Delayed Overshooting: The Case for Information Rigidities

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Abstract

We reconsider the delayed overshooting puzzle through the lens of a New Keynesian model with information rigidities. In the model, market participants do not directly observe the natural rate of interest and learn from unanticipated shifts in monetary policy about the state of the economy. We estimate the model and find that it can account for the joint responses of spot and forward exchange rates, excess returns, and macroeconomic indicators to monetary policy shocks. Our results suggest that information rigidities are important for understanding exchange rate dynamics.

Keywords: exchange rate, forward exchange rates, excess return, UIP puzzle, monetary policy, information effect, information rigidities
JEL-Codes: F31, E43

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1 Introduction

About 45 years ago, Dornbusch (1976) put forward a seminal account of exchange rate dynamics. In response to a contractionary monetary policy shock, Dornbusch argued, the exchange rate appreciates on impact, followed by a depreciation in subsequent periods. This overshooting hypothesis has been highly influential in international macroeconomics, and is supported by modern, micro-founded DSGE models (Galí, 2015). Alas, the empirical evidence in favor of overshooting is slim. While the exchange rate appreciates on impact following identified monetary policy shocks, it typically appreciates further in subsequent periods and starts to depreciate only much later, a finding that has been dubbed the "delayed overshooting puzzle" (Eichenbaum and Evans, 1995; Scholl and Uhlig, 2008).

What accounts for the sluggish response of the exchange rate to monetary policy shocks? In order to address this question, we build on the insight that expectations respond only sluggishly to macroeconomic shocks due to information rigidities (Coibion and Gorodnichenko, 2012, 2015). This matters for the adjustment of the exchange rate, because in Dornbusch's perfect-foresight account, expectations adjust instantaneously, consistent with conventional full-information rational expectations (FIRE). In response to a monetary policy shock, agents expect the exchange rate to appreciate in the long run. In the short run, agents expect the exchange rate to depreciate, as this ensures that the uncovered interest parity (UIP) condition holds. For expectations regarding the short and long run to be compatible, the exchange rate must overshoot on impact.

In the first part of the paper, we establish evidence on the exchange rate effects of monetary policy shocks that is suggestive for an important role of information rigidities. Specifically, we obtain three results regarding the response of the dollar to narratively identified US monetary policy shocks (Romer and Romer, 2004; Coibion et al., 2017). First, we confirm that the dollar appreciates only gradually against major currencies. Second, the impact response of forward exchange rates is flat across horizons. This is suggestive for information rigidities because—absent changes in the risk premium—changes in forward rates reflect changes of the exchange rate that are expected to occur in the future. A flat impact response of forward rates is thus consistent with the notion that the forthcoming appreciation takes market participants by surprise—which should not be the case under FIRE. Third, following monetary policy shocks, the dollar carries an excess return against major currencies which is persistent but dissipates over time. Excess returns and the concomitant departure from UIP are suggestive for a departure from FIRE. Moreover, the fact that excess returns dissipate over time suggests that the departure from FIRE is only transitory—consistent with expectations formation that is affected by information rigidities (Coibion and Gorodnichenko, 2012).

In the second part of the paper, we show that a small-scale New Keynesian model with information rigidities can account for the evidence. In the model, the central bank tracks the natural rate of interest, but subject to errors, that is, monetary policy shocks. We depart from full information by assuming that private agents do not observe the natural rate of interest, nor monetary policy shocks, directly. However, expectations formation is rational, because agents learn from observing the behavior of the central bank by using the Kalman filter. Whenever the central bank adjusts the policy rate beyond what the observed level of inflation calls for, agents cannot initially distinguish whether this represents a change in the natural rate or a monetary policy shock. The fact that central bank action reveals inside information to the private sector about the state of the economy goes back at least to Romer and Romer (2000). Recently, the "signal channel" of monetary policy and its "information effect" have featured prominently in empirically successful accounts of the monetary transmission mechanism in closed-economy models (Melosi, 2017; Nakamura and Steinsson, 2018).

To understand why our model can account for the evidence regarding exchange rate dynamics, consider first what happens in the FIRE benchmark. In response to a monetary policy shock, the exchange rate appreciates and displays overshooting, as in Dornbusch (1976). In contrast, following a rise in the natural rate that signals potential output growth, the exchange rate depreciates. In the presence of information rigidities, market participants cannot initially distinguish between monetary policy shocks and changes in the natural rate. Hence, the impact response of the exchange rate to a monetary policy shock is muted relative to the FIRE benchmark. In line with the evidence, this also implies that impact forward exchange rates remain flat across horizons, because agents cannot initially distinguish whether in the future, the exchange rate is going to appreciate or depreciate. As new information arrives over time, agents become better able to distinguish between monetary policy shocks and changes in the natural rate. Following a monetary policy shock, agents thus attach more weight over time that in the future, the exchange rate is going to appreciate. Because the exchange rate is a forward looking variable, this implies an immediate appreciation triggered by the arrival of new information. Following a modest impact response, the model thus predicts that the exchange rate appreciates further in subsequent periods—consistent with delayed overshooting. Moreover, the joint occurrence of gradual appreciation and high domestic interest rates gives rise to excess returns on the domestic currency and implies a departure from UIP. However, in line with the evidence, the model also predicts that excess returns arise only temporarily, as they dissipate with the arrival of new information.

We are not the first to stress that information frictions matter for exchange rate dynamics following monetary policy shocks. For example, Gourinchas and Tornell (2004) find that delayed overshooting can be explained by a model in which investors have systematically distorted beliefs about future interest rate differentials. What is new in our analysis is that investors are fully rational but merely lack full information about the state of the economy. As a result, while expectations formation in our framework is sluggish, expectations are not permanently misaligned from FIRE. We show that this is essential for the model to be able to account jointly for the behavior of the exchange rate, of forward rates and of excess returns in response to monetary policy shocks.

Our model also permits a deeper look at the violation of UIP following monetary policy shocks. On the one hand, the model reproduces the empirical fact that UIP fails temporarily in response to the shock. On the other hand, the model implies that UIP holds conditional on the information available to market participants. Intuitively, a change in the natural rate triggers a series of excess returns on foreign currency in the model—contrary to monetary policy shocks, which trigger a series of excess returns on domestic currency. Recall that in the model, agents cannot initially distinguish whether a policy rate rise reflects a monetary policy shock or a change in the natural rate. This implies that excess returns are equal to zero on average. Equivalently, excess returns are equal to zero in expectations, conditional on the information available to market participants. They can therefore not be exploited, in real time, by market participants in our model.

This also implies that, unconditionally, excess returns are equal to zero in our framework. It follows that we cannot account for unconditional violations of UIP, which have been documented extensively following Fama (1984) and others. Typically, unconditional UIP violations are explained by invoking either financial frictions (Farhi and Maggiori, 2018; Bacchetta and van Wincoop, 2010), risk premiums (Benigno et al., 2012; Lustig and Verdelhan, 2007), or departures from rational expectations (Froot and Frankel, 1989; Burnside et al., 2011). On the other hand, this literature may not speak to violations of UIP conditional on monetary policy shocks. This is because, in a model that predicts UIP to fail unconditionally, UIP may still be satisfied conditional on shocks (Faust and Rogers, 2003).[1] We thus consider our analysis of information rigidities as a natural complement to the literature which seeks to account for unconditional departures from UIP. Developing a framework which can jointly account for unconditional violations of UIP, as well as for transitory violations of UIP conditional on monetary policy shocks, remains a challenge for future research.[2]

[1] For instance, in Benigno et al. (2012), UIP fails unconditionally due to time-varying uncertainty. However, conditional on monetary policy shocks, UIP holds and the exchange rate overshoots. Intuitively, this happens because risk premiums are not much affected by monetary policy shocks in Benigno et al. (2012). Faust and Rogers (2003) elaborate on the difference between conditional and unconditional failures of UIP.

[2] The analysis in Bacchetta and van Wincoop (2019) shows that infrequent portfolio adjustment due to financial frictions can explain both conditional and unconditional UIP violations, as well as delayed overshoot-

Our empirical analysis is based on the narratively-identified monetary policy shocks due to Romer and Romer (2004) and Coibion et al. (2017). These shocks are unobserved in real time as identification hinges on the Fed's Greenbook which is published with a delay of five years only. As explained above, the fact that monetary policy shocks are not directly observed is the key feature of our model. As of late, a number of contributions have used high-frequency data to identify interest rate surprises following the pioneering work of Kuttner (2001), Gürkaynak et al. (2005) and Gertler and Karadi (2015). These surprises raise interesting questions regarding their information content (Jarociński and Karadi, 2020; Miranda-Agrippino and Ricco, 2020). What is important from our perspective is that these surprises, by their very nature, are observed by market participants in real time. Our model thus implies that excess returns are equal to zero conditional on interest rate surprises, and there is indeed evidence in support of this model prediction (Rüth, 2020). Our model is also consistent with evidence presented in Gürkaynak et al. (2020) and Stavrakeva and Tang (2019), who report that following interest rate surprises, the exchange rate may depreciate on impact. In our model, this happens if information rigidities are sufficiently severe. In related work, Schmitt-Grohé and Uribe (2020) identify transitory and permanent monetary policy shocks by combining short- and long-run restrictions in a structural VAR analysis. They find that conditional on these shocks, UIP fails, but only temporarily. This is consistent with our framework, because these shocks cannot be immediately distinguished by market participants.

The remainder of the paper is structured as follows. In the next section we describe our data and our empirical strategy and establish evidence on the dynamics of the dollar triggered by US monetary policy shocks. Section 3 introduces the New Keynesian open-economy model with information rigidities and presents details how we bring it to the data. Section 4 inspects the mechanism that operates at the heart of the model. A final section concludes.

2 Empirical evidence

In this section, we establish new evidence on how the exchange rate adjusts to monetary policy shocks. We focus on the response of the dollar (USD) to US monetary policy shocks, narratively identified by Romer and Romer (2004) and, more recently, by Coibion et al. (2017). After introducing our data and empirical strategy, we present our main results. We find, first, that the USD appreciates gradually following monetary policy shocks. Second, on impact, the response of forward exchange rates is flat across tenors. Third, the dollar carries an excess return after the shock, which dissipates slowly over time.

ing. However, their account relies on a failure of *covered* interest parity. As we discuss in the main text, there is little evidence that covered interest parity fails in our sample period.

2.1 Data and empirical strategy

For our baseline specification, we use quarterly data for the period 1976Q1 until 2008Q4, that is, our sample starts after the Bretton Woods system had been completely abandoned and ends before the financial crisis and the ensuing low interest-rate period. We estimate the response of the bilateral USD-GBP (GBP denoting the British pound) exchange rate in our baseline, because in this case, as we explain below, we are able to compute forward exchange rates for long horizons. Still, we make sure that our results also hold for other bilateral exchange rates, as well as for the narrowly defined effective exchange rate as compiled by the Bank for International Settlements (BIS).[3] In what follows, we use s_t to denote the log of the spot exchange rate and define it as the price of foreign currency in USD, such that a decline of s_t represents an appreciation of the USD.

The construction of monetary policy shocks is explained in detail in Romer and Romer (2004). Here we summarize the main idea. In a first step, Romer and Romer construct a time series for the change in the intended federal funds rate around FOMC meetings on the basis of narrative sources. In a second step, these changes are purged of the component that may be caused by the Fed's assessment of current economic conditions as well as of the economic outlook, as captured by the Fed's Greenbook. For this purpose Romer and Romer regress the change of the intended federal funds rate on the Greenbook forecasts for inflation, real output growth, and the unemployment rate. The residual of this regression, to which we refer as u_t below, captures non-systematic shifts in policy, that is, monetary policy shocks. Because the Greenbook is published only with a five year delay, u_t is not directly observable by market participants. In this regard, narratively-identified monetary policy shocks differ from interest rate surprises identified based on high-frequency data, which are immediately observable by market participants. We discuss this distinction and its implications in Section 4.4 in some detail.

We use local projections to directly estimate the impulse response of various exchange rates to monetary policy shocks, as in Coibion et al. (2017). Formally, our empirical model is given by the following expression:

$$s_{t+h} - s_{t-1} = c^{(h)} + \sum_{j=1}^{J} \alpha_j^{(h)} (s_{t-j} - s_{t-j-1}) + \sum_{k=0}^{K-1} \beta_k^{(h)} u_{t-k} + \varepsilon_{t+h}. \tag{2.1}$$

In this specification, we estimate the response of the spot rate s_{t+h} relative to the pre-shock level s_{t-1}. In this way we account for a possibly permanent effect of monetary policy shocks on the exchange rate (Stock and Watson, 2018). Our specification includes J lags of the exchange

[3] Our data source for bilateral exchange rates is datastream.

rate and K lags of the shock. Since we work with quarterly observations, in our baseline we set $J = 4$ and $K = 4$. However, our results are robust across alternative specifications for J and K. In our empirical model (2.1), $c^{(h)}$ is a constant for horizon h and ε_{t+h} is an iid error term with zero mean. We compute heteroscedasticity and autocorrelation consistent standard errors as in Newey and West (1987).[4]

Turn next to the forward exchange rate. We use f_t^h to denote the tenor-h forward exchange rate at time t, that is, the USD price in period t of foreign currency to be delivered in period $t + h$. Forward exchange rates are available from a number of sources, but typically only for selected tenors (or horizons). We therefore impute the USD-GBP forward exchange rate for horizons $h = \{1, \ldots, 20\}$, based on estimates of yield curves for GBP-denominated bonds and USD denominated bonds.[5] Specifically, assuming that covered interest rate parity (CIP) holds, we recover f_t^h from the following relation:

$$s_t - f_t^h = i_t^{h,\pounds} - i_t^h, \tag{2.2}$$

where i_t^h denotes the period-t interest rate on USD denominated bonds maturing in period $t+h$, and $i_t^{h,\pounds}$ the counterpart denominated in GBP. There is ample evidence that CIP holds, except in periods of substantial stress in financial markets. For example, Amador et al. (2019) and Du et al. (2018) document that CIP held well before the financial crisis of 2008, whereas deviations from CIP started to emerge during and in the aftermath of the financial crisis, a period which we exclude from our baseline sample.

