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CHANGING MONETARY POLICY RULES, LEARNING, AND REAL EXCHANGE RATE DYNAMICS

Nelson C. Mark

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ABSTRACT

When central banks set nominal interest rates according to an interest rate reaction function, such as the Taylor rule, and the exchange rate is priced by uncovered interest parity, the real exchange rate is determined by expected inflation differentials and output gap differentials. In this paper I examine the implications of these Taylor-rule fundamentals for real exchange rate determination in an environment where market participants are ignorant of the numerical values of the model's coefficients but attempt to acquire that information using least-squares learning rules. I find evidence that this simple learning environment provides a plausible framework for understanding real dollar--DM exchange rate dynamics from 1976 to 2003. The least-squares learning path for the real exchange rate implied by inflation and output gap data exhibits the real depreciation of the 70s, the great appreciation (1979.4-1985.1) and the subsequent great depreciation (1985.2-1991.1) observed in the data. An emphasis on Taylor-rule fundamentals may provide a resolution to the exchange rate disconnect puzzle.

Nelson C. Mark
Department of Economics and Econometrics
University of Notre Dame
Notre Dame, IN 46556
and NBER
nmark@nd.edu

Introduction

Understanding the macroeconomic determinants of the exchange rate has posed a challenge to research ever since Meese and Rogoff (1983) reported the seemingly nonexistent relationship between macroeconomic fundamentals and the exchange rate. Although some progress has been made at econometrically modeling long-horizon exchange rate movements, the general failure of open economy macroeconomic theory—ranging from disequilibrium Keynesian models of Dornbusch (1976), Mussa (1982) and Obstfeld (1985) to the new open-economy macroeconomics of Obstfeld and Rogoff (1995)—to explain the exchange rate in terms of macro fundamentals has come to be known as the *exchange rate disconnect puzzle* [Obstfeld and Rogoff (2000)].[1]

In this paper, I provide evidence to suggest that the disconnect puzzle has resulted from focusing on the wrong set of fundamentals. Standard models predict that levels of variables such as domestic and foreign prices, money supplies, and income determine the exchange rate. While one strand of the literature attempts to model the disconnect between these fundamentals and the exchange rate[e.g., Devereux and Engel (2002), Kollman (2001), and Duarte and Stockman (2001)], I investigate the linkage of the exchange rate to an alternative set of fundamentals that arise when monetary policy is guided by a nominal interest rate reaction function commonly referred to as the 'Taylor (1993) rule.' The Taylor-rule approach predicts that the exchange rate is determined by relative expected inflation gaps and relative output gaps.

In the environment that I study, market participants do not know the exact Taylor-rule coefficient values but attempt to acquire that information by least squares learning.[2] The learning model provides a plausible and useful framework for understanding observed real exchange rate dynamics over the post Bretton Woods float for the dollar-Deutschemark (DM) rate. The implied least-squares learning path displays many of the sizable and lengthy swings exhibited in the data–the depreciation of the late 1970s, the great appreciation of 1979.4–1985.1 and the subsequent great depreciation of 1985.2-1991.1.[3] The choice of the dollar-deutschemark (DM) exchange rate is guided in part

[1]See Mark (1995), Mark and Sul (2001), Groen (2000,2002), and Rapach and Wohar (2002) who report econometric evidence on the long-horizon predictability of exchange rate returns from standard monetary model pricing errors.

[2]Lewis (1989a, b) conducts an analysis of Bayesian learning in the foreign exchange market to examine the 1979 changes in the Fed's operating procedures. She focused on shifts in the stochastic process governing monetary aggregates. In the monetary policy literature, Bullard and Mitra (2002) study conditions under which the rational expectations equilibrium is learnable while Orphanides (2003) examines whether the Fed's imperfect knowledge of and attempts to learn the natural rate of unemployment responsible for the inflationary buildup of the 1970s.

[3]I adopt this terminology from Papell (2002). Engel and Hamilton (1990) referred to these fluctuations as 'long-swings,' while Frankel (1985) referred to dollar strength exhibited in the 80s as the 'dazzling dollar.'

because the Bundesbank is one of the non-US central banks identified by Clarida et. al. (1998) as having conducted monetary policy by following a variant of the Taylor rule.

This paper is part of a growing literature that recognizes the central role of interest rate reaction functions in exchange rate determination. Engel and West (2002) estimate the rational expectations time path of the real exchange rate implied by reaction function fundamentals and report a correlation of 0.4 between the implied rational expectations real dollar-DM rate and the historically observed real exchange rate from 1979 to 1998. In related work, Groen and Matsumoto (2004) calibrate a dynamic general equilibrium to the UK economy where monetary policy operates through interest rate reaction functions. The role of interest rate differentials in the determination of the real exchange rate is not new and many strategies for modeling their dynamics have been employed to explain exchange rate dynamics with varying degrees of success. However, modeling the interest rate with the Taylor rule introduces a multivariate structure that produces a richer set of dynamics and interest rate forecasts that may be more accurate than those obtained from univariate time-series specifications.[4]

Modeling the learning process in exchange rate determination can be motivated by both general and specific considerations. From a general perspective, we not that in light of the poor track record of the macroeconomic rational expectations framework, it seems worthwhile to relax the strong informational assumptions that market participants already know the very structure that econometricians are struggling to learn. Both direct evidence of structural instability and indirect evidence through the inability of econometric exchange rate models to fit out of sample point to an important feature of the environment that should be explicitly accounted for.[5] Adaptive learning schemes provide a plausible and straightforward strategy for modeling a public that must deal with a changing environment.

More specifically, a significant change in the economic environment that is important to take into account is the change in central bank interest rate response to expected inflation that occurred with the appointment of Paul Volker to the Federal Reserve

[4]e.g., Frankel (1979), Meese and Rogoff (1988), Edison and Pauls (1993), Campbell and Clarida (1987), and Baxter (1994). Mark and Moh (2004) consider nonlinear (threshold) models for real interest rate differentials and find that the implied rational expectations path for the real exchange rate has very little power to explain historical movements in the real exchange rate. For evidence on the importance of a multivariate approach, see Clarida and Taylor (1997) who show that information in the term structure of the forward premium provides significant out-of-sample predictive power for the exchange rate.

[5]That is the Meese and Rogoff (1983) problem. See Cheung, Chinn and Pascual (2003) for a recent and nearly as discouraging assessment of the ability of econometric models to generate out-of-sample exchange rate predictions. My analysis does not suggest an out-of-sample forecasting experiment as a way to evaluate the model. Least squares learning, which itself is estimation with a recursively updated sample, is the standard method of generating out-of-sample forecasts. Since dozens of articles have shown this technique to be unable to significantly improve over the random walk forecast, it is unlikely that we will be able to do so here, especially if the underlying coefficient values are changing over time.

chairmanship in 1979. Clarida et. al. (2000) found that in the pre-1979 data, an increase in expected inflation led to a reduction in the real interest rate because the Fed typically reacted by raising the nominal interest rate by less than the increase in expected inflation. Following the appointment of Paul Volker as Chairman of the Federal Reserve System, they found the real interest rate to be increasing in expected inflation because the Fed now reacts by raising the nominal interest rate by more than the increase in expected inflation. When I estimate the central bank reaction functions in differential form my estimates exhibit instability similar to that found in the Fed's reaction function by Clarida et. al. The implied shift in the interest differential reaction function is significant in the pricing of the exchange rate because the shift fundamentally changes the relationship between the real exchange rate and national inflation differentials.

