997) trend.

We use the Dickey-Fuller test to assess whether these series are either stationary or trend stationary. Clearly, for the exchange rate and the price differential series, we cannot reject the unit root hypothesis. We reject it for the remaining series: output gap differential, inflation differential and interest rate differentials. For the exchange rate and the price differentials series, we carry out cointegration tests. We find that they form one significant cointegration equation indicating that in the long run PPP holds for UK and US.

[6] Because all the series except for interest rates are expressed in monthly terms, we divide the latter by 12.

6.2 Parameters and results of calibration

For Taylor-rule parameters we use the values proposed by Clarida, Galí and Gertler (1998), i.e. $\gamma_s = 0.1, \gamma_y = 0.25$ and $\gamma_\pi = 1.75$ and implied discount factor $1 - \gamma_s \equiv \theta = 0.9$. To avoid any bias towards underparametrization, we assume that initially the agents choose the model M_0^{BIC} which is the RE solution of the Taylor-rule model. Initial values of $\beta_{j,0}$ are drawn from the normal distribution centered around parameter values β_{RE} given by RE solution. In order to make sure that the model choice is robust to the initial values choice, we calibrate it 10000 times for each period t and calculate the mode model. Furthermore, we set all the shocks to zero so that they do not drive the results. Table 6 in Appendix reports the values given to all the model parameters.

Figure (2) plots the model choice and the volatility of British Pound/US Dollar returns during the sample period between 1974 and 2006. The figure shows that the BIC applied to the data makes agents regularly underparametrize the Taylor-rule model of the exchange rate. The RE solution of the latter is displayed on the right $y - axis$ and is not chosen by the agents during the whole sample period. It appears only in the first period $1974M1$ due to the initialization. In the beginning of the sample period, between 1974 and 1978 several shifts take place but it seems like the model with only interest differential prevails. Because it is a relatively short period, we focus on the second shift depicted in Figure (2) and two following regimes. Since 1978, the agents use only one variable as the exchange rate predictor, i.e. the price level differential.

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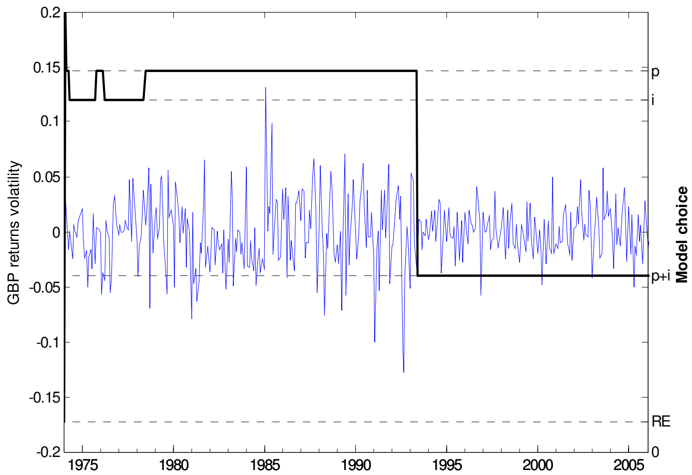
Figure 2: **Choice of the best model to predict GBP/USD exchange rate**

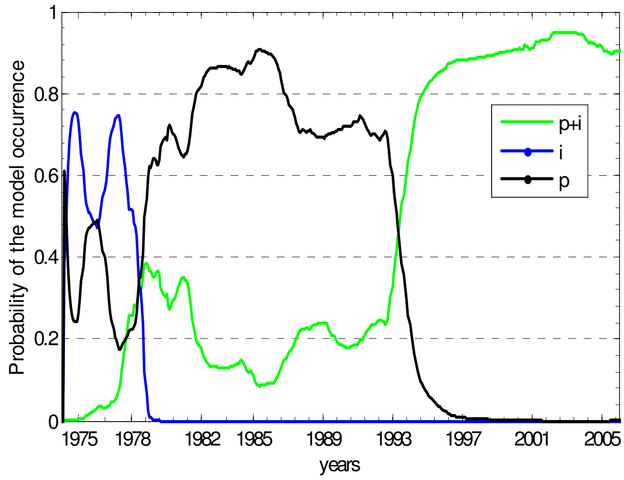


The *x-axis* reports time dimension (years). The left *y-axis* reports the British Pound/US Dollar returns and the right *y-axis* shows model chosen by agents. The degree of underparametrization increases in the right y. Note that although the agents can choose between 15 available combinations of Taylor-rule variables, we report only 3 of them. The first one denoted RE corresponds to the RE model, i.e. when all the variables of the Taylor-rule model are included as in (32). The model denoted by p is chosen by agents between 1978:M1 and 1993:M6 and it only includes price levels differential. The model denoted by $p+i$, chosen by agents after 1993:M7, includes price and interest rate differential.

prevails. Because it is a relatively short period, we focus on the second shift depicted in Figure (2) and two following regimes. Since 1978, the agents use only one variable as the exchange rate predictor, i.e. the price level differential. In $1993M7$ however they shift to a new, larger model. This shifts clearly cuts the exchange rate returns volatility into two regimes. This seems to occur when the volatility of British Pound/US Dollar returns experienced a sharp decrease, as Figures (2) and (1)suggests.