We complement forward exchange rates that we extract from the yield curve with market-based forward exchange rates. This is for two reasons. First, estimates for the short end of the yield curve are not always available in the early part of the sample. Second, we use market-based forward exchange rates to assess the viability of our imputed forward exchange rates based on yield curve data. We use two sources for market-based forward exchange rates. First, Thomson Reuters provide three months-ahead forward exchange rates (f_t^1 in our notation) for the period 1976-1978. For the period after 1979, we obtain forward rates, f_t^h, for $h \in \{1, 2, 4\}$, from the Bank of England.[6]

Figure 1 shows two examples of our forward rate data, the two-quarters-ahead and the four-quarters-ahead forward rates. It shows that the forward rates implied by the yield curve

[4]Note also that the shocks u_t are generated regressors. Pagan (1984) shows that the standard errors on the generated regressors are asymptotically valid under the null hypothesis that the coefficient is zero; see also the discussion in Coibion and Gorodnichenko (2015).

[5]For the US yield curve, updates of the estimates of Gürkaynak et al. (2006) are available at a website maintained at the Federal Reserve Board. For the UK we access the historical data via a website maintained at the Bank of England. We construct the forward rates at monthly frequencies and aggregate to quarterly frequency afterwards.

[6]The data are available at https://www.bankofengland.co.uk/boeapps/database/.

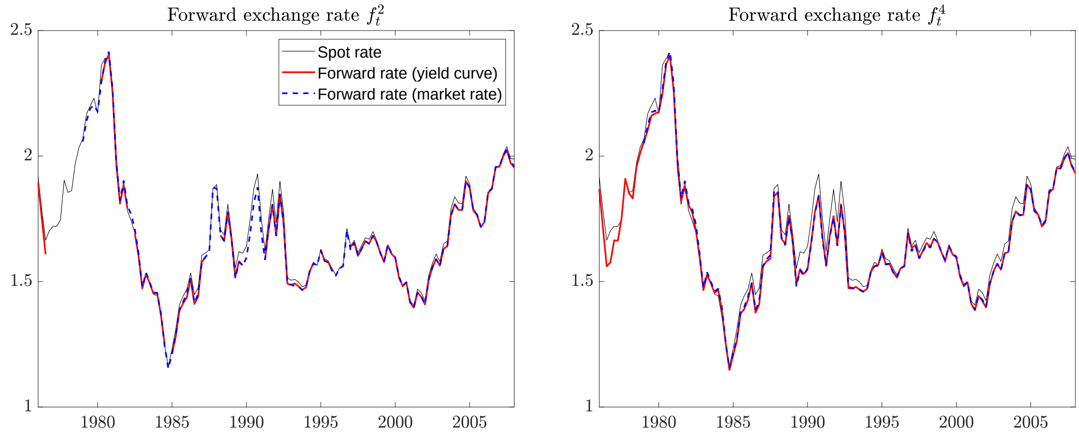

Figure 1: USD-GBP forward exchange rates, two-quarters-ahead (f_t^2) and four-quarters-ahead (f_t^4), imputed from yield curve data versus market-based. For comparison, the black solid line shows the spot exchange rate.

data and the market-based forward rates, in periods where both are available, line up very well. This lends support to our methodology. To the extent that there are gaps in the time series based on yield curve data, we simply close them by using market-based forward rates. The figure also contrasts the forward and the spot exchange rates. According to equation (2.2), the gap between the two captures the USD-GBP interest rate differential.

To study the response of forward exchange rates following monetary policy shocks, we rely again on local projections. Specifically, we use a variant of model (2.1):

$$f_t^h - s_{t-1} = c^{(h)} + \sum_{j=1}^{J} \alpha_j^{(h)} (s_{t-j} - s_{t-j-1}) + \sum_{k=0}^{K-1} \beta_k^{(h)} u_{t-k} + \varepsilon_{t+h}. \tag{2.3}$$

In this specification, we estimate the *impact* response of the forward exchange rate for various horizons, in each case relative to the pre-shock level of the spot exchange rate. Hence, our setup mimics specification (2.1) as closely as possible—we merely replace future spot rates with current forward rates for each horizon h.

We also study the response of excess returns on GBP-denominated over USD-denominated bonds, conditional on monetary policy shocks. We use λ_t^h to denote the (ex-post) excess return of GBP over USD over an h-period horizon:

$$\lambda_t^h \equiv (i_{t-h}^{h,£} - i_{t-h}^h) + s_t - s_{t-h}. \tag{2.4}$$

The excess return corresponds to the return from shorting the USD, going long in GBP in period $t - h$, and receiving the proceeds from this transaction in period t. The excess return represents, in other words, the ex-post deviation from uncovered interest parity (UIP).

Equivalently, using equation (2.2) to substitute for the interest differential in (2.4), the excess return can be written as

$$\lambda_t^h = s_t - f_{t-h}^h. \tag{2.5}$$

Recall that equation (2.2) holds as long as covered interest parity (CIP) is satisfied. Therefore, as long as CIP holds, the excess return can equivalently be seen as a prediction error in the forward exchange market. The USD carries an excess return ($\lambda_t^h < 0$), whenever it is more appreciated than had been anticipated by the forward exchange market in period $t - h$. Notice that, as with the forward exchange rate, there exist multiple excess returns, one for each horizon $h \geq 1$.

Empirically, we measure excess returns directly by using equation (2.5), as we have access to the necessary forward rate data. This is in contrast to previous studies, which measure the response of excess returns as a residual given the estimated impulse responses of the variables that enter the UIP condition (e.g., Scholl and Uhlig, 2008; Rüth, 2020). Instead, we provide direct estimates of the response of excess returns to monetary policy shocks. For this purpose, we rely on the following specification:

$$\lambda_t^h = c^{(h)} + \sum_{j=1}^{J} \alpha_j^{(h)} \lambda_{t-j}^h + \sum_{k=0}^{K-1} \beta_k^{(h)} u_{t-k} + \varepsilon_{t+h}. \tag{2.6}$$

Compared to models (2.1) and (2.3), the distinguishing element in model (2.6) is that λ_t^h enters in levels, rather than in first differences. This reflects the fact that, according to theory, the excess return is not a trending variable.

Last, we also estimate the response of the federal funds rate in response to monetary policy shocks. To do so, we use the model (2.6) and replace λ_t^h with the (quarterly) nominal interest rate $i_t \equiv i_t^1$.

2.2 The exchange rate response to monetary policy shocks

Figure 2 shows the impulse response to a monetary policy shock. The shock is normalized so that the federal funds rate increases initially by 100 basis points. The solid lines represent the point estimate, while shaded areas indicate 68 percent and 90 percent confidence bands. The horizontal axis measures time in quarters. The vertical axis measures deviations from the pre-shock level, in percentage points for the federal funds rate and in percent for the other variables.

The upper-left panel shows that the federal funds rate rises persistently for about 1.5 years, before it gradually converges back to zero. The upper-right panel shows the response of the spot exchange rate. Recall that the exchange rate measures the price of GBP in terms of

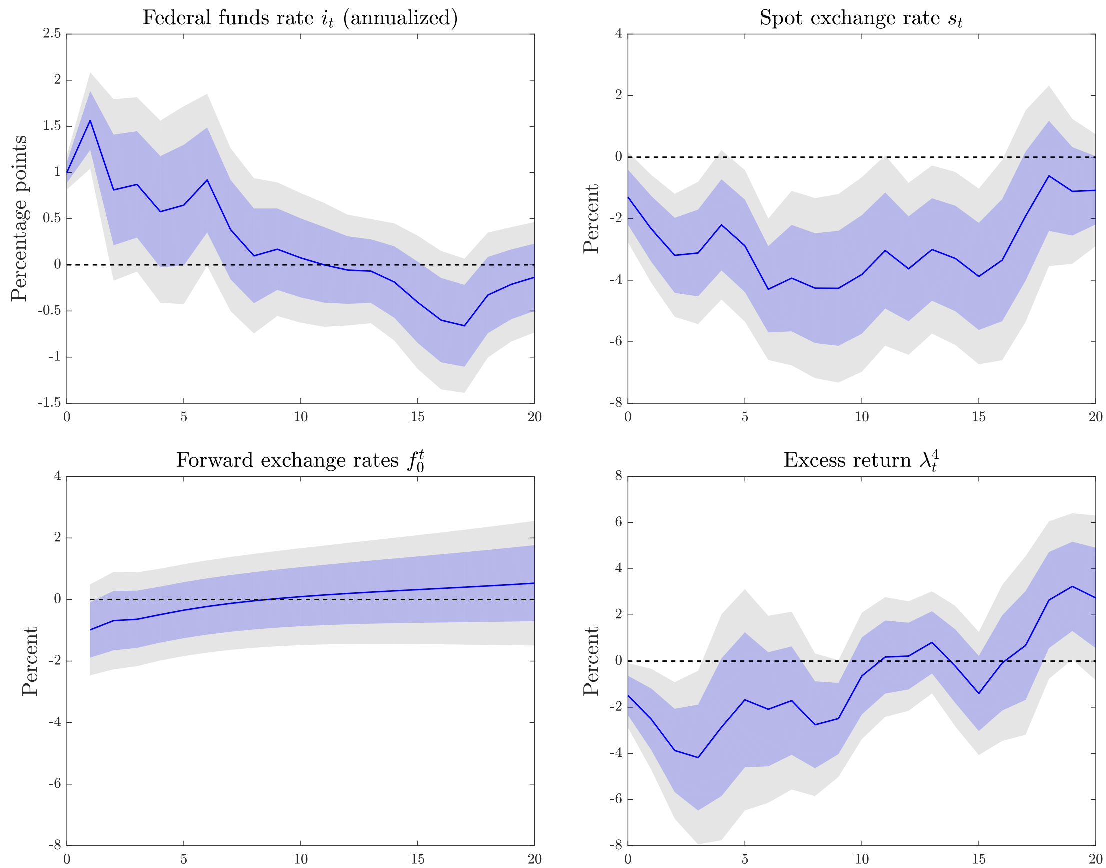

Figure 2: Adjustment to monetary policy shock, baseline specification. The empirical specification and data used is explained in Section 2.1. The solid lines represent the point estimate, while shaded areas indicate 68 percent and 90 percent confidence bands. The horizontal axis measures time in quarters. Vertical axis measures deviation from pre-shock level in percentage points (federal funds rate) or in percent (for the other variables).

USD. Hence, a decline represents an appreciation of the USD. We observe a significant impact response. The USD appreciates immediately by approximately 1.5 percent in response to the shock. However, the appreciation continues over time. Three years after the shock, the USD has gained some 4 percent value. Only after this period does the USD start to depreciate—the delayed overshooting established in earlier work (Eichenbaum and Evans, 1995; Scholl and Uhlig, 2008).

The lower-left panel shows the impact response of forward exchange rates f_0^h, for each horizon $h \in \{1, \dots, 20\}$. We find that forward exchange rates appreciate only at the short end, by about 1 percent and the response is only marginally significant. For longer horizons there is no response of forward rates on impact. This is in sharp contrast to the response of the spot exchange rate, which appreciates immediately and continues to appreciate over time. Hence, the impact response of forward exchange rates does not predict the forthcoming appreciation of the spot exchange rate over time.

Turn last to the excess return. The lower-right panel shows the response of the one-year-ahead excess return, λ_t^4. We highlight two main results. First, we find that the excess return is persistently negative.[7] Second, we find that the excess return converges back to zero over time. The violation of UIP following monetary policy shocks is thus only transitory. These results can be interpreted in light of equation (2.5). On the one hand, the fact that excess returns are negative reflects that forward exchange rates persistently under-predict the forthcoming appreciation of the USD. This is in line with the previous discussion about the different behavior of the spot and the forward exchange rate in response to the shock. On the other hand, the fact that excess returns dissipate over time implies that forward exchange rates gradually become a better predictor of the future spot exchange rate. The finding that forward exchange rates do not predict the forthcoming appreciation of the USD thus merely applies to the first periods after the shock. Instead, as time passes, the forward and spot rate responses become continuously more aligned.[8]

To summarize, our analysis first confirms that the exchange rate displays delayed overshooting in response to a monetary contraction. Second, our results are consistent with the notion that the forthcoming appreciation of the spot exchange rate takes market participants by surprise. Third, the discrepancy between spot and forward exchange rates is largest on impact, but disappears over time. As time elapses, in fact, the excess return vanishes, implying that the forward market predicts better the forthcoming adjustment of the USD.