The remainder of the paper is as follows. The next section describes the data. The least-squares learning exchange rate that I study is the outcome of agent's attempts to learn the rational expectations real exchange rate priced by uncovered interest parity with interest rates determined by the Taylor rule. To set the stage for constructing the learning exchange rate paths, Section 2 reports estimates of the differential in central bank's interest rate reaction function under cross-country homogeneity of the response coefficients. The empirical analysis of the real exchange rate is contained in Section 3. There, I begin with an examination of the estimated rational expectations real exchange rate. The model with learning is presented in subsection 3.2. Section 4 concludes.

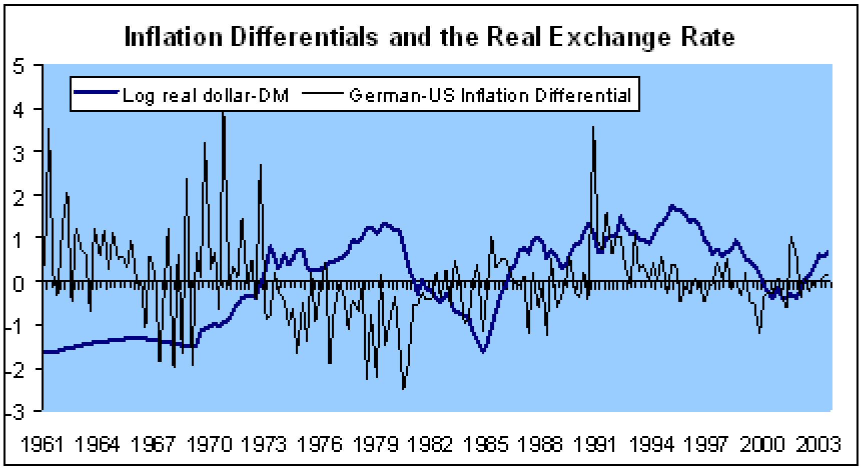
1 The Data

The observations are quarterly and span from 1960.1 to 2003.3. The nominal exchange rate, German short-term nominal interest rates, GDP and potential GDP are from the OECD's Economic Outlook. The imputed DM rate is used from 1998 to the end of the sample. Goods prices are measured by the real GDP deflator from the International Financial Statistics (series code 13499BIRZF). The U.S. Federal funds rate, GDP and potential GDP were obtained from FRED, the St. Louis Fed's economic data web site.

The output gap is defined as the percentage deviation of actual GDP from potential GDP. The availability of German potential GDP from source begins in 1966.1. These data are spliced together with the deviation from the Hodrick-Prescott (1997) (HP) trend to create a series that begins 1960.1. Quarterly inflation, the output gap and the nominal exchange rate return are stated in percent per annum. An increase in the real exchange rate signifies a real depreciation of the dollar.

Figure 1 plots standardized values of the log real dollar-DM rate and the German–U.S. inflation differential. The inflation differential appears to be characterized by several distinct trends. From 1960 to 1979, rising relative US inflation generates a downward

Figure 1: German–U.S. inflation differential and log real dollar–DM exchange rate



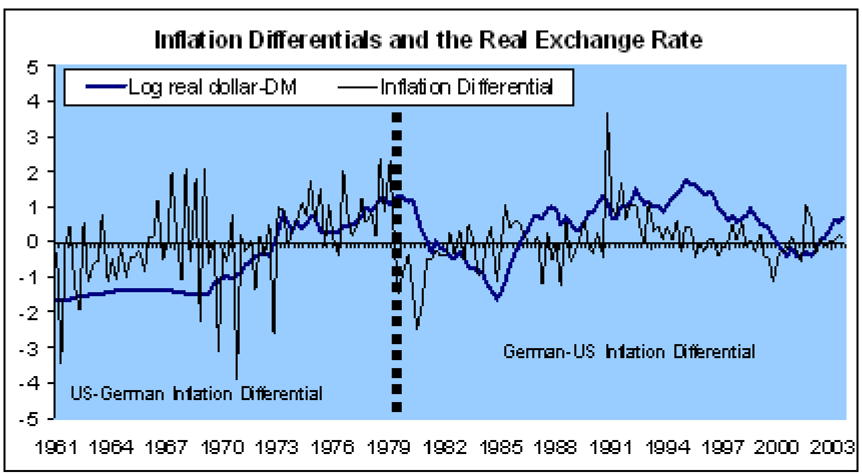


Figure 2: U.S.–German inflation differential from 1960.2–1979.2, German–U.S. inflation differential from 1979.3–2003.4, and log real dollar–DM exchange rate.

trend in the inflation differential. The inflation differential then increases from 1979 to 1992, declines from 1992 to 2000 and increases from 2000 through the end of the sample.

The trends in the log real exchange rate coincides with that of the German-U.S. inflation differential in the post 1979 sample but the two series move in opposite directions in the pre 1979 sample, suggesting that a change in the relationship between the two series may have occurred at that time. Figure 2 allows for a regime change by plotting the US-German inflation differential from 1960 to 1979 and the German-US differential over the post 1979 sample. Allowing for this one-time regime change produces coincident trends in the real exchange rate and the inflation differential.

Two preliminary conclusions can be drawn from this informal examination of the data. First, the figures suggest shifting the emphasis on exchange rate determinants away from relative levels of macroeconomic fundamentals towards variables such as the differences in differences of national price levels may be a sensible thing to do. Second, impression one gets from the figures is that the relationship between the real exchange rate trend and the inflation differential changed around 1979. An obvious candidate for such a regime shift, is the change in the conduct of monetary policy. We now turn to an examination of the regime shift in the context of real exchange rate determination.

2 Differentials in interest rate reaction functions

This section presents evidence to support modeling the interest differential as a differential in monetary policy reaction functions under cross-country homogeneity restrictions on coefficients for expected inflation and the output gap.

Let German variables be denoted with a 'star' and let German-U.S. differentials be denoted with a tilde. Then $\widetilde{\pi}_t = (\pi_t^* - \pi_t)$, $\widetilde{i}_t = (i_t^* - i_t)$, and $\widetilde{x}_t = (x_t^* - x_t)$ are German-U.S. differentials in inflation, short-term nominal interest rates and output gaps, respectively.[6] The log real exchange rate is q_t.