At this point in time, the agents added the interest rate differential as a

Figure 3: **Robustness test: Probability of the mode model occurrence**



The *x-axis* reports time dimension (years). The *y-axis* reports the probability that the mode models displayed in Figure(2) occur. In this robustness exercise, initial values of $\beta_{j,0}$ are drawn from the normal distribution centered around parameter values β_{RE} given by RE solution. The model was calibrated 10000 times for each period t.

prediction variable to their model. It suggests that they start learning the Taylor rule model of the exchange rate, as the number of variables in their model increases.

Figure (3) demonstrates that our results are robust. It displays the probability that the mode model occurs for each period t after Bretton-Woods and for 10000 different initial condition values. We observe that the model with only interest rate variable obtained the probability of occurrence of around 70% between 1974 and 1978. Then between 1979 and 1993, the model with the price differential was most likely to occur, with probability of outcome reaching 93 %. Finally, after September 1993, the model including both price and interest rate differentials received the highest probability of event, reaching 95 % of chances of occurrence.

7 Structural break tests

We find that the agents shifted between the predictors in mid-1993. Although the plotted returns in Figure (1) quite clearly point to a break in volatility between 1992 and 1993, we explicitly test for this. Additionally, we attempt to identify the sources of the break. The theory set out above suggests that a decrease in exchange rate volatility can be due to a change in the forecasting model that the agents use or to a change in the volatility of the fundamentals in the model used by agents. Consequently, we test for structural breaks in the volatility of the fundamental variables that the agents use in their model, that is the price differential and the interest rate differential.

We test for structural breaks using the test proposed by Bai and Perron (1998). Consider the general model represented by multiple linear regression model given by Bai and Perron (2003):

$$\begin{aligned} y_t &= x_t^{'}\beta + z_t^{'}\delta_1 + u_t, \quad t = 1, ..., T_1 \\ y_t &= x_t^{'}\beta + z_t^{'}\delta_2 + u_t, \quad t = T_1 + 1, ..., T_2 \\ &\vdots \\ y_t &= x_t^{'}\beta + z_t^{'}\delta_{m+1} + u_t, \quad t = T_m + 1, ..., T \end{aligned} \tag{34}$$

where we allow for m breaks. y_t is a dependent variable at time t, x_t $(p \times 1)$ is a vector of regressors with parameters β which are assumed to be constant over time and z_t $(q \times 1)$ is a vector of regressors with coefficients δ_j $(j = 1, ..., m + 1)$, which are potentially time varying and u_t is the disturbance at time t. First consider the case of the unconditional volatility of the British Pound/US Dollar returns, where we test for a structural break in the mean of the absolute value of the demeaned series, so that in equation (34) , $y_t = |ds_t - \hat{\mu}|$, $p = 0$ and $z = 1$. First, we estimate up to five breaks in the series. Second, we apply the $supF(j + 1|j)$ test, which is designed to detect the presence of $(j + 1)$ breaks conditional on having found j breaks $(j = 0, 1, \ldots, 5)$. The statistical rule is to reject j in favour of a model with $(j + 1)$ breaks if the overall minimal value of the sum of squared residuals (over all the subsamples where an additional break is included) is sufficiently smaller than the sum of squared residuals from the model with j breaks. The dates of the breaks selected are the ones associated with this overall minimum. We identify the breaks if the test statistic allows rejection of the null hypothesis at at least a 10 per cent level of significance.

The results of this test for the volatility of British Pound/US Dollar returns are reported in Table 1.

Table 1: **Timing of breaks in British Pound/US Dollar returns**

Exchange rate returns volatility			
	Unconditional Volatility	Conditional Mean	Conditional Volatility
1st Break date	**1993:M3*****	–	**1993:M2*****
95% CI	(1992:M11,1996:M4)		(1992:M3,1998:M6)
2nd Break date	2000:M3*	–	–
95% CI	(1994:M11,2003M:2)		

CI stands for confidence intervals. ***, ** and * denote significance at the 1, 5 and 10 percent levels, respectively.

We find that there are two breaks in the unconditional volatility of exchange rate returns which are reported in the first column of Table 1. The first of the breaks is estimated in March 1993. This break is clearly visible in Figure (1) which plots British Pound/US Dollar returns and it is very close to the shift between the predictors displayed in Figure (2). The second break is estimated in March 2000.