2.3 Further evidence

We consider a number of alternative specifications and USD exchange rates in order to assess the robustness and scope of our results. To keep the exposition compact, we delegate the figures showing the results to Appendix A.

First, we estimate the response of the USD-GBP spot exchange rate on an alternative sample period. Recall that our baseline sample runs from 1976Q1–2008Q4. Kim et al. (2017) use a sign restriction approach to identify US monetary policy shocks and find that delayed overshooting is largely driven by the Volcker-disinflation period. For this reason, we consider

[7] By construction, in the first four quarters after impact ($t \in \{0, 1, 2, 3\}$), the excess return tracks exactly the response of the spot exchange rate and is therefore negative. This is because, in these quarters, the forward rate f_{t-4}^4 is predetermined and thus not affected by the shock (see equation (2.5)). However, even after the initial quarters, the excess return remains negative until about three years after the shock.

[8] As we highlight in the introduction, we focus on excess returns conditional on monetary policy shocks. They may converge to zero, even though excess returns are different from zero *unconditionally* as documented by a large literature following Fama (1984) and others. We discuss the relationship of conditional and unconditional violations of UIP in more detail in Section 4.3 below.

an alternative sample that starts in 1988. Because this sample is rather short, we use monthly rather than quarterly observations. Unlike Kim et al. (2017), but in line with Rüth (2020) and others, we find no evidence that the exchange rate response is much different in a sample that excludes the Volker-disinflation period (see left panel of Figure A.1).

In a second experiment, we extend the sample period to include observations up to 2012. This is the most recent data for which Romer-Romer shocks are available. Specifically, we use the series compiled by Breitenlechner (2018) which provides observations for the period after 2008. Again, we find that the basic adjustment pattern of the exchange rate is unchanged relative to our baseline (see right panel of Figure A.1).

Next, we verify that our results are not specific to the USD-GBP exchange rate, as we estimate the responses of the effective USD exchange rate and of the real exchange rate, both available at the BIS (see Figure A.2). Furthermore, we estimate the response of bilateral USD exchange rates of all remaining so-called G10 currencies.[9] Again, we find that adjustment dynamics are similar to the USD-GBP exchange rate shown in Figure 2. In particular, we find evidence for a gradual appreciation of the USD. In no instance do we observe an initial overshooting (see Figure A.3).

As explained above, we focus on the USD-GBP exchange rate in our baseline specification, because in this case we are able to compute forward exchange rates on the basis of existing (and easily accessible) yield-curve estimates. For the remaining G10 currencies, yield curve estimates are not easily available. However, even in this case, we can study market-based forward exchange rates which are available for 1- and 3-months tenors. Specifically, the Bank of England provides GBP-forward exchange rates at monthly frequency for 1 and 3-months tenors since 1976 for many G10 currencies.[10] Given these, we compute USD-forwards by multiplying the GBP-forwards with the USD-GBP forward exchange rate (see Burnside et al., 2010). For later periods we obtain direct observations for USD-forward exchange rates from datastream (BBI).[11]

We summarize our results in Table 1. The left panel shows the responses to a US monetary policy shock of both the spot exchange rate one month after impact (s_{t+1}) and the impact response of the forward exchange rate for a one month tenure (f_t^1). In the right panel, we compare the spot rate 3 months after impact (s_{t+3}) and the impact response of the forward

[9] The data is obtained from datastream (MSCI) and from the Bank of England.

[10] For some currencies, however, market-based forward rates are not available as early as 1976. For these currencies, we therefore restrict ourselves to a shorter sample.

[11] For EUR, we use USD-Deutsche Mark forwards from October 1983 to December 1998. For CHF, we obtain USD forwards from January 1986 onwards, for NOK and CAD from December 1984 onwards, for SEK from February 1985 onwards. For JPY, the series of the Bank of England starts only in June 1978; from October 1983, we obtain direct observations for USD forwards. For AUS and NZD, there are no forward data at the Bank of England. Here our sample starts in December 1984 only.

	1-month horizon			3-months horizon		
	s_{t+1}	f_t^1	λ_{t+1}^1	s_{t+3}	f_t^3	λ_{t+3}^3
GBP	-0.71 (0.30)	-0.44 (0.19)	-0.26	-1.10 (0.39)	-0.38 (0.19)	-0.72
CHF	-0.55 (0.38)	-0.72 (0.28)	0.17	-1.35 (0.51)	-0.63 (0.30)	-0.72
EUR	-0.74 (0.28)	-0.62 (0.25)	-0.12	-1.17 (0.48)	-0.53 (0.26)	-0.64
NOK	-0.63 (0.26)	-0.39 (0.22)	-0.24	-0.85 (0.33)	-0.30 (0.24)	-0.55
SEK	-0.38 (0.35)	-0.29 (0.30)	-0.09	-0.54 (0.45)	-0.26 (0.30)	-0.29
CAD	-0.34 (0.13)	-0.16 (0.08)	-0.18	-0.27 (0.12)	-0.12 (0.09)	-0.15
JPY	-0.60 (0.39)	-0.48 (0.36)	-0.12	-0.69 (0.52)	-0.37 (0.33)	-0.33
AUD	1.24 (1.23)	0.59 (1.24)	0.65	-3.12 (1.83)	0.70 (1.26)	-3.82
NZD	2.29 (1.43)	0.99 (1.00)	1.29	-1.44 (1.93)	0.99 (1.02)	-2.43

Table 1: Response of bilateral USD exchange rates to US monetary policy shock. Shown are the response of spot exchange rates and the impact response of forward exchange rates. Monthly observations for G10 currencies. Sample period: 1976M1–2008M12, except for JPY (starts in 1978:M6) and AUS and NZD (start in 1984:M12), which are based on a shorter sample. Standard errors are given in parentheses. More details are in the text.

with 3-months tenure (f_t^3). In each instance we also report the implied excess return, defined as the difference between spot and forward rate, according to equation (2.5). We find that for both tenures it is negative for almost all currencies reflecting a relatively weak response of the forward rate—in line with our findings for the USD-GBP exchange rates in our baseline.

Last, we also study how excess returns for G10 currencies against the USD evolve over time after a US monetary policy shock. For this purpose, we estimate the impulse responses of the one-quarter excess return (λ_t^1) and find for all currencies an adjustment pattern similar to what is shown for the baseline in the lower-right panel of Figure 2 above. Namely, we find that excess returns on foreign currency are initially negative (and positive for the USD), and dissipate over time (see Figure A.4).

3 The model

We now study how information rigidities alter the monetary transmission mechanism in an otherwise standard New Keynesian open-economy model. We also estimate the model and show that information rigidities are essential for the model to be able to account for the evidence established in Section 2.

3.1 Setup

Our point of departure is a version of the New Keynesian small-open economy model due to Galí and Monacelli (2005), which we modify to account for information rigidities. In the model, the central bank adjusts the policy rate to track the natural rate of interest, but subject to errors, that is, monetary policy shocks. We depart from FIRE by assuming that private agents do not directly observe potential output and the natural rate of interest, nor monetary policy shocks. Each time the central bank adjusts its policy rate, this reveals information about the state of the economy to the private sector, in line with recent imperfect information models in monetary economics (Melosi, 2017; Nakamura and Steinsson, 2018). Private agents learn about fundamentals gradually by using the Kalman filter, in line with recent insights about the way expectations are formed following macroeconomic shocks (Coibion and Gorodnichenko, 2012, 2015).

The environment underlying our model is standard. The domestic country is small such that domestic developments have no bearing on the rest of the world. In the domestic economy, monopolistically competitive firms produce a variety of goods which are consumed domestically as well as exported. The law of one price holds at the level of varieties. Prices are set in the currency of the producer and adjusted infrequently due to a Calvo constraint. Goods markets are imperfectly integrated as domestically produced goods account for a non-zero fraction of the final consumption good. The real exchange rate may deviate from purchasing power parity as a result. International financial markets are complete so that there is perfect consumption risk sharing between the domestic economy and the rest of the world.

Because the non-linear model as well as its first-order approximation are not affected by the presence of information rigidities, to save space, we delegate the exposition of the household and firm problem to Appendix B. In what follows, we provide a compact exposition of the approximate equilibrium conditions and discuss expectation formation in some detail.

3.1.1 Approximate equilibrium conditions

We approximate equilibrium dynamics in the neighborhood of the steady state. The structural parameters in the domestic economy are the same as in the rest of the world. The steady state is therefore symmetric. There is no inflation in steady state and international relative prices are unity. All variables are expressed in logs. Foreign variables are denoted with a star. They are constant because there are no shocks in the rest of the world, and because they are not affected by developments in the (small) domestic economy.

Inflation dynamics are determined by the New Keynesian Phillips curve:

$$\pi_t = \beta \mathbb{E}_t^{\mathcal{P}} \pi_{t+1} + \kappa (y_t - \mathbb{E}_t^{\mathcal{P}} y_t^n), \tag{3.1}$$

where π_t is inflation of domestically produced goods, y_t is output and y_t^n is potential output. We assume that private agents do not observe potential output directly. As a consequence, firms base their hiring decisions on their best guess for potential output, $\mathbb{E}_t^{\mathcal{P}} y_t^n$, rather than on potential output y_t^n itself. The superscript $\mathcal{P}$ of the expectation operator $\mathbb{E}_t^{\mathcal{P}}$ indicates that the information set of the private sector is restricted. We specify it below. $0 < \beta < 1$ is the time-discount factor and $\kappa > 0$ captures the extent of nominal rigidities.

A second equilibrium condition links output and the real exchange rate

$$\theta(y_t - y^*) = s_t + p^* - p_t, \tag{3.2}$$

where θ^{-1} denotes the intertemporal elasticity of substitution. Here, y^* denotes output in the rest of the world, s_t denotes the spot exchange rate, defined as the price of foreign currency expressed in terms of domestic currency, p_t is the price index of domestically produced goods (such that $\pi_t = p_t - p_{t-1}$) and p^* is the foreign price level. The composite term $s_t + p^* - p_t$ in expression (3.2) represents the country's terms of trade, which move proportionately to the real exchange rate in our model. Specifically, the real exchange rate is given by

$$q_t = (1 - \omega)(s_t + p^* - p_t), \tag{3.3}$$

where the degree of openness of the domestic economy is $0 \leq \omega \leq 1$. A value $\omega < 1$ indicates that the domestic economy is not fully open, or, equivalently, that there is home bias in consumption. An increase in s_t indicates a nominal depreciation of the domestic currency, whereas an increase in q_t indicates a depreciation in real terms. To obtain equation (3.2), we combine the market clearing condition for domestically produced goods with the risk-sharing condition implied by complete international financial markets (Backus and Smith, 1993). Equation (3.2) shows that a real depreciation goes together with increased demand for domestically produced goods.

The nominal exchange rate, in turn, is determined via the uncovered interest rate parity (UIP) condition

$$\mathbb{E}_t^{\mathcal{P}} \Delta s_{t+1} = i_t - i^*. \tag{3.4}$$

Here, i_t is the domestic short-term nominal interest rate, and i^* is the foreign counterpart. According to this condition, the exchange rate is expected to depreciate whenever domestic interest rates exceed foreign rates. We stress that the expected depreciation $\mathbb{E}_t^{\mathcal{P}} \Delta s_{t+1}$ is conditional on the information available to investors at time t.

In order to confront the model predictions with the evidence established in Section 2, we also define forward exchange rates and excess returns. The forward exchange rate f_t^h is the period-t price of foreign currency to be exchanged in period $t+h$. In our model, absence of arbitrage then implies

$$f_t^h = \mathbb{E}_t^{\mathcal{P}} s_{t+h}. \tag{3.5}$$

In our (linearized) model the forward rate equals the market-based expectations of the period-$t+h$ spot rate. Using equation (3.5) to substitute for the forward rate in equation (2.5) implies for the excess return:

$$\lambda_t^h = s_t - \mathbb{E}_{t-h}^{\mathcal{P}} s_t. \tag{3.6}$$

In other words, the excess return amounts to a forecast error in the foreign exchange market in our (linearized) model.

For monetary policy, we posit the following interest rate feedback rule

$$i_t = r_t^n + \phi \pi_t + u_t. \tag{3.7}$$

Here the central bank responds to inflation, where $\phi > 1$, in line with the Taylor principle. In addition, it adjusts the policy rate to track the natural rate r_t^n, but subject to errors u_t, that is, monetary policy shocks. As a consequence, an increase in i_t that is not accounted for by the term $\phi\pi_t$ represents either an increase of the natural rate or a monetary policy shock—in this way information rigidities impact the monetary transmission mechanism in our model, as we discuss in detail below.

We assume that the monetary policy shock follows an autoregressive process

$$u_t = \rho_u u_{t-1} + \varepsilon_t^u, \quad \varepsilon_t^u \sim \mathcal{N}(0, \sigma_u^2). \tag{3.8}$$

As in Melosi (2017), we thus model monetary policy inertia as a persistent monetary policy shock, rather than adding a smoothing component.