My specification of the interest rate reaction functions draws on Clarida et. al. (1998, 2002). They estimated the Fed's inflation response coefficient to be less than 1 in the pre-Volker sample and to be greater than 1 in the post-Volker sample. The weak nominal interest rate response exhibited during the pre-1979 sample, meant that an increase in expected inflation caused the real interest rate to decline whereas in the post-1979 sample an aggressive interest rate response meant that an increase in expected inflation would cause an increase in the real interest rate. Clarida et. al. (1998) estimate monetary policy reaction functions for the Bundesbank and several other countries using data spanning from 1979 to 1993. They find that over this period, Bundesbank reactions

[6] Actual GDP lies above potential GDP when $x_t > 0$.

to changes in inflation were similar to those of the post-1979 Fed.[7]

For my analysis, the Fed is assumed to set the deviation of its target for the Federal funds rate i_t^T, from the desired level $\bar{i}$ in response to the deviation of the public's expected inflation from the target inflation rate $(E_t\pi_{t+1} - \overline{\pi})$, and the output gap x_t, according to

$$i_t^T = \bar{i} + \gamma_\pi \left(E_t\pi_{t+1} - \overline{\pi}\right) + \gamma_x x_t, \tag{1}$$

where the central bank and the public employ the same model to forecast future inflation. The actual interest rate is subject to an exogenous and i.i.d. policy shock η_t, and is set according to a partial adjustment mechanism to reflect the central bank's desire to limit interest rate volatility,

$$i_t = (1-\rho)i_t^T + \rho i_{t-1} + \eta_t. \tag{2}$$

The Bundesbank is assumed to act in an analogous fashion. In addition, it may also react to nominal exchange rate deviations from its 'natural level,' which is given by purchasing-power parity. Clarida et. al. (1998) found that the feedback from the exchange rate to the German interest rate was statistically significant but quantitatively very small. The German interest rate target is set by the rule,

$$i_t^{*T} = \overline{i^*} + \gamma_\pi \left(E_t\pi_{t+1}^* - \overline{\pi^*}\right) + \gamma_x x_t^* + \gamma_s q_t. \tag{3}$$

Imposing homogeneity on (γ_π, γ_x) across countries gives the empirical specification of the interest differential,

$$\widetilde{i}_t = (1-\rho)\widetilde{i}_t^T + \rho\widetilde{i}_{t-1} + \widetilde{\eta}_t, \tag{4}$$

$$\widetilde{i}_t^T = \widetilde{\zeta} + \gamma_\pi E_t\widetilde{\pi}_{t+1} + \gamma_x\widetilde{x}_t + \gamma_s q_t, \tag{5}$$

$$\widetilde{\zeta} \equiv \left(\overline{i^*} - \bar{i}\right) - \gamma_\pi\left(\overline{\pi^*} - \overline{\pi}\right), \tag{6}$$

$$\widetilde{\eta}_t \overset{iid}{\sim} (0, \sigma_{\widetilde{\eta}}^2). \tag{7}$$

To estimate the differential in interest rate reaction functions, add and subtract $(1-\rho)\gamma_\pi\widetilde{\pi}_{t+1}$ on the right side of (4) and rearrange to obtain the regression

$$\widetilde{i}_t = \delta + (1-\rho)\left[\gamma_\pi\widetilde{\pi}_{t+1} + \gamma_x\widetilde{x}_t + \gamma_s q_t\right] + \rho\widetilde{i}_{t-1} + \widetilde{\eta}'_t, \tag{8}$$

where $\delta = (1-\rho)\zeta$ and $\widetilde{\eta}'_t = \widetilde{\eta}_t - (1-\rho)\gamma_\pi\left[\widetilde{\pi}_{t+1} - E_t\widetilde{\pi}_{t+1}\right]$. Under rational expectations, the composite error term $\widetilde{\eta}'_t$ is uncorrelated with date t information so (8) can be estimated by generalized method of moments (GMM).[8] The instrumental variables that I

[7]See also, Gerlach and Schnabel (1999) who estimate monetary policy reaction functions for an average of the EMU countries over a sample spanning from 1990 to 1998.

[8]The monetary policy literature places a great deal of emphasis on the magnitude of γ_π. Values less

Table 1: Bundesbank–Fed Relative Interest-Rate Reaction Function Estimates by GMM

Output gap from source

Sample	γ_π (s.e.)	γ_x (s.e.)	γ_q (s.e.)	ρ (s.e.)	δ (s.e.)	J-statistic (p-value)
60.2-79.2	0.148	-0.126	-0.016	**0.858**	-0.439	2.571
	(0.482)	(0.221)	(0.015)	(0.063)	(0.267)	(0.860)
79.3-03.4	**1.987**	0.573	-0.012	**0.825**	**0.258**	1.384
	(0.505)	(0.289)	(0.013)	(0.068)	(0.108)	(0.967)

Structural Change Test

All coeffs.	Test statistic	**13.461**	p-value	0.019
Inflation coeff.	Test statistic	**5.680**	p-value	0.017

Output gap estimated by HP filter

Sample	γ_π (s.e.)	γ_x (s.e.)	γ_q (s.e.)	ρ (s.e.)	δ (s.e.)	J-statistic (p-value)
60.2-79.2	-0.127	-0.556	-0.029	**0.877**	**-0.516**	2.336
	(0.580)	(0.453)	(0.020)	(0.062)	(0.247)	(0.886)
79.3-03.4	**2.048**	0.016	0.001	**0.795**	0.119	1.287
	(0.520)	(0.280)	(0.009)	(0.088)	(0.116)	(0.972)

Structural Change Test

All coeffs.	Test statistic	9.968	p-value	0.084
Inflation coeff.	Test statistic	**8.599**	p-value	0.003

Notes: Bold face indicates significance at the 5 percent level.

employ are a constant, three lags of the inflation differential, three lags of the output gap differential, three lags of the nominal interest differential, and one lag of the real exchange rate.

I estimate eq. (8) over pre- and post-1979 sub-samples with the split occurring on 1979.3 to conform to evidence reported by Clarida et. al. (2002). The results are reported in Table 1. The inflation response coefficient is estimated to be less than 1 over the pre-1979 period and is estimated to be greater than 1 in the post-1979 period. The estimated output gap coefficient has the wrong sign in the pre-1979 sample but is not statistically significant. The estimated exchange rate response coefficient is also not significant. Hansen's GMM test of the over identifying restrictions does not reject the specification. The results are qualitatively similar for both constructions of the output gap.

The structural shift of the Fed's interest rate reaction function reported in the literature also appears to describe the reaction function differential. To formally examine the evidence for a structural shift, I run Hodrick and Srivastava's (1984) GMM-test for structural change.[9] The hypothesis of no structural change in any of the coefficients is strongly rejected when the output gap is constructed by the source agency and is marginally rejected when the output gap is estimated by the HP filter. The hypothesis of no structural change in the inflation response coefficient is strongly rejected for both constructions of the output gap.

A visual account of the fit is provided in Figure 3 which plots the actual interest differential and fitted values. In generating these fitted values, I employ forecasts of the inflation differential generated by a fourth order bivariate autoregression in the inflation differential and the output gap (from source agency) differential. It can be seen that this simple specification appears to work reasonably well in describing the dynamics of the interest differential. Tractability in the ensuing analysis is facilitated by imposing coefficient homogeneity in the interest rate rule across countries, and the estimation results suggest that imposing these restrictions is not unreasonable. Since the empirical analysis does not find that γ_s is significant, I set it to zero in the remainder of the analysis.

than 1 indicate that an increase in expected inflation elicits a weak response from the central bank that results in a reduction of the real interest rate which stimulates the economy, leading to a further increase in inflation. Values greater than 1 imply that the central bank responds aggressively to an increase in inflation by raising the nominal interest rate sufficiently to raise the real interest rate.