The changes in unconditional volatility may be due to either the changes in conditional variance or in the conditional mean or in both. We explore this issue in the following way. First, we test for a change in the conditional mean by applying the sequential procedure to the AR(1) coefficient. Thus, in equation (34) we set $y_t = ds_t$, $z_t = ds_{t-1}$ and $p = 0$. As reported in Table 1, there is no structural break in the mean of the exchange rate returns.

Second, we check whether there is a change in the conditional volatility by applying the sequential method to the absolute value of the residuals from the $AR(1)$ regression, so that in equation (34), the dependent variable $y_t = |\hat{\epsilon}_t|$

where $\hat{\epsilon}_t$ are fitted residuals. The fourth column of Table 1 shows that indeed the change in the conditional volatility of British Pound/US Dollar returns coincides with the first change in the unconditional one. Since we find no structural breaks in the mean, we conclude that the unconditional volatility change in the mid-1993 is due to a change in conditional volatility.

We also observe that the shift between the exchange rate predictors coincides with the change in British Pound/US Dollar returns volatility. Furthermore, as reported in Table 2, the returns volatility before the break in March 1993 was roughly twice as high as after the break. This is the case of both, unconditional and conditional volatilities.

Table 2: **Estimated volatility of the British Pound/US Dollar returns**

Exchange rate returns		
Unconditional volatility		
Coefficient (regime)	Estimate	Standard Error
δ_1(1974:M1-1993:M3)	0.027	0.0017
δ_2(1993:M4-2000:M3)	0.013	0.0012
δ_3(2000:M4-2006:M5)	0.018	0.0016
Conditional volatility		
Coefficient (regime)	Estimate	Standard Error
δ_1(1974:M1-1993:M2)	0.027	0.0016
δ_2(1993:M3-2006:M5)	0.015	0.0010

δ_j where $j = 1, ..., 3$ are the estimated coefficients in (34) and the regimes reported in brackets are the subsamples defined by estimated breaks in Table 1.

We find evidence that there is a structural break in the volatility of exchange rate returns when agents shift to a new model of the exchange rate and we now turn to investigate the sources of this break. We found that the price differential is a variable that agents use as an exchange rate predictor at each point in time and that they add the interest rate differential in the mid-1993. Thus, the decrease in the volatility of British Pound/US Dollar returns could have occurred as a result of the shift in the volatility of the price differential, as a result of incorporating an interest rate differential into the model or a combination of these two effects.

Since the Bank of England adopted inflation targeting strategy in October 1992, the price differential series could have experienced a one time decrease in the volatility shortly afterwards. We investigate this hypothesis by applying again the test for multiple structural breaks proposed by Bai and Perron (1998). Since price differential series are not stationary, its variance is undefined. Therefore, we test for the volatility shift in price inflation. This is implemented by testing for a structural break in the mean of the absolute value of the demeaned price inflation, so that in equation (34) the dependent variable is $y_t = |d\widehat{p}_t - \hat{\mu}|$, $p = 0$ and $z = 1$[7].

Table 3 reports the results. We find only one structural break in the inflation

Table 3: **Timing of breaks of price differential volatility**

Unconditional Volatility of Price Differential		
1st Break date	1980:M3***	
95% CI	(1979:M12 1987:M5)	
Coefficient (regime)	Estimate	St. Error
δ_1(1974:M1-1980:M3)	0.00823	0.0014
δ_2(1980:M4-2006:M6)	0.00367	0.0004

CI stands for confidence intervals. ***, ** and * denote significance at the 1, 5 and 10 percent levels, respectively.

differential volatility, in March 1980. The fact that the volatility of the price differential did not experience a structural break in 1993 suggests that this fundamental variable was not responsible for the change in volatility in the exchange rate.

Finally, we apply the test of Bai and Perron (1998) to the volatility of the interest rate differential, and report the results in Table 4. The interest rate differential volatility experienced a structural break in September 1993, roughly the date when the British Pound/US Dollar volatility shifted downwards, and shortly after the introduction of inflation targeting by the Bank of England.

In Table 4, we also report the estimates of the interest rate differentials dur-

[7] We test only for the break in unconditional volatility of price differential. This is because, we do not seek to identify the sources of the change in price differential volatility but whether it could explain the decrease in the volatility of the GBP returns.