Finally, we turn to potential output and the natural real rate. We assume that potential output growth follows a first-order autoregressive process:

$$\Delta y_t^n = \rho_y \Delta y_{t-1}^n + \varepsilon_t^y, \quad \varepsilon_t^y \sim \mathcal{N}(0, \sigma_y^2), \tag{3.9}$$

where $0 \leq \rho_y < 1$. This process implies that a positive disturbance $\varepsilon_t^y > 0$ sets in motion a gradual increase of y_t^n to a permanently higher level. Potential output and the natural rate of interest are closely interlinked. We define the natural real rate as the real interest rate that would prevail absent price and information rigidities. In our model this implies

$$r_t^n \equiv (i_t - \mathbb{E}_t^{\mathcal{F}} \pi_{t+1})|_{\kappa=\infty} = \bar{r} + \theta \mathbb{E}_t^{\mathcal{F}} \Delta y_{t+1}^n = \bar{r} + \theta \rho_y \Delta y_t^n, \tag{3.10}$$

where $\bar{r} = -\log(\beta) > 0$ and where $\mathbb{E}_t^{\mathcal{F}}$ is the expectation operator under full information (in which case potential output is perfectly observed by private agents: $\mathbb{E}_t^{\mathcal{F}} y_t^n = y_t^n$). Equation (3.10) reveals that the natural rate is an exogenous variable, as it is a function of potential output only. It also reveals that when potential output y_t^n rises, the natural rate of interest increases temporarily, as this foreshadows a growing economy.

3.1.2 Information processing

We now describe how private agents filter the available information in order to learn about the state of the economy. Our first assumption is that all endogenous variables $\{p_t, y_t, s_t, i_t, q_t\}$ are perfectly observed by private agents at all times t. In contrast, we assume that potential output y_t^n and hence the natural rate (see equation (3.10)) are *not* directly observed by private agents. However, in each period t private agents learn about potential output in two ways.

First, there is a signal given by

$$\varsigma_{1,t} = y_t^n + \eta_t, \tag{3.11}$$

where $\eta_t \sim_{iid} \mathcal{N}(0, \sigma_\eta^2)$ represents stochastic noise. In the micro-foundation that we present in the Appendix, (log) potential output is linear in the level of total factor productivity (TFP). In principle, firms should be able to measure TFP from observing jointly the number of working hours and the level of production. However, we assume that firms are not able to infer TFP because there is time-varying effort per worker, unobserved by firms. Whenever output is low, firms cannot be sure whether this represents low effort or low TFP. However, firms receive a signal about the level of effort exerted by their workers—rewriting this in terms of potential output yields equation (3.11).

In addition, the private sector observes the central bank. In fact, because the central bank sets its policy rate with reference to the natural rate, a second signal about the natural rate and hence potential output (growth) is given by

$$\varsigma_{2,t} = r_t^n + u_t = \bar{r} + \theta\rho_y \Delta y_t^n + u_t. \tag{3.12}$$

The monetary policy shock u_t can thus be viewed as stochastic noise in the second signal. Note that, in equation (3.7), the endogenous variables i_t and π_t are perfectly observed by private agents, such that the realization of these variables does not appear in the signal (3.12). Indeed, the realization of i_t and π_t matters only insofar as it determines the realization of the signal, because of $\varsigma_{2,t} = i_t - \phi\pi_t$ in each period.[12] The key feature of this setting is that, whenever private agents observe a rise in the policy rate i_t (implying a rise in $\varsigma_{2,t}$), they do not know

[12] Alternatively, we may think of $\varsigma_{2,t}$ as being determined by the exogenous variables y_t^n and u_t, from equation (3.12), and the endogenous variables i_t and π_t adjusting such that $i_t - \phi\pi_t = \varsigma_{2,t}$ holds in equilibrium.

whether this represents a monetary policy shock or a rise in potential output and therefore the natural rate of interest.

Formally, the expectation operator $\mathbb{E}_t^{\mathcal{P}}$ can be written as $\mathbb{E}(\cdot|\mathcal{I}_t)$, conditional on information set $\mathcal{I}_t$, where $\mathcal{I}_t = \{p_t, y_t, s_t, i_t, q_t, \varsigma_{1,t}, \varsigma_{2,t}, \mathcal{I}_{t-1}\}$. The information set contains the history of all observable variables plus the history of all signals up to time t. We now describe how expectations are formed by private agents. Because both signals are linear functions of y_t^n and u_t, by assuming that expectations are rational, private agents solve the signal extraction problem by using the Kalman filter, as in Coibion and Gorodnichenko (2012).[13] An implication is that expectations adjust only sluggishly to the arrival of new information. Moreover, this setup implies that expectations are not permanently misaligned from FIRE. Both of these features are consistent with empirical evidence on how expectations adjust to macroeconomic shocks. The Kalman filter is represented by a state-space system, which consists of a transition equation

$$\begin{pmatrix} y_t^n \\ y_{t-1}^n \\ u_t \end{pmatrix} = \begin{pmatrix} 1+\rho_y & -\rho_y & 0 \\ 1 & 0 & 0 \\ 0 & 0 & \rho_u \end{pmatrix} \begin{pmatrix} y_{t-1}^n \\ y_{t-2}^n \\ u_{t-1} \end{pmatrix} + \begin{pmatrix} \varepsilon_t^y \\ 0 \\ \varepsilon_t^u \end{pmatrix} = F \begin{pmatrix} y_{t-1}^n \\ y_{t-2}^n \\ u_{t-1} \end{pmatrix} + \begin{pmatrix} \varepsilon_t^y \\ 0 \\ \varepsilon_t^u \end{pmatrix}$$

as well as of an observation equation

$$\begin{pmatrix} \varsigma_{1,t} \\ \varsigma_{2,t} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ \theta\rho_y & -\theta\rho_y & 1 \end{pmatrix} \begin{pmatrix} y_t^n \\ y_{t-1}^n \\ u_t \end{pmatrix} + \begin{pmatrix} \eta_t \\ 0 \end{pmatrix} = H \begin{pmatrix} y_t^n \\ y_{t-1}^n \\ u_t \end{pmatrix} + \begin{pmatrix} \eta_t \\ 0 \end{pmatrix}. \tag{3.13}$$

Solving the state-space system yields a recursive representation of expectations $\mathbb{E}_t^{\mathcal{P}}$ of the unobserved variables y_t^n, y_{t-1}^n and u_t, given by

$$\mathbb{E}_t^{\mathcal{P}} \begin{pmatrix} y_t^n \\ y_{t-1}^n \\ u_t \end{pmatrix} = F\mathbb{E}_{t-1}^{\mathcal{P}} \begin{pmatrix} y_{t-1}^n \\ y_{t-2}^n \\ u_{t-1} \end{pmatrix} + K_t \left(\begin{pmatrix} \varsigma_{1,t} \\ \varsigma_{2,t} \end{pmatrix} - HF\mathbb{E}_{t-1}^{\mathcal{P}} \begin{pmatrix} y_{t-1}^n \\ y_{t-2}^n \\ u_{t-1} \end{pmatrix} \right). \tag{3.14}$$

Because the filtering problem does not have an analytical solution, we compute the Kalman-gain matrix K_t numerically, assuming, as is standard in the literature, that the agents' learning problem has already converged such that the matrix $K_t = K$ is time-invariant (e.g., Lorenzoni, 2009).

[13] See also Lorenzoni (2009) and Erceg and Levin (2003). Expectations are rational under the Kalman filter, because subjective probabilities entering private agents' expectations $\mathbb{E}_t^{\mathcal{P}}$ and objective probabilities underlying the model's stochastic structure coincide.

3.2 Estimation

We estimate key model parameters by matching impulse response as in Rotemberg and Woodford (1997) and Christiano et al. (2005). Specifically, in a first step, we fix a number of basic parameters at conventional values. In a second step, we estimate the remaining parameters by matching the model-implied impulse responses following a monetary policy shock and the empirical responses shown in Figure 2 above.

A period in the model corresponds to one quarter. We set $\beta = 0.99$, such that the (per-quarter) real interest rate in steady state amounts to one percent. For the coefficient of relative risk aversion, we assume that $\theta = 2$. We use the conventional value for the interest-rate rule coefficient and set $\phi = 1.5$. For the degree of openness we use $\omega = 0.15$, because imports account for roughly 15% of GDP in the US in the last decades. We assume that $\kappa = 0.01$, consistent with evidence on a flat Phillips curve in the US during our sample period (Gali and Gertler, 1999). As we show below, this slope of the Phillips curve gives rise to a price level response following monetary policy shocks consistent with US data. Finally, without loss of generality we normalize $p^* = y^* = 0$.

The remaining parameters determine the persistence and standard deviation of the shock processes and, as such, the extent of information rigidities. We collect them in the vector $\varphi = [\rho_u, \rho_y, \sigma_y, \sigma_\eta]'$. Note that φ does not include the standard deviation of monetary innovations σ_u because the Kalman filter (3.14) depends on variance (signal-to-noise) *ratios*, not on the levels of standard deviations as such. Therefore, without loss of generality, we may normalize one of the standard deviations and set $\sigma_u = 0.1$. Finally, we stress that the full-information case is nested in our model for $\sigma_\eta = 0$. In this case, the signal $\varsigma_{1,t}$ is perfectly informative about the level of potential output, as can be seen from equation (3.11).

We estimate the parameters collected in vector φ by making sure that the model prediction for the responses to a monetary policy shock matches the empirical responses that we have estimated on time-series data and discussed above, see again Figure 2. Formally, we solve the following problem

$$\hat{\varphi} = argmin_{\varphi}\ (\hat{\Lambda}^{emp} - \Lambda^{model}(\varphi))'\hat{\Sigma}^{-1}(\hat{\Lambda}^{emp} - \Lambda^{model}(\varphi)). \tag{3.15}$$

Here $\hat{\Lambda}^{emp}$ are the (vectorized) empirical impulse responses, Λ^{model} are the impulse responses implied by the model which depend on the parameter draw φ, and $\hat{\varphi}$ is our estimated vector of parameters. The matrix $\hat{\Sigma}$ is a diagonal weighting matrix which contains the estimated variances of the empirical impulse response functions. Therefore our estimator ensures that the model-implied impulse response functions are as close as possible to the empirical responses in terms of estimated standard deviations.

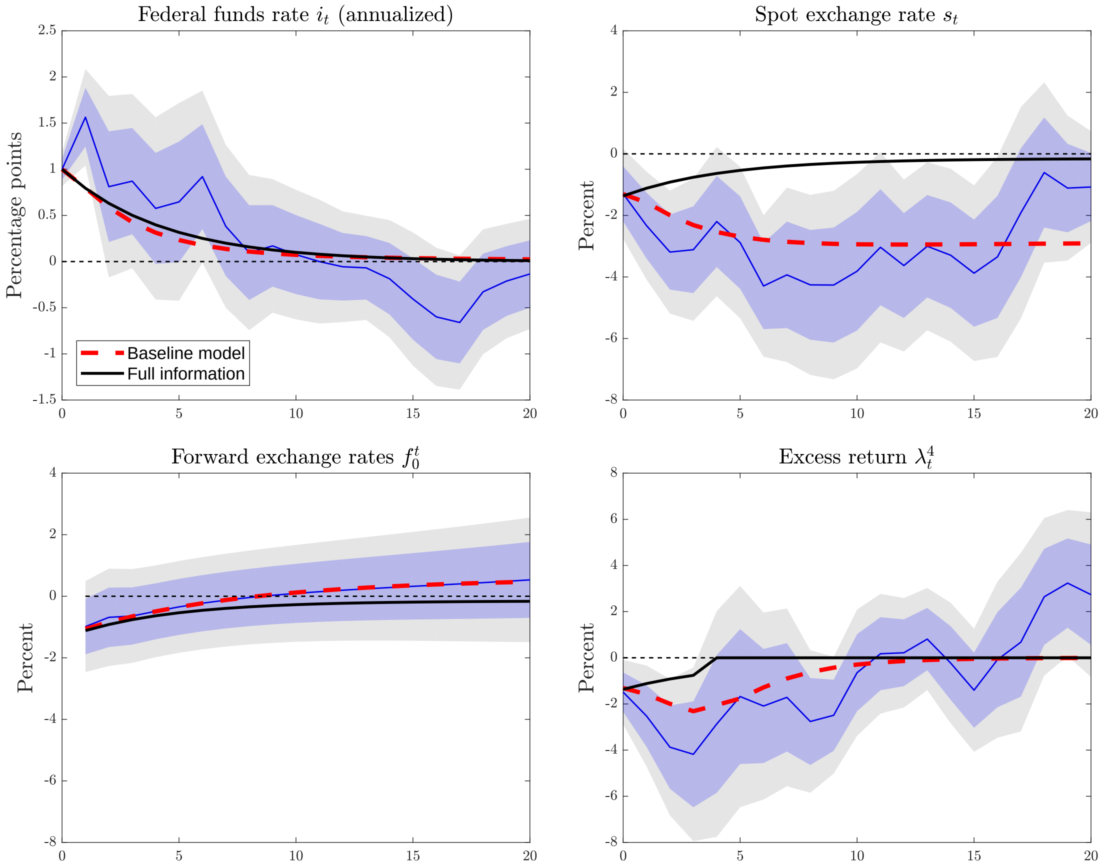

Figure 3: Empirical impulse responses reproduced from Figure 2, given by blue solid line (point estimate) and shaded area (confidence bounds), and model prediction with information rigidities (red dashed line) and under full information ($\sigma_\eta = 0$; black solid line). The horizontal axis measures time in quarters. Vertical axis measures deviation from pre-shock level in percentage points (federal funds rate) or in percent (for the other variables).