[9]The $k-$dimensional coefficient vector estimated from subsample $j = 1, 2$ be $\widehat{\beta}_j$ is has asymptotic distribution $\sqrt{T_j}\left(\widehat{\beta}_j - \beta_j\right) \sim N\left(0, \Omega_j\right)$. If the observations from the two subsamples are independent, then under null hypothesis of no structural change $H_0 : \beta_1 = \beta_1$ the test statistic $HS = \left(\widehat{\beta}_1 - \widehat{\beta}_1\right)' \left(\frac{\Omega_1}{T_t} + \frac{\Omega_2}{T_2}\right)^{-1} \left(\widehat{\beta}_1 - \widehat{\beta}_1\right)$ is asymptotically distributed as a chi-square variate with k degrees of freedom.

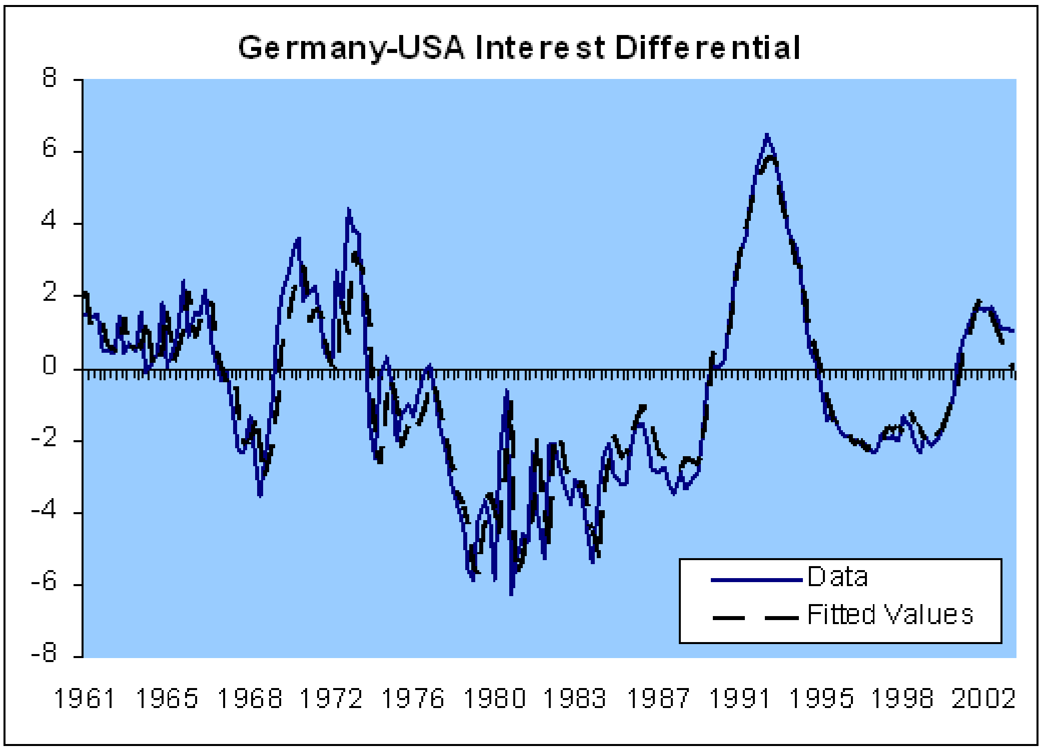


Figure 3: Fitted values employ one-period ahead forecast of inflation differential generated from a fourth-order bi-variate autoregression for the inflation differential and the output gap differential.

3 An empirical model of the real exchange rate

Since the goal of the learning public is to discover the (minimum state variable) rational expectations equilibrium, I begin with a discussion of this case in subsection 3.1. In subsection 3.2, the model is extended to incorporate the public's implementation of least-squares learning.

3.1 Rational Expectations Real Exchange Rate

My primary aim is to study Taylor-rule fundamentals as determinants of real exchange rate movements. It is not to test a particular dynamic general equilibrium model. Thus, to model expectations formation, I adopting a relatively unstructured approach in the sense that the dynamics of the inflation differential and the output gap differential are taken to be exogenously generated from a bivariate vector autoregression (VAR). Market participants view this unrestricted VAR as the data generating process for inflation and the output gap which they use to construct forecasts of future inflation.

Let $\widetilde{Y}_t' = (\widetilde{\pi}_t, \ldots, \widetilde{\pi}_{t-p+1}, \widetilde{x}_t, \ldots, \widetilde{x}_{t-p+1})$, and $\widetilde{Z}_{vt}' = \left(1, \widetilde{Y}_t'\right)$. The two-equation $p-$th order VAR in regression form is,

$$\begin{aligned} \widetilde{\pi}_t &= b_\pi' \widetilde{Z}_{vt-1}' + \widetilde{v}_{1t}, \\ \widetilde{x}_t &= b_x' \widetilde{Z}_{vt-1}' + \widetilde{v}_{2t}, \end{aligned}$$

which is convenient for estimation. For forecast generation, it is convenient to rewrite the VAR in companion form,

$$\widetilde{Y}_t = \alpha + A\widetilde{Y}_{t-1} + \widetilde{v}_t.$$

To obtain the one-step ahead forecast of the inflation differential, let e_1 be the row selection vector that has 1 as the $(1,1)-$th element and zeros elsewhere such that $\widetilde{\pi}_t = e_1 \widetilde{Y}_t$. Since $E_t \widetilde{Y}_{t+1} = \alpha + A\widetilde{Y}_t$, we have

$$E_t \widetilde{\pi}_{t+1} = e_1 \left(\alpha + A\widetilde{Y}_t\right). \tag{9}$$

The output gap differential can be recovered from the companion form of the VAR by defining the selection vector e_2 that has 1 as the $(1,p)-$th element and zeros elsewhere such that

$$\widetilde{x}_t = e_2 \widetilde{Y}_t. \tag{10}$$

The log nominal exchange rate s_t, is priced by uncovered interest parity,

$$s_t = E_t s_{t+1} + \widetilde{i}_t. \tag{11}$$

To price the real exchange rate, add and subtract $E_t \widetilde{\pi}_{t+1}$ from the right hand side of (11) and rearrange to get

$$q_t = E_t q_{t+1} + \widetilde{i}_t - E_t \widetilde{\pi}_{t+1}. \tag{12}$$

Substituting (4),(5), (9), and (10) into (12) gives

$$\begin{aligned} q_t &= E_t q_{t+1} + \left[\delta + (1-\rho)\left(\gamma_\pi - 1\right) e_1 \alpha\right] \\ &\quad + \left\{(1-\rho)\left(\gamma_x e_2 + \gamma_\pi e_1 A\right) - e_1 A\right\} \widetilde{Y}_t + \rho\, \widetilde{i}_{t-1} + \widetilde{\eta}_t. \end{aligned} \tag{13}$$

Notice that the relationship between the expected real depreciation and the expected inflation differential depends on the central bank's inflation response coefficient γ_π. The observed shift in the estimated response coefficient suggests an explanation for the divergence between the trends in the real exchange rate and inflation differentials in the pre-Volker sample and subsequent trend convergence. Because $\gamma_\pi < 1$ in the pre-Volker sample, a decline in the expected German-US inflation differential led the public to expect an increase in the German-US real interest differential and a real depreciation of the dollar whereas with $\gamma_\pi > 1$ in the post-1979 sample, a decline in the expected inflation differential led the public to expect a decline in the German-US interest differential and a real appreciation of the dollar.