Table 4: **Timing of breaks in interest rates differential volatility**

Unconditional Volatility of Interest Rates Differential	
1st Break date	1982:M9***
95% CI	(1981:M11,1990:M9)
2nd Break date	**1993:M9***
95% CI	(1990:M10,2002:M6)

Coefficient (regime)	Estimate	St. Error
δ_1(1974:M1-1982:M9)	0.013	0.0019
δ_2(1982:M10-1993:M9)	0.006	0.0007
δ_3(1993:M10-2006:M5)	0.003	0.0004

Table reports the result of the Bai and Perron (1998) test applied to the interest rate differential between the UK and the US. This is implemented by testing for a structural break in the mean of the absolute value of the demeaned first difference of the interest rates differential, so that in equation (34) the dependent variable is $y_t = \left|\widehat{di}_t - \hat{\mu}\right|$, $p = 0$ and $z = 1$. CI stands for confidence intervals. ***, ** and * denote significance at the 1, 5 and 10 percent levels, respectively. δ_j where $j = 1, ..., 3$ are the estimated coefficients in (34) and the regimes reported in brackets are the subsamples defined by estimated breaks.

ing the subsamples defined by the breakdates. We find that after the mid 1993 this volatility became much lower and calibration results suggested that, at the same time, the agents added this variable to their model. Because the inflation targeting strategy of the Bank of England was introduced shortly before, it could have had an impact on the choice of variables by agents. However, we carried out all the econometric tests for the fundamentals of the Taylor-rule model, i.e. differentials between the UK and US variables. Therefore, we cannot draw from their results any conclusions about the national economic policies. For this reason, we test for structural breaks in the national interest rates. Table 5 reports the results.

Both interest rates experienced a structural break in the beginning of the 1980. However, only the volatility of the UK interest rate shifted at the time close to the date when the volatility of the interest rate differential changed. It suggests that the break in the volatility of interest rate differential was triggered by the one in the UK interest rate volatility and thus new monetary policy strategy of the Bank of England.

Our findings are in line with the literature. Benati (2003) finds that UK in-

Table 5: **Timing of breaks in interest rates**

Volatility of Interest Rates		
	UK	US
1st Break date	1981:M9***	1981:M7***
2nd Break date	**1992:M9****	-

Table reports the result of the Bai and Perron (1998) test applied to the UK and the US interest rate. This is implemented by testing for a structural break in the mean of the absolute value of the demeaned first difference of the interest rates, so that in equation (34) the dependent variable is $y_t = |di_t - \hat{\mu}|$, $p = 0$ and $z = 1$. CI stands for confidence intervals. ***, ** and * denote significance at the 1, 5 and 10 percent levels, respectively.

terest rates decreased substantially after mid-1993. Apart from setting a quantitative objective for the inflation rate, the inflation targeting strategy also implies a more transparent monetary policy. This practice is likely to have reduced the uncertainty about interest rates. Haldane (2000) notes that, during the period when British Pound/US Dollar was part of the ERM, the average "surprise" in three-month interest rates following a 1 percentage point rise in official rates was around 50 basis points. Since the Bank of England adopted inflation targeting, this surprise has dropped to around 12 basis points. As a result, the interest rate became a more useful variable for predicting the exchange rate movements, which may be the reason why the agents included interest rate differential variable into their model.

8 Conclusion

In this paper we proposed an explanation for shifts in the volatility of the exchange rate returns. We assume that agents face model uncertainty and behave as econometricians to deal with it. First, given a model of the exchange rate, they estimate the coefficients of all the possible combinations of the variables within this model. Second, using a model selection criterion, they choose the best set of variables to use as a forecast of the future exchange rate.

Using a simple version of the asset pricing model, we demonstrated that, if agents use only one fundamental variable to forecast the exchange rate, this variable would eventually be a major determinant of the exchange rate process and thus dominate its statistical properties.

We introduced this BIC model selection framework into the Taylor-rule based model of the exchange rate and applied it to the UK, one of the successful inflation targeting economies. Calibration exercises suggested that the agents shifted models in the mid-1993. In particular, at this point in time, in addition to the price differential variable, the agents also focused on the interest rate differential.

We used a set of structural break tests to assess whether the calibrated change date corresponds to the break dates in realized volatility of the exchange rate returns and underlying macroeconomic variables. We find that there was a significant instantaneous decrease in the volatilities of British Pound/US Dollar returns. We find an evidence for sudden decrease in the volatility of the interest rate differential but no evidence for a change in the volatility of the price differential. These results suggest that the change in the volatility of the exchange rate was triggered by the shift of the model. Accordingly, there was a shift from a high to a low volatility exchange rate regime. Since the break in the volatility of interest rate differential was triggered by the one in the UK interest rate volatility, we think that the inflation targeting strategy adopted by the Bank of England in October 1992 largely contributed to this result.

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Appendix 1

Table 6: **Parameter values in calibration**

Parameter	Value
γ_s	0.1
γ_π	1.75
γ_y	0.25
$\theta = (1 - \gamma_s)$	0.9
$\hat{\beta}^j_{n,0}$	$\sim N\left(\hat{\beta}^j_{RE}, 1\right)$
M_0^{BIC}	M_{RE}
$\widehat{v}_t$	0