Figure 3 shows the result. It shows model-based impulse responses jointly with the empirical estimates, reproduced from Figure 2. The red dashed lines represent our baseline results, the prediction of the estimated model with information rigidities. We contrast these with a case in which we rerun the estimation, but restrict σ_η to be equal to zero. In this case, therefore, we restrict the model to full information (black solid lines).

The model with information rigidities is able to account for the key features of the data, not only qualitatively but also quantitatively. First, the model tracks the response of the nominal exchange rate rather well. In particular, the model is able to generate a gradual, further appreciation of the exchange rate in the periods after the shock—the distinct feature of the exchange rate dynamics triggered by monetary policy shocks according to our estimates reported in Section 2. Second, the estimated model tracks the impact response of forward exchange rates very well, too. In particular, the model can predict that the forward exchange rate response is rather muted, and that it deviates persistently from the ex-post spot exchange rate response. Third, the model can also account for the behavior of excess returns. In particular, the model generates a persistently negative excess return (that is, a positive excess return on domestic currency), which gradually converges back to zero.

We conclude that the New Keynesian model with information rigidities is able to account for the evidence shown in Section 2. Absent information rigidities, instead, the model has a hard time matching the evidence. In this case, in fact, the spot rate response is characterized by overshooting, reminiscent of the analysis in Dornbusch (1976). Moreover, the impact response of the forward rate predicts perfectly the future path of the spot rate. Last, the excess return jumps to zero in the first period where the forward exchange rate can adjust to the new information.[14]

In Table 2 we show the implied parameter estimates, including standard errors in parentheses.[15] The shock process for potential output growth features an autocorrelation of $\rho_y = 0.86$, and a standard deviation of the innovations of $\sigma_y = 0.21$. The autocorrelation is not inconsistent with previous estimates for the driving process of the natural rate (Laubach and Williams, 2003). In interpreting the standard deviation, recall that in our framework, the volatility of the natural rate is not identified. What is identified is the volatility relative to the volatility of monetary policy shocks, which we have normalized to $\sigma_u = 0.1$. Thus, choosing a smaller normalization for σ_u would also imply that σ_y is estimated to be smaller.

As for the monetary policy shock, we estimate a high degree of autocorrelation ($\rho_u = 0.93$). This reflects that, to keep the analysis simple, we have abstracted from interest rate smoothing in the interest-rate feedback rule. Therefore, the persistence of the federal funds rate observed empirically is absorbed by a high autocorrelation of the monetary policy shocks. In this sense, our estimates are in line with earlier estimates (e.g. Smets and Wouters, 2007).

The standard deviation of the noise term η_t is estimated to be $\sigma_\eta = 0.17$, and is highly statistically significant. Recall that the full information model corresponds to the case $\sigma_\eta = 0$. Our estimates therefore reject the FIRE version of the model.

[14]Even under full information, the excess return is non-zero in the periods where the forward exchange rate is predetermined. In the case of four-quarters-ahead excess returns λ_t^4, this is the case for quarters $t \in \{0, 1, 2, 3\}$. See equation (3.6) for details.

[15]To compute the standard errors, we follow Meier and Müller (2005) and use the following statistic

$$\hat{V}(\hat{\varphi}) = (G'(\hat{V}(\hat{\Lambda}^{emp})^{-1}G)^{-1},$$

where $G = \nabla_\varphi \Lambda^{model}(\hat{\varphi})$ denotes the Jacobian of the model-implied impulse response function at the estimated vector of parameters $\hat{\varphi}$, and where $\hat{V}(\hat{\Lambda}^{emp})$ is the estimated covariance matrix of the empirical impulse response functions.

Parameter	ρ_y	ρ_u	σ_y	σ_η
Estimate	0.86 (0.021)	0.93 (0.007)	0.21 (0.029)	0.17 (0.067)

Table 2: Parameter estimates, standard errors in parentheses, based on impulse response matching approach.

3.3 External validity

Having established that our model can account well for observed exchange rate dynamics, we now assess its external validity and turn to model predictions for the behavior of variables that have not been targeted in the estimation. Here we focus on key macroeconomic indicators that are typically the focus in much work on the monetary transmission mechanism, namely output and prices.

Specifically, we first estimate the responses of US real GDP and the consumer price index (CPI) to monetary policy shocks. As before, we consider quarterly data running from 1976Q1–2008Q4. To characterize the response of both variables to monetary policy shocks, we estimate again empirical model (2.1), replacing the nominal exchange rate with the log of real GDP and the CPI, respectively.[16] Figure 4 shows the result. It is organized in the same way as Figure 2: the blue solid line is the point estimate, and the shaded areas indicate 68 percent and 90 percent confidence bands. The left panel shows the response of output which displays a distinct hump-shaped pattern, familiar from earlier work on the monetary transmission mechanism (Christiano et al., 1999). We observe a maximum effect after about one year, when output has declined by approximately 1 percent relative to its pre-shock level. The effect on output ceases to be significant after 2-3 years. The right panel of Figure 4 shows the response of the price level. Initially, prices adjust sluggishly. We observe a significant decline of prices only after about 1.5 to 2 years, again a familiar finding of earlier studies. However, the price level continues to decline markedly afterwards. Five years after the shock the price level is reduced by some 3 percent.

Figure 4 also shows the prediction of the estimated model, both with and without information rigidities—as in Figure 3 above. We find that our baseline model predicts the output response rather well. In particular, unlike the full-information model, our baseline model is able to generate a hump-shaped response of real GDP. This is particularly remarkable

[16]The data is taken from the St. Louis Fed (FRED Economic Data). We also follow Coibion et al. (2017) and restrict the contemporaneous effect of monetary policy shocks on GDP and the CPI to be equal to zero. In this case, the second sum in equation (2.1) thus runs from $k = 1$ to K.

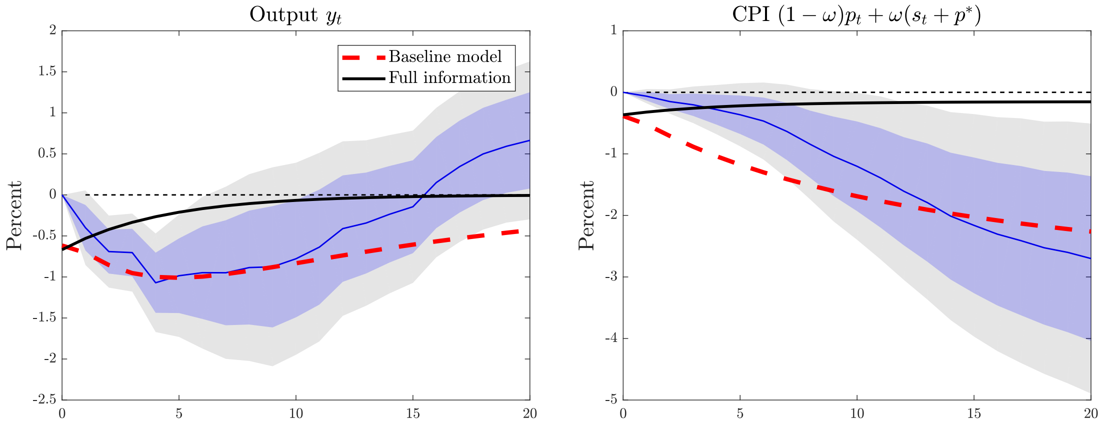

Figure 4: Impulse responses of output and the CPI to monetary policy shock according to local projection (blue solid line with shaded areas indicating 68 percent and 90 percent confidence bands) and according to estimated model with information rigidities (red dashed line) and in the case of FIRE (black solid line). The horizontal axis measures time in quarters. Vertical axis measures deviation from pre-shock level in percent.

because the output response has not been used in the estimation.[17] Similarly, unlike the full-information model, the model with information rigidities predicts an adjustment pattern of the price level that is quite similar to what is implied by the estimated impulse response function.

In sum, not only can our model account for the observed response of exchange rates in response to monetary policy shocks, but it also accounts rather well for the impulse response functions of macroeconomic aggregates.

3.4 Quantifying the extent of information rigidities

In order to quantify the extent of information rigidities implied by our estimates, we specify the limiting cases of full and zero information in terms of the Kalman filter. The last row of the Kalman filter (3.14) describes the perceived evolution of the monetary policy shock, $\mathbb{E}_t^{\mathcal{P}} u_t$. Under full information, it holds that $\mathbb{E}_t^{\mathcal{P}} u_t = u_t$. The last row of the Kalman gain matrix K then implies two parametric restrictions. Formally, the last row of K becomes

$$\varepsilon_t^u = \begin{pmatrix} K_{3,1} & K_{3,2} \end{pmatrix} H \begin{pmatrix} \varepsilon_t^y \\ 0 \\ \varepsilon_t^u \end{pmatrix} = \begin{pmatrix} K_{3,1} & K_{3,2} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ \theta\rho_y & -\theta\rho_y & 1 \end{pmatrix} \begin{pmatrix} \varepsilon_t^y \\ 0 \\ \varepsilon_t^u \end{pmatrix},$$

[17] We note, however, that imperfect information models are known to generate a hump-shaped adjustment pattern for GDP (Mackowiak and Wiederholt, 2015).

which can be rearranged to yield

$$0 = (K_{3,2} - 1)\varepsilon_t^u + (K_{3,1} + \theta\rho_y K_{3,2})\varepsilon_t^y.$$

This equation can only hold at all times in case $K_{3,1} = -\theta\rho_y$ and $K_{3,2} = 1$. In the other limiting case where noise is infinite, agents attach zero weight to new information contained in any of the two signals. In this case, therefore, $K_{3,1} = K_{3,2} = 0$.[18]

We can quantify the degree of information frictions that are implied by our estimates by locating the estimated coefficients $\hat{K}_{3,1}$ and $\hat{K}_{3,2}$ in the interval spanned by the boundaries of the two limiting cases. If the estimated coefficients $\hat{K}$ are relatively close to zero, the degree of information frictions is large. We find that $-\hat{K}_{3,1}/(\theta\rho_y) = 0.20$ and $\hat{K}_{3,2} = 0.34$. Note that the second statistic reflects the information content of the signal stemming from the central bank.[19] It implies that when private agents observe a policy rate increase, they attach about 34 percent of the probability weight to this reflecting a monetary policy shock (see also Figure 6 below). Although based on an entirely different approach and data set, our results regarding the extent of information rigidities are remarkably similar to what Nakamura and Steinsson (2018) report: they find that one third of interest rate surprises are due to monetary policy shocks, whereas the remaining two thirds are due to innovations to the natural rate.

4 Inspecting the mechanism

In this section we zoom in on the transmission mechanism of our model in order to explore how information frictions impact exchange rate dynamics. To set the stage, we first consider the case of full information. We then study the case of information rigidities.

4.1 Full information benchmark

As explained above, our model nests the case of FIRE for $\sigma_\eta = 0$. Figure 5 illustrates how the economy reacts to a monetary policy shock (red dashed line) and to a natural rate shock (blue solid line) in this case. In solving the model numerically, we use the estimated parameters from Section 3 except that we assume an identical autocorrelation for the two shock processes, equal to $\rho_u = \rho_y = 0.8$, for reasons that become apparent shortly.

Focus first on the monetary policy shock. The left panel shows that, in response to the shock, the nominal interest rate i_t rises persistently. The right panel shows that the nominal

[18] To generate "zero" information in the model, it is not sufficient to set the noise variance to infinity $\sigma_\eta^2 = \infty$. In this case, even though $\varsigma_{1,t}$ becomes uninformative, agents can still infer about y_t^n from $\varsigma_{2,t}$. Therefore, zero inference about the monetary policy shock is implied by setting simultaneously $\sigma_\eta^2 = \infty$ as well as $\sigma_y^2 = \infty$.

[19] To see this, note from (3.4) that $K_{3,2}$ multiplies the second row of H, which, from the observation equation (3.13), captures the signal stemming from the central bank.

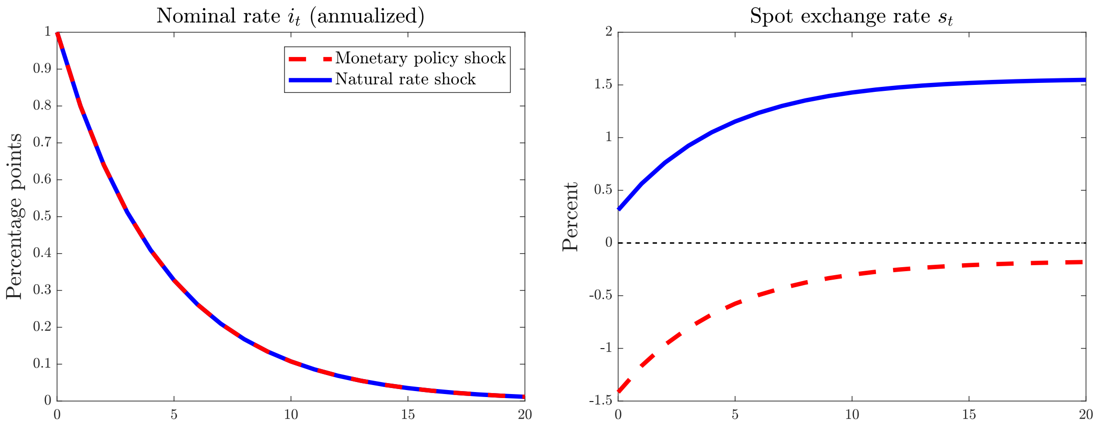

Figure 5: Impulse response to monetary policy shock ε_t^u and natural rate shock ε_t^y under full information ($\sigma_\eta = 0$), with autocorrelation parameters $\rho_u = \rho_y = 0.8$. All other parameters are equal to estimated values, reported in Section 3.2.

exchange rate s_t appreciates, both on impact and in the long run. Yet, after the impact period, the exchange rate depreciates as it converges to its new long-run level from below. The nominal exchange rate thus appreciates more strongly on impact than in the long run: there is overshooting, just like in Dornbusch (1976).