With $\gamma_s = 0$, forward iteration of real interest parity gives the real exchange rate as the undiscounted present value of expected future real interest differentials.[10] A rational expectations real exchange rate is the MSV solution

$$q_t = \beta_0 + {\beta_1}' Y_t + \beta_2 \widetilde{i}_{t-1} + \beta_3 \widetilde{\eta}_t, \tag{14}$$

where

$$\beta_2 = \frac{\rho}{1-\rho}, \tag{15}$$

$$\beta_3 = \frac{1}{1-\rho}, \tag{16}$$

$$\beta_1' = \left(\left[\gamma_x e_2 + \gamma_\pi e_1 A\right] - e_1 A\right)(I - A)^{-1}, \tag{17}$$

$$\beta_0 = -\left(\beta_1' + \beta_2 e_1\right)\alpha\,(I - A)^{-1}. \tag{18}$$

[10] A solution exists provided that the real interest differential has unconditional mean 0 which requires $\bar{i}^* - \bar{i} = \overline{\pi}^* - \overline{\pi}$. It follows that $\delta = (1-\rho)(1-\gamma_\pi)\left(\overline{\pi}^* - \overline{\pi}\right)$.

The restriction on β_0 ensures that the log real exchange rate has zero unconditional mean but because the price data are index numbers, the constant cannot be identified in the empirical work and this restriction cannot be imposed.

3.1.1 Estimated Rational Expectations Real Exchange Rate Path

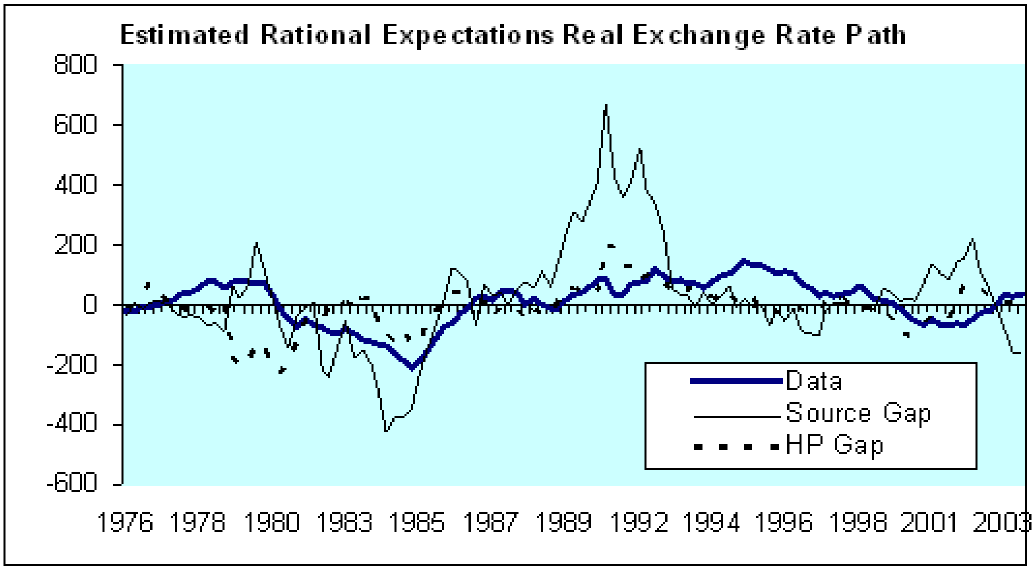
Here, I present the estimated rational expectations (RE) real exchange rate path using coefficients $(\rho, \gamma_\pi, \gamma_x, \alpha, A)$ estimated on the full sample with a known breakpoint at 1979.3. Market participants are thus assumed to have known about the regime change, the Taylor rule coefficient values and the VAR coefficient values under each regime. From these estimated coefficients I obtain values for the exchange rate coefficients in eqs. (15)-(17).[11] It is worth pointing out that the implied real exchange rate path is generated entirely by the fundamentals data and does not directly depend on actual exchange rate observations.

It is well known that the real exchange rate behaves much differently under a flexible exchange rate regime than it does under a fixed regime [e.g., Mussa (1986), Baxter and Stockman (1989)] and because exchange controls were in place in the 1960's through the 1970s, the uncovered interest parity pricing model would not be expected to work well prior to the float. Since my primary objective is to understand the determination of the real exchange rate during the floating rate period, I generate the implied rational expectations real exchange rate beginning in 1976.2. This particular date draws upon a suggestion by Hansen and Hodrick (1982). They argued that after the 1973 breakdown of the Bretton Woods system, the public had expected a return to some form of pegged exchange rates and that the flexible exchange rate regime only became fully credible after the IMF's Articles on Exchange Rate arrangements were amended.

The estimated time path of the RE real dollar-DM rate are displayed in Figure 3.1.1. The observations are scaled to express exchange rate returns in percent per annum. Using the HP-filtered output gap, the RE real exchange rate path shows only a very loose connection with the real exchange rate data. The implied RE real exchange rate generated with the source constructed output gaps fares better. This implied RE path misses the real dollar depreciation of the late 1970s but captures the real appreciation through the mid 1980s and the subsequent depreciation. The implied turning point occurs in 1984.2 whereas in the data it occurs in 1985.1. The implied exchange rate then depreciates from 1984.3 to 1992.2 whereas in the data, the depreciation more or less continues until 1995.3.

The implied RE depreciation from 1984 to 1992 is much larger than that observed in the data. This occurs in part because there was a one-time upward spike in relative Ger-

[11] I employ a 4th order VAR for the inflation and output gap differentials, which the BIC rule suggested was appropriate.



man inflation in 1991.1 that coincided with a negative value of the relative German-US output gap. Because the VAR coefficients are estimated over the full sample, information about the spike is contained in these estimates. As time approaches 1991.1, agents are thus partially able to anticipate the spike. A large expected inflation differential combined with a low output gap differential leads people to expect, through the interest rate reaction function, an increase in the German interest differential and a real dollar depreciation.

From 1994.1 to 1997.3, both the implied RE real exchange rate and the data show a gradual real dollar appreciation. The final turning point for the implied RE real exchange rate leads the data somewhat. The turning point for the RE path is at 1997.3 and for the data is at 2000.4.

The implied RE real exchange rates are substantially more volatile than the data. The sample standard deviation of the 1-quarter real exchange rate return in the data is 20.06 percent whereas the implied return volatility is 76.83 percent using the source constructed output gap and is 36.81 percent when using the HP filter constructed output gap.

Table 2 quantifies the co-movements between the implied RE real exchange rate path and the data. The table reports results from regressing the data on the estimated RE real exchange rate. I run the regressions both in log levels and in percent changes at 1, 4, 8, and 16 quarter horizons. The estimated slope coefficients, regression R^2s and both the short-and-long horizon return correlations exhibit systematic co-movements both in the level as well as in the changes between the estimated rational expectations fundamental

Table 2: Regressions of Real Exchange Rate Data on RE Rate

	Regression slope	(s.e.)	corr	R^2
Source output gap				
Level	**0.214**	(0.071)	0.486	0.248
1-qtr return	**0.067**	(0.024)	0.256	0.068
4-qtr return	**0.111**	(0.059)	0.312	0.100
8-qtr return	**0.135**	(0.072)	0.349	0.124
16-qtr return	0.168	(0.120)	0.411	0.180
HP filter output gap				
Level	**0.313**	(0.097)	0.304	0.104
1-qtr return	0.083	(0.066)	0.151	0.024
4-qtr return	0.099	(0.123)	0.136	0.020
8-qtr return	0.087	(0.164)	0.108	0.012
16-qtr return	0.011	(0.243)	0.009	0.010

Notes: Bold face indicates significance at the 5 percent level in a one-sided test. Newey and West (1987) standard errors. Correlation is denoted by corr.

real exchange rate and the actual exchange rate.[12]

3.2 Learning Dynamics

Unless strong assumptions are made about the knowledge held by market participants regarding the underlying economic environment, the analysis of the RE real exchange rate path begs the question as to whether the observed real exchange rate data over the float could have been generated by the model. I now relax some of these informational assumptions by setting market participants in a learning environment. Agents know the relevant functions so there is no model misspecification but they do not know the parameter values in the policy rule or the coefficient values in the VAR that governs

[12] My results are qualitatively similar to those reported in Engel and West (2002) who undertake a related analysis. There are several differences between our analyses of the implied RE real dollar-DM rate. First, Engel and West work with a discounting model $(\gamma_s > 0)$. Second, they equate the actual interest differential to the target interest differential $\left(\widetilde{i}_t = \widetilde{i}_t^T\right)$, whereas my analysis takes account of central bank's desire to smooth interest rate changes. Third, they impose parameter values for the interest rate reaction functions drawn from estimates reported in the literature whereas mine are estimated from the sample being studied. Fourth, they employ monthly data. They measure goods prices by the CPI and output with industrial production. Also, they construct their output gap as the residual from an output regression on a quadratic trend. Finally, they do not consider the implications of the Volker regime shift and begin their analysis in 1979 under assumption of a single fixed regime.

actual inflation differentials and the output gap. In 'real time,' the public proceeds as a would-be econometrician who acquires knowledge of the relevant coefficients using least-squares learning rules [Evans and Honkapojian (2001)].

The observations generated by the learning model are obtained as follows. At time t, using observations through $t-1$ to obtain coefficient values of the bivariate VAR on the inflation differential and output gap differential (α_{t-1}, A_{t-1}), and the interest rate reaction functions $(\delta_{t-1}, \rho_{t-1}, \gamma_{\pi,t-1}, \gamma_{x,t-1})$, beliefs about the nominal interest differential and expected inflation are formed as[13]

$$\begin{aligned} \widetilde{i}_t &= \left(\delta_{t-1} + \left(1-\rho_{t-1}\right)\gamma_{\pi,t-1}e_1\alpha_{t-1}\right) \qquad (19)\\ &\quad + \left(1-\rho_{t-1}\right)\left(\gamma_{x,t-1}e_2 + \gamma_{\pi,t-1}e_1A_{t-1}\right)\widetilde{Y}_t + \rho_{t-1}\widetilde{i}_{t-1} + \widetilde{\eta}_t, \\ E_t\widetilde{\pi}_{t+1} &= e_1\left(\alpha_{t-1} + A_{t-1}\widetilde{Y}_t\right). \qquad (20) \end{aligned}$$

Given coefficient values $\beta'_{t-1} = \left(\beta_{0t-1}, \beta'_{1t-1}, \beta_{2t-1}, \beta_{3t-1}\right)$, agent's perceived law of motion for the real exchange rate draws on the conjectured form of the rational expectations solution,

$$q_t = \beta_{0t-1} + \beta'_{1t-1}\widetilde{Y}_t + \beta_{2t-1}\widetilde{i}_{t-1} + \beta_{3t-1}\widetilde{\eta}_t. \qquad (21)$$

The expected future real exchange rate is then obtained from the perceived law of motion,

$$E_tq_{t+1} = \beta_{0t-1} + \beta'_{1t-1}\left(\alpha_{t-1} + A_{t-1}\widetilde{Y}_t\right) + \beta_{2t-1}\widetilde{i}_t. \qquad (22)$$

The actual law of motion for the real exchange rate is obtained by substituting (20)−(22) into the real interest parity condition (12) which gives

$$q_t = \tau_{0t} + \tau'_{1t}\widetilde{Y}_t + \tau_{2t}\widetilde{i}_{t-1} + \tau_{3t}\widetilde{\eta}_t, \qquad (23)$$

where

$$\begin{aligned} \tau_{0t} &= \beta_{0,t-1} + \left(\beta_{1,t-1} - e_1 + \gamma_{\pi,t-1}\left(\beta_{2,t-1}+1\right)\right)\alpha_{t-1} + \left(1+\beta_{2,t-1}\right)\delta_{t-1}, \\ \tau'_{1t} &= \gamma_{x,t-1}e_2 + \beta_{2,t-1}\left(\gamma_{x,t-1}e_2 + \gamma_{\pi,t-1}e_1A_{t-1}\right) \\ &\quad + \left(\left(\gamma_{\pi,t-1}-1\right)e_1 + \beta'_{1,t-1}\right)A_{t-1}, \\ \tau_{2t} &= \rho_{t-1}\left(1+\beta_{2,t-1}\right), \\ \tau_{3t} &= 1+\beta_{2,t-1}. \end{aligned}$$

[13] Central banks know the monetary policy reaction functions. That is how they set $\widetilde{i}_t$. The public does not know the coefficient values and must estimate them. The recursive least squares estimates of the policy reaction functions are used in the actual law of motion to account for the possibility that the policy rule itself has evolved over time. The analysis accounts for this possibility.

The coefficients are then updated as follows:

1. For the VAR coefficients,

$$\begin{aligned} R_{v,t} &= R_{v,t-1} + g_t \left(\widetilde{Z}_{vt-1} \widetilde{Z}'_{vt-1} - R_{v,t-1} \right), && (24) \\ (b_{\pi,t}, b_{x,t}) &= (b_{\pi,t-1}, b_{x,t-1}) + g_t R_{vt}^{-1} \widetilde{Z}_{vt-1} \left[(\widetilde{\pi}_t, \widetilde{x}_t) - \widetilde{Z}'_{vt-1} (b_{\pi,t-1}, b_{x,t-1}) \right], && (25) \end{aligned}$$

   where g_t is the gain. In standard recursive least-squares estimation, the gain is decreasing with $g_t = 1/t$. Letting $(\alpha, A) = C(b_\pi, b_x)$ be the mapping from the regression to companion form coefficients, the VAR coefficients are updated according to the rule, $(\alpha_t, A_t) = C(b_{\pi,t}, b_{x,t})$.

2. The monetary policy reaction function coefficients are updated by letting $\phi' = (\delta, (1-\rho)\gamma_\pi, (1-\rho)\gamma_x, \rho)$ and $\widetilde{Z}'_{it} = \left(1, \widetilde{\pi}^e_t, \widetilde{x}_t, \widetilde{i}_{t-1}\right)$, where $\widetilde{\pi}^e_t = e_1(\alpha_{t-1} + A_{t-1}Y_t)$. Compactly restating the relative reaction function as $\widetilde{i}_t = \phi' \widetilde{Z}_{it} + \widetilde{\eta}_t$ allows the updating to proceed according to,

$$\begin{aligned} R_{i,t} &= R_{i,t-1} + g_t \left(\widetilde{Z}_{i,t-1} \widetilde{Z}'_{i,t-1} - R_{i,t-1} \right), && (26) \\ \phi_t &= \phi_{t-1} + g_t R_{i,t-1}^{-1} \widetilde{Z}_{i,t-1} \left(\widetilde{i}_t - \phi'_{t-1} \widetilde{Z}_{i,t-1} \right). && (27) \end{aligned}$$

3. The real exchange rate coefficients are updated by letting $\widetilde{Z}'_{qt} = \left(1, \widetilde{Y}'_t, \widetilde{i}_{t-1}, \widetilde{\eta}_t\right)$ and

$$\begin{aligned} R_{q,t} &= R_{q,t-1} + g_t \left(\widetilde{Z}_{q,t} \widetilde{Z}'_{q,t} - R_{q,t-1} \right), && (28) \\ \beta_t &= \beta_{t-1} + g_t R_{q,t-1}^{-1} \widetilde{Z}_{q,t} \left(q_t - \beta'_{t-1} \widetilde{Z}_{q,t} \right). && (29) \end{aligned}$$

Notice that the implied learning path employs observations only on the Taylor-rule fundamentals and does not directly employ observations on the real exchange rate.