Overshooting is the result of two equilibrium conditions which govern the nominal exchange rate response. The first is equation (3.2), repeated here for convenience:

$$\theta(y_t - y^*) = s_t + p^* - p_t.$$

This equation determines how the exchange rate reacts in the *long run*. In the long run a monetary policy shock is neutral in terms of economic activity ($y_\infty = y^*$). However, because it generates a temporary decline in inflation, the domestic price level p_t declines permanently to a lower level, $p_\infty < p_{-1} = p^*$. To restore purchasing power parity, the exchange rate must appreciate in the long run, even though the monetary contraction is transitory, $s_\infty < s_{-1}$.[20]

The second equation is the UIP condition (3.4), also repeated here for convenience. This equation determines how the exchange rate reacts in the *short* run. In the case of FIRE, it is given by

$$i_t - i^* = \mathbb{E}_t^{\mathcal{F}} \Delta s_{t+1},$$

where we replace the expectation operator $\mathbb{E}_t^{\mathcal{P}}$ with $\mathbb{E}_t^{\mathcal{F}}$.

A monetary contraction implies a surprise increase of the policy rate at time 0, $i_0 > i^*$. After this period, all uncertainty is resolved. This implies $\mathbb{E}_t^{\mathcal{F}} \Delta s_{t+1} = \Delta s_{t+1}$, because under

[20]The precise levels of p_∞ and s_∞ are equilibrium objects, determined by the responses of inflation and the nominal exchange rate in the short run.

FIRE, agents are not making expectational errors absent fundamental surprises. Hence we can write $i_t - i^* = \Delta s_{t+1}$, for $t \geq 0$. A positive interest differential $i_t - i^* > 0$ requires that the domestic currency depreciates going forward: $\Delta s_{t+1} > 0$. Because the exchange rate appreciates in the long run (recall that $s_\infty < s_{-1}$), depreciation in the short run requires that the exchange rate appreciates more strongly on impact than in the long run: the exchange rate overshoots.

Focus next on the natural rate shock. According to equation (3.9), potential output rises over time in response to the shock until it plateaus on a permanently higher level. The natural rate rises temporarily, indicating that resources are relatively scarce compared to the long run, see again equation (3.10). According to the interest rate rule (3.7), the central bank tracks the natural rate by raising its policy rate accordingly. This, in turn, implements the flexible price allocation by keeping inflation constant (Galí, 2015).

The right panel in Figure 5 shows that the nominal exchange rate depreciates in response to the natural rate shock—both on impact and in subsequent periods. To understand this result, consider again equation (3.2). It illustrates that as domestic output rises gradually to a higher level, the real exchange rate depreciates. Because the price level is perfectly stabilized by monetary policy, real depreciation comes about via a nominal depreciation. Intuitively, the exchange rate depreciates because domestic supply expands with productive capacity at home. As the supply of domestic goods rises permanently on the world market, their price must decline in real terms.

Taken together, our analysis shows that an *identical* response of the policy rate, shown in the left panel of Figure 5, can be associated with completely different exchange rate responses: in the case of monetary policy shocks, the exchange rate appreciates, while in the case of natural rate shocks, the exchange rate depreciates. This feature of the model is at the heart of the inference problem facing private agents under information rigidities.[21]

4.2 Information rigidities

When information rigidities are present, it takes agents time to distinguish natural rate and monetary policy shocks after observing a rise in interest rates that is not warranted by a response to inflation. In Figure 6, we illustrate the extent of mis-perception by contrasting the perceived (blue dashed line) versus the actual (red dashed-dotted line) path of the monetary policy shock and the natural rate in the estimated model. The monetary policy shock is shown in the left panel: u_t rises initially by 0.36 percent, then returns to zero slowly over time. The right panel shows the path of the natural rate r_t^n. Because we study the response

[21] When $\rho_u \neq \rho_y$, the policy rate responses following the two shocks are not exactly identical. Still in this case, the inference problem facing private agents is nontrivial in the presence of information rigidities.

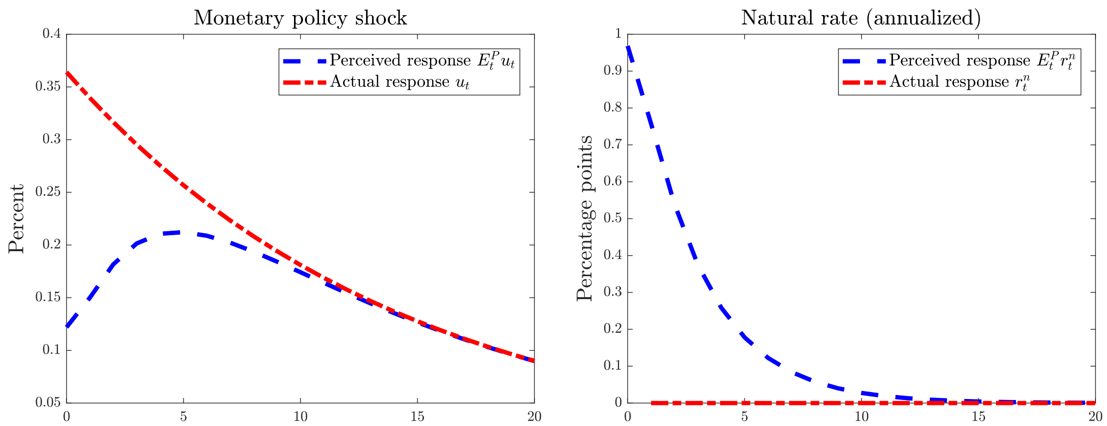

Figure 6: Perceived (blue dashed line) versus actual (red dashed-dotted line) responses to monetary policy shock (left) and the natural real rate (right) in the estimated model with information rigidities.

of the economy following a monetary policy shock, the actual response of the natural rate is equal to zero.

As Figure 6 shows, agents initially underestimate the size of the monetary policy shock, as $\mathbb{E}_t^{\mathcal{P}} u_t$ rises only by 0.125 percent on impact—about one third its actual value.[22] In contrast, while the actual response of r_t^n is equal to zero, agents initially believe that r_t^n has increased. Initially, agents thus attribute the increase of the policy rate to a mix of a monetary policy shock and a natural rate increase. By observing the response of the economy over time, agents update their beliefs and adjust their estimates of the two shocks accordingly. After the first year, the gap between perceived and actual value has shrunk to a large extent. But it is fully closed only after about 3 years. This reflects that, for the model to match the empirical impulse response functions following a monetary policy shock, the necessary degree of sluggishness in the adjustment of expectations is substantial.

We are now ready to understand the implications of information rigidities for the exchange rate response following monetary policy shocks. Because private agents cannot initially distinguish monetary policy shocks and natural rate shocks, they cannot know whether the exchange rate is going to depreciate or appreciate in the long run (see again Figure 5). Because the exchange rate is a forward looking variable, its impact response reflects this lack of information. This intuition can be made formally precise. By iterating the UIP condition

[22] More precisely, the probability weight attached to monetary policy shocks is 34 percent. We had highlighted this result before, in Section 3.4.

(3.4) forward, we may write for the exchange rate in the impact period:

$$s_0 = -\mathbb{E}_0^{\mathcal{P}} \sum_{j=0}^{\infty} (i_j - i^*) + \mathbb{E}_0^{\mathcal{P}} s_\infty. \tag{4.1}$$

This expression shows that the impact response of the exchange rate is governed by the expected interest differential and the expected long-run value of the exchange rate. The interest differential evolves similarly under monetary policy shocks and natural rate shocks, as we have argued before. However, the long-run response of the exchange rate differs fundamentally depending on which shock hits the economy. If agents initially attach a high probability weight to a natural rate shock, they expect a depreciation in the long run: $\mathbb{E}_0^{\mathcal{P}} s_\infty > 0$. This in turn accounts for a muted exchange rate response on impact—even though there is a positive expected interest rate differential.

This also matters for the impact response of forward exchange rates. Recall that in our model, forward exchange rates are given by market-based expectations of future spot exchange rates (see equation (3.5)). Iterating forward the UIP condition (3.4) in a generic period $t > 0$, taking time-0 expectations, and using the law of iterated expectations, we obtain the following expression for the impact response of the forward exchange rate with tenure t:

$$f_0^t = \mathbb{E}_0^{\mathcal{P}} s_t = -\mathbb{E}_0^{\mathcal{P}} \sum_{j=0}^{\infty} (i_{t+j} - i^*) + \mathbb{E}_0^{\mathcal{P}} s_\infty. \tag{4.2}$$

Since the expected long-run value of the exchange rate $\mathbb{E}_0^{\mathcal{P}} s_\infty$ enters this equation as well, the impact response of forward exchange rates is governed by the same force as the impact response of the spot exchange rate given by (4.1). Namely, its response is muted following the monetary policy shock, reflecting the fact that the long-run response of the exchange rate is not initially known by market participants.[23]

We next explore how the exchange rate evolves dynamically over time. Evaluating (3.4) in a generic period $t > 0$ and $t + h > 0$, where $h > 0$, yields

$$s_t = -\mathbb{E}_t^{\mathcal{P}} \sum_{j=0}^{\infty} (i_{t+j} - i^*) + \mathbb{E}_t^{\mathcal{P}} s_\infty. \tag{4.3}$$

$$s_{t+h} = -\mathbb{E}_{t+h}^{\mathcal{P}} \sum_{j=0}^{\infty} (i_{t+h+j} - i^*) + \mathbb{E}_{t+h}^{\mathcal{P}} s_\infty. \tag{4.4}$$

Assume now that $\mathbb{E}_{t+h}^{\mathcal{P}} s_\infty < \mathbb{E}_t^{\mathcal{P}} s_\infty$, such that agents have updated their expectations regarding the long-run value of the exchange rate. Specifically, in period $t + h$ they consider a

[23]Note from equation (4.2) that, to the extent that the interest rate differential $i_{t+j} - i^*$ is positive, f_0^t is monotonically rising in t, reaching $\mathbb{E}_0^{\mathcal{P}} s_\infty$ as $t \to \infty$. The fact that f_0^t monotonically rises in theory is also borne out empirically, see Figure 3.

long-run appreciation more likely compared to period t, because they have revised upwards the probability that they are facing a monetary policy shock (see Figure 6). Combining equations (4.3) and (4.4) reveals that $s_{t+h} < s_t$, provided the updating effect is strong enough. In this case, therefore, the exchange rate has appreciated dynamically over time despite a positive interest rate differential.

From the perspective of period t, moreover, this appreciation was not expected to happen which explains why the model predicts persistent negative excess returns conditional on monetary policy shocks. Formally, we can write

$$\lambda_{t+h}^h = s_{t+h} - \mathbb{E}_t^{\mathcal{P}} s_{t+h} = -\mathbb{E}_t^{\mathcal{P}} \sum_{j=0}^{h-1} (i_{t+j} - i^*) + s_{t+h} - s_t < 0. \tag{4.5}$$

The first equality uses that excess returns can be written as the difference between the realized and expected spot exchange rate, see equation (3.6). The second equality takes time-t conditional expectations in (4.4) and uses equation (4.3) and the law of iterated expectations to replace $\mathbb{E}_t^{\mathcal{P}} s_{t+h}$. Equation (4.5) reveals that excess returns, equivalently, represent the ex-post deviation from uncovered interest parity.[24] The inequality sign then results from combining $s_{t+h} < s_t$ (the exchange rate has appreciated dynamically over time, see above) and from the fact that $\mathbb{E}_t^{\mathcal{P}} \sum_{j=0}^{h-1} (i_{t+j} - i^*) > 0$, that is, interest rate differentials are expected to be positive. Taking stock, in our model, excess returns reflect (temporary) forecast errors in the foreign exchange market, and are persistently negative following monetary policy shocks when information frictions are sufficiently pervasive.

4.3 The uncovered interest parity condition

In this section we perform a decomposition of the estimated nominal exchange rate response based on the uncovered interest parity (UIP) condition. In doing so we clarify an important distinction. In our framework, UIP is violated *ex-post* conditional on monetary policy shocks. However, UIP is satisfied *ex-ante*, based on the information available to market participants.

To perform the decomposition, we use equation (3.6) to write $\Delta s_{t+1} - \mathbb{E}_t^{\mathcal{P}} \Delta s_{t+1} = s_{t+1} - \mathbb{E}_t^{\mathcal{P}} s_{t+1} = \lambda_{t+1}^1$. Using this in UIP condition (3.4) yields

$$i_t - i^* + \lambda_{t+1}^1 = \Delta s_{t+1}. \tag{4.6}$$

This equation shows that UIP is violated ex post whenever monetary policy shocks induce excess returns $\lambda_{t+1}^1 \neq 0$. In fact, we argued earlier that following monetary policy shocks, the domestic currency continues to appreciate despite a positive interest rate differential: there

[24] The equivalence holds, because covered interest parity holds in our model as discussed in Section 2 above.

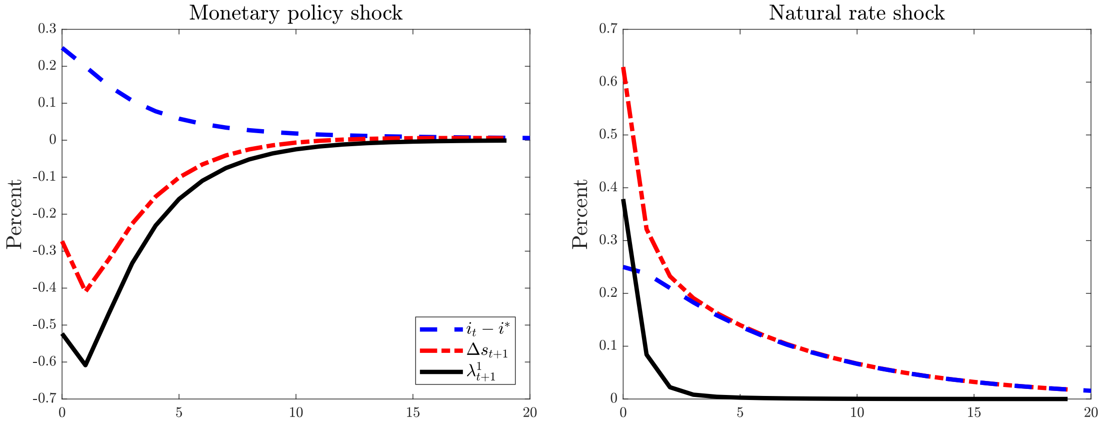

Figure 7: Decomposition of exchange rate response according to equation (4.6), contrasting monetary policy shocks ε_t^u and natural rate shocks ε_t^y.

are negative excess returns on foreign currency. We illustrate this point in the left panel of Figure 7. It shows that $\lambda^1_{t+1} < 0$ can account for $\Delta s_{t+1} < 0$, that is, an ongoing appreciation, in the presence of a positive interest rate differential.

Conditional on the information available to investors, however, the fact that UIP is violated following monetary policy shocks and the implied negative excess returns cannot be exploited, that is, there are no arbitrage opportunities. To understand this point, consider the right panel of Figure 7, which represents the decomposition (4.6) in response to a *natural rate* shock, that is, following an innovation in ε_t^y. In this case, excess returns are positive, that is, they have the opposite sign than conditional on monetary policy shocks. Positive excess returns arise, because agents are continuously surprised that the exchange rate continues to depreciate following a shock to the natural rate.

Now recall that agents in the model cannot initially distinguish monetary policy shocks and shocks to the natural rate. This implies that excess returns are equal to zero on average. Equivalently, excess returns are equal to zero unconditionally, that is, based on the information available to investors. As a result, there are no arbitrage possibilities to be exploited based on the information available to investors.

4.4 Interest rate surprises

The essential characteristic of monetary policy shocks around which our model is centered is that they are unobservable by market participants. This is an essential feature of the shocks identified by Romer and Romer, because identification hinges on the Fed's Greenbook which is released to the public only with a delay of 5 years.

Against this background, we briefly discuss the implications of an alternative strategy that has recently become very popular to identify monetary policy shocks. It is based on interest rate surprises: unanticipated changes of short-term interest rates, typically measured on the basis of high frequency data in the context of monetary policy announcements (Kuttner, 2001; Gürkaynak et al., 2005). Stavrakeva and Tang (2019) and Gürkaynak et al. (2020) investigate the exchange rate response to interest rate surprises and find that the USD *depreciates*, at least in certain periods. Rüth (2020), in turn, argues that the USD features no hump-shaped response and that excess returns are equal to zero once interest rate surprises are used as external instruments in an SVAR model à la Gertler and Karadi (2015).

In our model, interest rate surprises are defined as follows:

$$\phi_t \equiv i_t - \mathbb{E}^{\mathcal{P}}_{t-1} i_t. \tag{4.7}$$

What sets ϕ_t apart from monetary policy shocks u_t is that ϕ_t is, by definition, fully observable by market participants. According to our analysis, the (lack of) observability of shocks matters greatly for exchange rate dynamics.

To illustrate this once more, we resort to a Monte-Carlo simulation. We first simulate data from the estimated model for 131 quarters, the same number of quarters as in our empirical analysis in Section 2. We then estimate our empirical models (2.1) and (2.6) on simulated data and project the exchange rate and excess returns on the current interest rate surprise. We repeat this analysis 100 times and compute an average response.[25]

Figure 8 shows the result. The left panel shows the estimated response of the exchange rate. We highlight two features. First, the response is not hump-shaped (unlike the response following monetary policy shocks, see Figure 3), in line with the empirical results in Rüth (2020). Second, the exchange rate depreciates (if only mildly, and not significantly) on impact. This is in line with Stavrakeva and Tang (2019) and Gürkaynak et al. (2020), who emphasize that the exchange rate may depreciate on impact following interest rate surprises.[26]

The right panel shows the response of the one-year excess return. In line with the evidence reported in Rüth (2020), the excess return is indeed *zero* following interest rate surprises (recall that in the first quarters after the shock, the excess return is by definition non-zero because the forward exchange rate in these quarters is predetermined). This is different

[25] As emphasized in Miranda-Agrippino and Ricco (2020), interest rate surprises are not in fact shocks, but equilibrium objects. It follows that, in the model, there is no direct theoretical counterpart to impulse responses following interest rate surprises.

[26] In addition to not being hump-shaped, Rüth (2020) stresses that the response of the exchange rate is characterized by overshooting, as it appreciates on impact in his analysis. This is in contrast to Stavrakeva and Tang (2019) and Gürkaynak et al. (2020), who stress that the exchange rate may depreciate on impact following interest rate surprises. Our model can be consistent with all of these findings, depending on which part of interest rate surprises is due to monetary policy shocks rather than innovations to the natural rate.

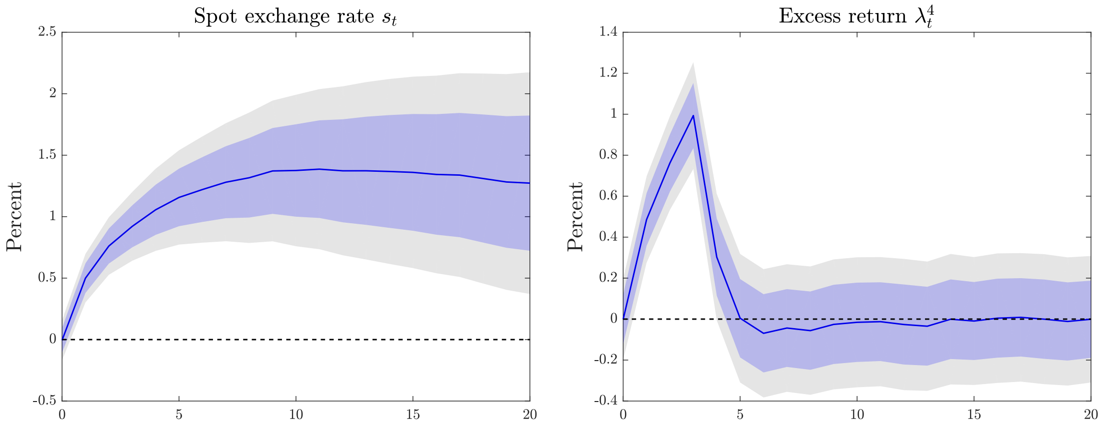

Figure 8: Model-implied impulse response of spot exchange rate s_t and of one-year excess return λ_t^4 to interest rate surprise ϕ_t, based on Monte-Carlo simulations (length of simulation: 131 quarters, 100 repetitions). Impulse responses are normalized, such that the interest rate i_t (annualized) rises initially by 100 basis points.

compared to the response of excess returns following monetary policy shocks, which are persistently negative (Figure 3). To gain intuition, recall that interest rate surprises are perfectly observable by market participants in real time. As a result, conditional on interest rate surprises, excess returns should equal zero, for otherwise they could be exploited by market participants.[27]

5 Conclusion

What accounts for the sluggish response of the exchange rate to monetary policy shocks? In this paper, we first provide empirical evidence which points to a prominent role for information rigidities in answering this question. First, the dollar response to US monetary policy shocks is sluggish. Second, the impact response of forward exchange rates does not suggest that market participants expect delayed overshooting. Third, while UIP fails following US monetary policy shocks, this failure of UIP is only temporary.

We show that a straightforward modification of the New Keynesian open-economy model ensures that the model predictions align well with the evidence, namely, once we move away from full-information rational expectations (FIRE) and instead assume that shocks are not directly observed by market participants. However, we maintain the assumption of rationality

[27] Another interpretation is that interest rate surprises are not in fact shocks, but an "average" of monetary policy shocks and shocks to the natural rate (Miranda-Agrippino and Ricco, 2020). Recall that in our model, excess returns are negative following monetary policy shocks, but positive following natural rate shocks (Section 4.3). This explains that, following an "average" shock, excess returns are equal to zero.

by assuming that agents update their beliefs by using the Kalman filter such that departures from FIRE are only temporary. This set of assumptions is both plausible and finds compelling support in earlier work on the formation of expectations (Coibion and Gorodnichenko, 2012, 2015).

Importantly, our analysis documents and accounts for exchange rate dynamics conditional on monetary policy shocks. We offer no explanation of a number of exchange rate puzzles which hold unconditionally, notably the Fama puzzle. Still, a full-fledged account of exchange rate dynamics will not only need to account for unconditional moments—it will also have to be assessed by its ability to account for conditional moments, such as the shape of impulse responses triggered by specific shocks. In light of our results, we consider a more comprehensive assessment of the role of information rigidities for exchange rate dynamics a promising avenue for future research.

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A Additional evidence

In this Appendix, we collect additional empirical evidence on the impact of US monetary policy shocks on the exchange rate. All details are described in Section 2.3.

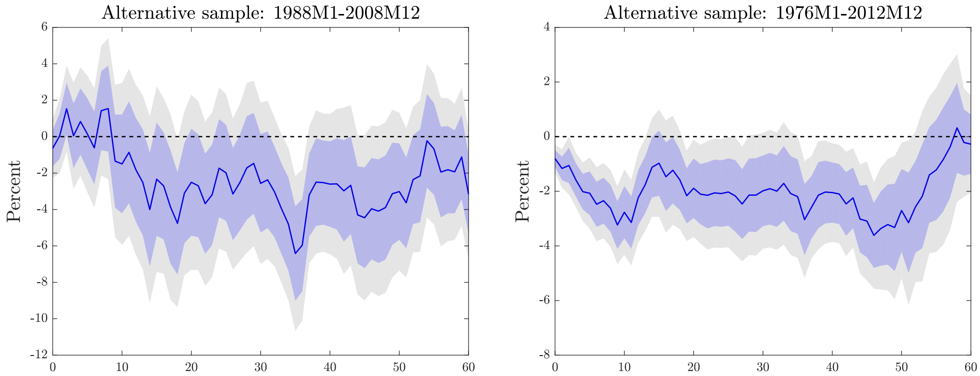

Figure A.1: Response of USD-GDP spot exchange rate; alternative sample periods, monthly observations.

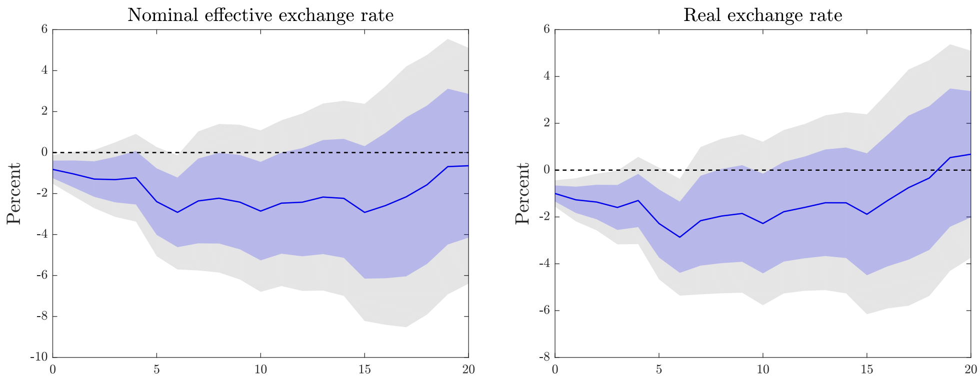

Figure A.2: Response of effective USD nominal exchange rate (left) and of USD real exchange rate (right).