The following considerations were taken into account in parameterizing the gain function. The standard declining gain ($g_t = 1/t$) is appropriate if the public believes that there is a single time-invariant structure. In this case, the learning model converges to the rational expectations equilibrium under standard regularity conditions. On the other hand, if the public believes that a regime change occurred at date t', then it make sense to reset the gain at the time of the known break point ($g_t = 1/(t - t' + 1)$ for $t \geq t'$). A third possibility is that the public understands that they are operating in a continually changing environment but they may not know when or if the regime changes have occurred. In this case, it makes sense to employ recursive least squares with a constant gain specification as in Orphanides and Williams (2003). Under a constant gain, the least squares coefficients do not converge to fixed values.

The international finance environment has been subject to several potential sources of parameter instability over the past three decades. In addition to the shift in monetary policy reaction functions discussed above, I allow for two additional sources of structural instability. These include the German reunification (1990.3) and the breakdown of the European Monetary System following the 1992 crisis. To allow for the potential importance of these events, I consider the following alternative specifications of the gain.

Gain type 1: Constant gain with $g = 0.02$. This is the value assumed by Orphanides and Williams (2003), who calibrated the gain to the expectations of professional forecasters.

Gain type 2: Decreasing gain $g_t = 1/t$ throughout the entire sample.

Gain type 3: Decreasing gain that is reset at 1979.3 to coincide with the change in monetary policy.

Gain type 4: Decreasing gain that is reset both at 1979.3 and at 1990.3, the time of German reunification.

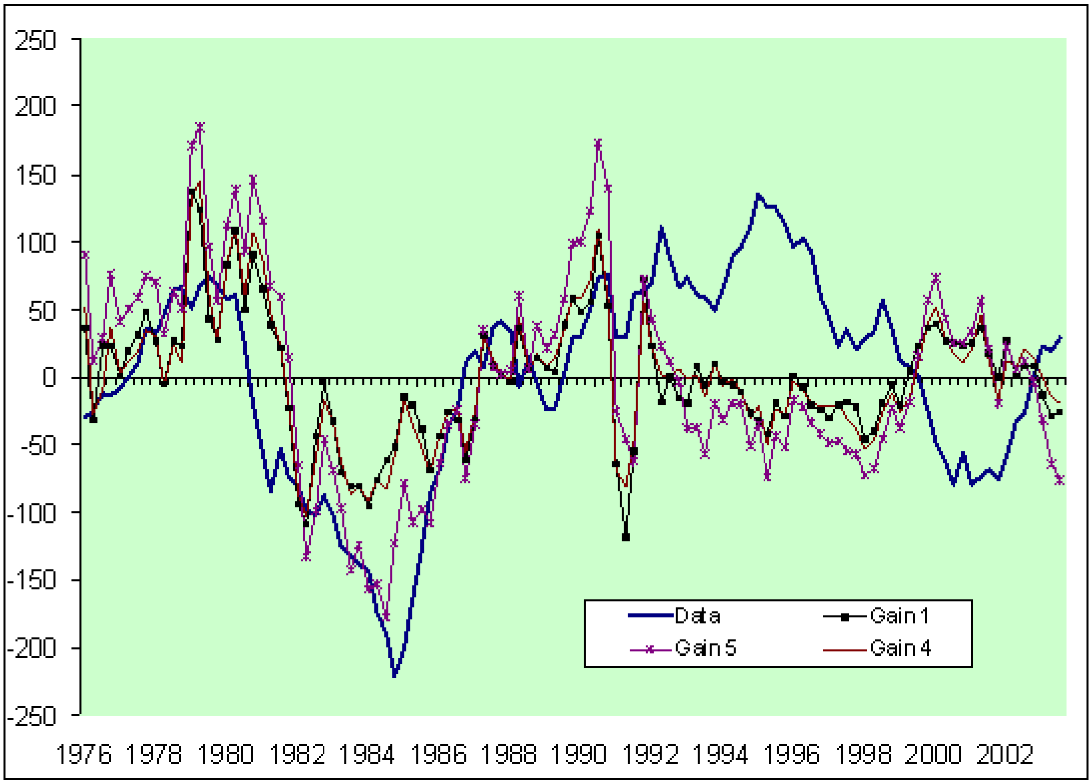
Gain type 5: Decreasing gain that is reset at 1992.3 to coincide with the European Monetary System crisis.

As in the analysis of the rational expectations path, I generate the implied learning real exchange rate beginning in 1976.2. Pre-sample observations during the float (beginning in 1973) are employed to estimate initial values of the least-squares coefficients and associated moment matrices. The learning paths associated with the alternative gain specifications are qualitatively very similar. To avoid excessive clutter, Figure 4 plots the implied learning paths only for gain specifications 1,4, and 5 generated with the output gap defined by the source statistical agencies along with the exchange rate data.[14] Each of the learning paths exhibit, in varying degrees, the real dollar depreciation in the late 1970s, the great appreciation observed in the first half of the 1980s and the subsequent great depreciation.

The learning paths exhibit real dollar depreciation from 1976 through 1981.1 whereas the turning point in the data is 1980.1. The learning path for gain type 5 shows the real

[14]The learning paths associated with gain specifications 2 and 3 are suppressed to reduce clutter on the graph. Learning paths with the output gap as the deviation from the HP trend are not presented. While the HP trend may be a reasonable retrospective detrending device, due to the truncation of the HP filter at the endpoints of the sample, it is not appropriate to assume that the retrospectively constructed gap is what the public believed the output gap to have been at the time. To employ the HP trend, one would have to compute the HP gap recursively.

Figure 4: Implied learning paths and the data for the real dollar-DM rate for alternative gain specifications. Output gap constructed at source.



dollar appreciating through 1984.3, marking a turning point two quarters prior to that observed in the data (1985.1). From this point, the real value of the dollar in the data falls until 1988.1, gains for a year then more or less trends downward until 1995.2. The implied learning path trends with the data from 1985 but unlike the implied RE path does not exaggerate the depreciation of 1992.1.

Table 3 reports regressions of the real exchange rate data on the alternative learning exchange rates. The correlation between the data in levels and the alternative implied learning exchange rates range from 0.304 (constant gain) to 0.380 (gain type 3). The correlations of quarterly rates of change range from 0.05 to 0.07 whereas the correlations of log changes at the 16 quarter horizon range from 0.51 to 0.56. In comparison to Table 2, it can be seen that the regressions on the implied RE real exchange rate exhibit higher R^2 values but the slope coefficients are smaller because the RE exchange rate is so much more volatile than the implied learning exchange rates. At short horizons, the RE depreciation exhibits higher correlation with the depreciation observed in the data, but the slope coefficients are not significant at longer horizons. This pattern is reversed for the learning paths where the long-term trends are better explained by the learning model. Here, the slope coefficients are not significant at the 5 percent level in the 1-quarter depreciation regressions but are all significant at the 16-quarter horizon.

Figure 6 compares the estimated RE path, the constant gain learning path and the data. There are several differences between the RE and the learning paths. First, the learning path produces real exchange rate volatility that is a much closer match to that in the data. Second, the learning path captures the 1976-1981 real dollar depreciation better than the estimated rational expectations path. Third, while both sets of estimates capture the great appreciation and the great depreciation of the 1980s, the estimated rational path predicts too much of a depreciation from 1985 to 1991 whereas the learning path predicts not enough of a depreciation. Both estimates exhibit the turning points in 1991.1 and 1991.3 found in the data. From about 1994 onwards, the qualitative dynamics of the estimated rational path and the learning path are not substantially different.

4 Conclusion

Standard open economy models predict that the exchange rate is determined by differences in the levels of macroeconomic variables. The traditional focus on standard macro fundamentals in exchange rate determination has perhaps led to a rush of judgment about the irrelevance of macro-modeling of exchange rates. In contrast, the fundamental determinants of the exchange rate are relative expected inflation gaps and relative output gaps when central banks conduct monetary policy by setting interest rates according to Taylor rules.

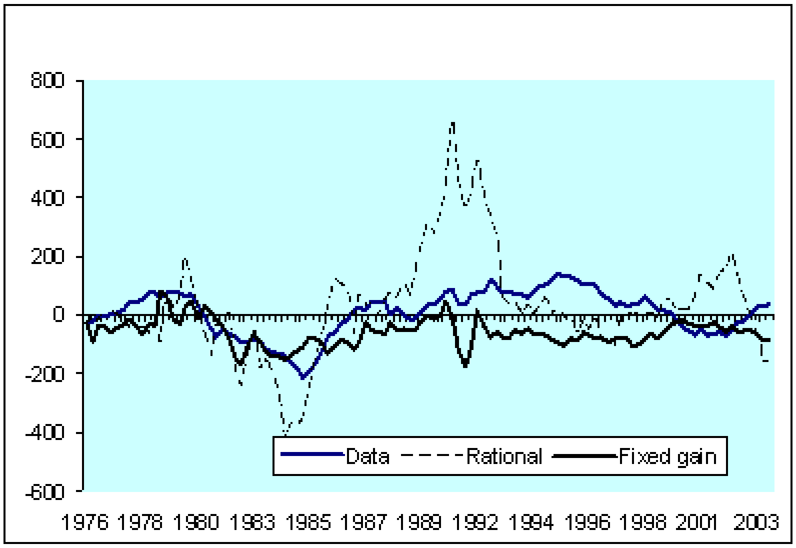
This paper has presented evidence that the real dollar-DM exchange rate is linked to Taylor rule fundamentals. I presented evidence that the interest differential can be modeled as a differential Taylor rule. Market participants were set in a learning environment where coefficients of the Taylor rule changed over time. This simple framework provides a reasonably good macro-fundamentals driven explanation of the great appreciation and the subsequent great depreciation of the 1980s. While alternative approaches based on multiple equilibria (e.g., Flood and Rose (1999)) or micro market structure (Lyons and Evans (2003)) or are worthwhile avenues to pursue, the analysis in this paper suggests that additional work in the macroeconomic context is worthwhile.

Table 3: Regressions of the real dollar-DM rate on the implied learning real exchange rate in log levels and percent changes. Output gap constructed at source.

		Gain Specification				
		1	2	3	4	5
Level	slope	**0.507**	**0.516**	**0.381**	**0.392**	**0.543**
	(s.e.)	(0.258)	(0.263)	(0.189)	(0.187)	(0.260)
	corr	0.304	0.321	0.370	0.380	0.337
	R^2	0.104	0.115	0.149	0.156	0.125
1-qtr return	slope	0.029	0.023	0.032	0.037	0.025
	(s.e.)	(0.070)	(0.071)	(0..059)	(0.060)	(0.072)
	corr	0.049	0.039	0.064	0.072	0.040
	R^2	0.003	0.002	0.005	0.006	0.002
4-qtr return	slope	0.118	**0.150**	**0.183**	**0.188**	**0.159**
	(s.e.)	(0.094)	(0.088)	(0.087)	(0.087)	(0.088)
	corr	0.115	0.148	0.231	0.238	0.156
	R^2	0.014	0.023	0.055	0.058	0.026
8-qtr return	slope	0.331	**0.373**	**0.323**	**0.326**	**0.379**
	(s.e.)	(0.221)	(0.212)	(0.172)	(0.173)	(0.210)
	corr	0.242	0.281	0.346	0.350	0.286
	R^2	0.060	0.080	0.122	0.125	0.084
16-qtr return	slope	**0.756**	**0.750**	**0.484**	**0.500**	**0.787**
	(s.e.)	(0.304)	(0.296)	(0.207)	(0.199)	(0.275)
	corr	0.510	0.528	0.543	0.556	0.549
	R^2	0.273	0.292	0.308	0.323	0.315
One-quarter return volatility		Gain specification				
	Data	1	2	3	4	5
	20.060	34.207	33.248	40.055	39.747	33.178

Notes: Bold face indicates significance at the 5 percent level in a one-sided test. Newey and West (1987) standard errors. Correlation is denoted by corr.

Figure 5: Implied rational, learning, and actual real dollar-DM exchange rate.



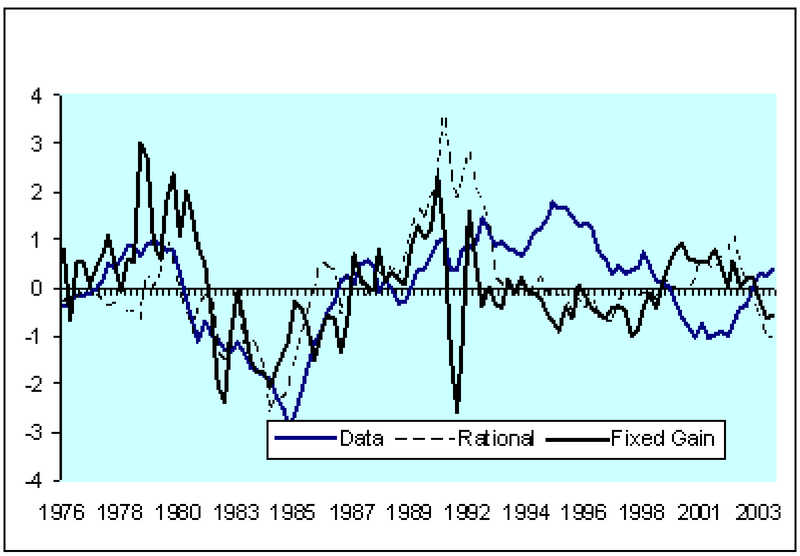


Figure 6: Standardized values of implied rational, learning, and actual real dollar-DM exchange rate.

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