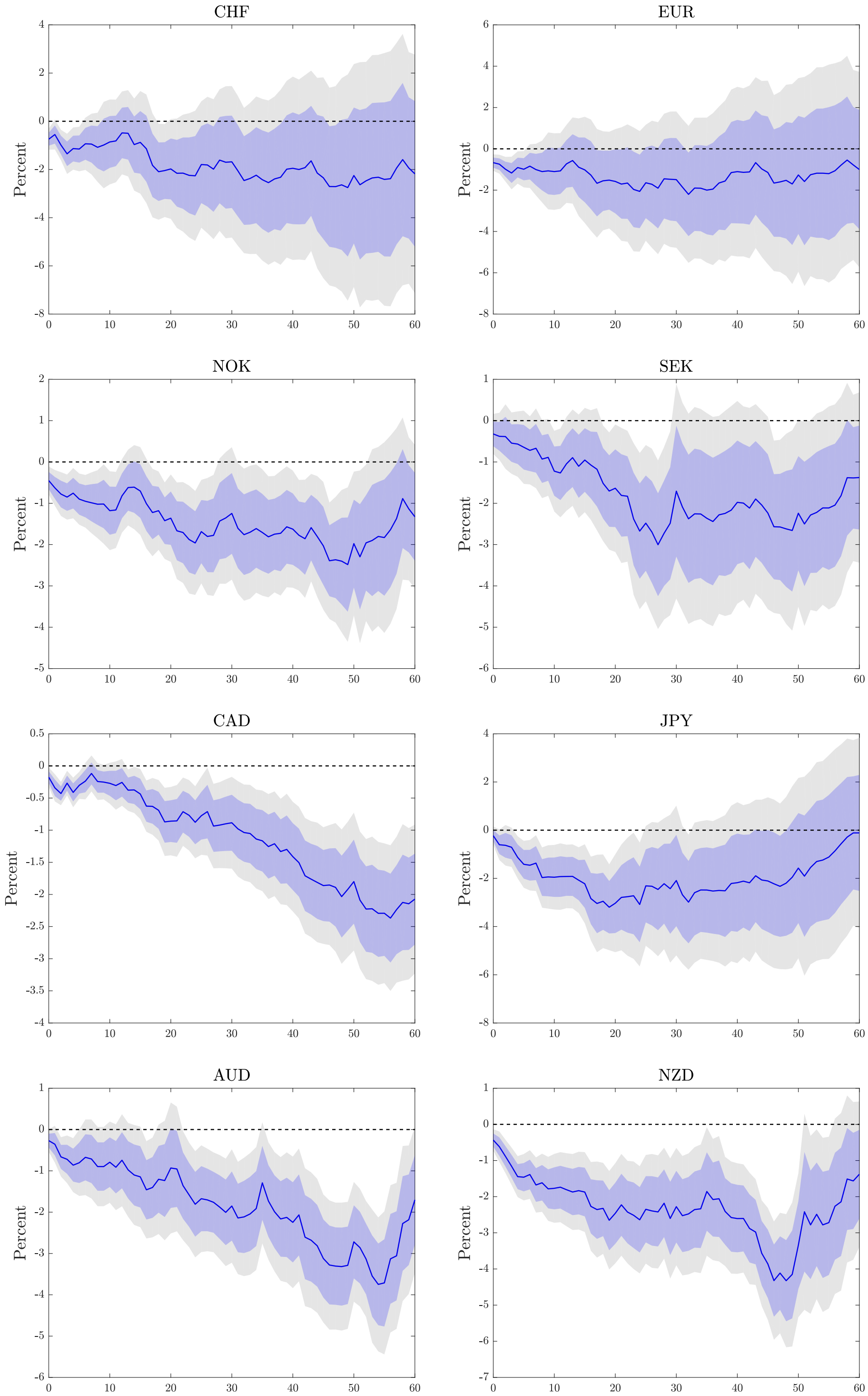

Figure A.3: Response of bilateral dollar exchange rates vis-à-vis G10 currencies; monthly observations from 1976M1–2008M12.

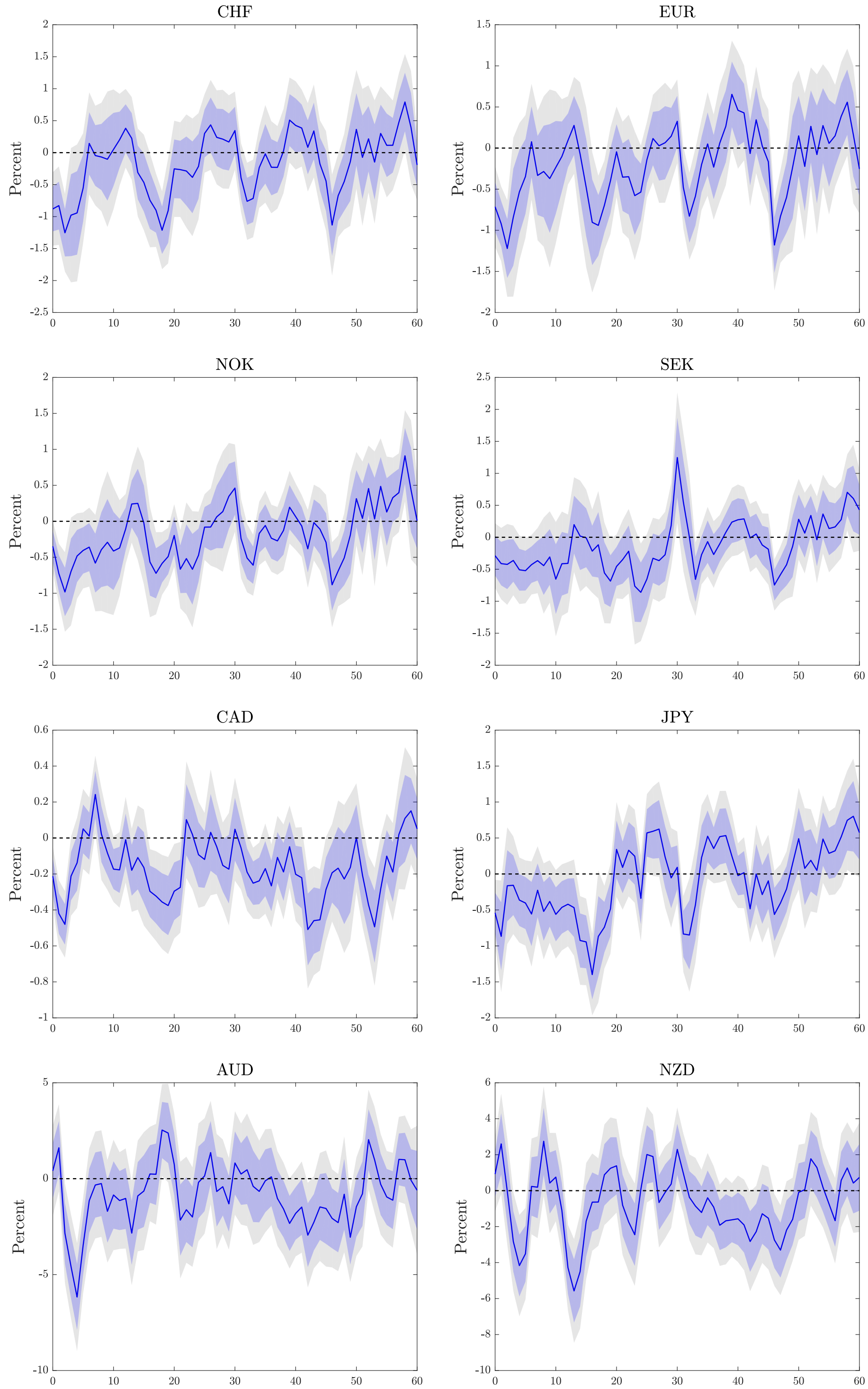

Figure A.4: Response of 1-quarter excess return of G10 currencies vis-à-via USD; monthly observations from 1976M1–2008M12.

B Model Appendix

In this Appendix we describe the non-linear model in some detail, and we present details on the log-linearization. The model is based on Galí and Monacelli (2005). More details on the foundations of the model can be found in this paper.

Firm problem. There is a continuum of identical final good firms, indexed $j \in [0,1]$. Firm $j's$ technology is

$$Y_{jt} = A_t e_{jt} H_{jt}, \tag{B.1}$$

where Y_{jt} is output, A_t is TFP (common to all firms), e_{jt} is worker effort, and H_{jt} is the number of workers employed by firm j.

We assume that all firms have common information (see Melosi (2017) for a model in which firms have dispersed information), that TFP A_t is unobserved by firms, and that worker effort e_{jt} is equally unobserved by firms.

We divide each period into two stages. In the first stage, firms hire workers by taking as given i) the downward sloping demand that they face for their goods ii) the perceived level of TFP, assuming that worker effort in the production stage will be equal to 1. Specifically, firms' problem is given by

$$\max_{\tilde{P}_{jt}} \ \mathbb{E}_t^{\mathcal{P}} \sum_{k=0}^{\infty} \zeta^k \rho_{t,t+k} C_{jt+k} \left[P_{jt}^* - \frac{W_{t+k}}{\mathbb{E}_{t+k}^{\mathcal{P}} A_{t+k}} \right], \tag{B.2}$$

where $\tilde{P}_{jt}$ is the optimal reset price, $\zeta \in (0,1)$ is the Calvo-probability of keeping a posted price for another period, W_t is the nominal wage, C_{jt} is households' demand, and $\rho_{t,t+k}$ is households' stochastic discount factor. Note that firms' (expected) marginal cost is given by $W_t/\mathbb{E}_t^{\mathcal{P}} A_t$, where we assume that firms expect workers to work with an effort of one in each period ($\mathbb{E}_t^{\mathcal{P}} e_{jt} = 1$).

In the second stage, production takes place. To the extent that firms misperceived the productivity of their workers ($\mathbb{E}_t^{\mathcal{P}} A_t \neq A_t$), the market clears via an adjustment in worker effort ($e_{jt} \neq 1$). While we assume that worker effort is not verifiable by firms, we still allow for the possibility that firms extract a signal on the effort exerted by the workers (and thus on the level of TFP). We assume that the signal is given by

$$\tilde{\varsigma}_{1,t} = \frac{1+\varphi}{\varphi+\theta} a_t + \eta_t, \tag{B.3}$$

where we denote $a_t = \log(A_t)$. The signal is the same for all firms, in line with our assumption that firms have common information.[1] In equilibrium, the signal implies that firms' perceived

[1] An alternative interpretation is that firms' signals are idiosyncratic, but that firms share their information about worker effort in each period. The combined signal of the firm sector is then given by (B.3).

evolution of TFP and the actual level of TFP are not permanently misaligned.

As is well known, up to first order, firms' problem implies a New Keynesian Phillips curve

$$\pi_t = \beta \mathbb{E}_t^{\mathcal{P}} \pi_{t+1} + \lambda \left(w_t - p_t - \log\left(\frac{\epsilon - 1}{\epsilon}\right) - \mathbb{E}_t^{\mathcal{P}} a_t \right), \tag{B.4}$$

where $\lambda \equiv (1-\zeta)(1-\beta\zeta)/\zeta$ and where $\epsilon > 1$ denotes the elasticity of substitution between varieties. Here we use lower-case letters to denote the log of upper-case letters, and we define $\pi_t \equiv p_t - p_{t-1}$ as inflation of goods produced domestically. Due to the linearity of expectations, the linearization is not affected by the presence of incomplete information.

Household problem. The problem of households is standard. Households obtain utility from consumption and dis-utility from working. Households' period utility is $U(C_t) - V(H_t)$. The price of consumption is P_t^C (the consumer price index, or CPI). The price of labor is W_t. The labor supply curve, in linearized terms, is given by

$$w_t - p_t^C = \theta c_t + \varphi h_t, \tag{B.5}$$

where $\theta > 0$ denotes households' risk aversion (assumed to be constant, and equal to the inverse elasticity of inter temporal substitution), and where $\varphi > 0$ denotes households' inverse Frisch elasticity of labor supply (assumed to be constant as well). Moreover, households' Euler equation, in log-linear terms, is given by

$$c_t = \mathbb{E}_t^{\mathcal{P}} c_{t+1} - \theta^{-1} \left(i_t - \mathbb{E}_t^{\mathcal{P}} \pi_{t+1}^C - \rho \right), \tag{B.6}$$

where we define $\rho \equiv -\log(\beta)$. In equation (B.6), we assume that households and firms share the same information set, as expectations are given by $\mathbb{E}_t^{\mathcal{P}}$. This assumption can be justified on the grounds that firms are owned by the households, such that households have access to firms' information. This assumption also makes the model easier to solve. Melosi (2017) considers a model in which households' and firms' information sets are not identical.

An identical Euler equation holds also in the foreign country. We assume that the domestic country is small, implying that domestic developments have no bearing on the equilibrium in the rest of the world. We also abstract from shocks in the foreign country. By implication, consumption and prices in the foreign country are constant. As a result, the Euler equation simply becomes $i^* = \rho$.

We introduce home-bias in consumption by assuming that households consume a steady-state share $\omega \in (0,1)$ of imported varieties. The elasticity of substitution between foreign and domestic goods is denoted $\sigma > 0$. The price of domestic goods is P_t, the price of foreign goods in domestic currency is $S_t P^*$ - the nominal exchange rate times the price of foreign goods in foreign currency, which is a constant.

These assumptions imply three equilibrium conditions (see Galí and Monacelli 2005 for details). First, market clearing for domestically-produced goods is given by

$$y_t = -\sigma(p_t - p_t^C) + (1-\omega)c_t + \omega(1-\omega)\sigma(s_t + p^* - p_t) + \omega y^*. \tag{B.7}$$

In this equation, we use that the domestic country is small, such that imports account for a negligible fraction of consumption in the foreign country (implying the market clearing condition $c^* = y^*$ in the foreign country).

Second, the CPI, in linear terms, is given by the following expression

$$p_t^C = (1-\omega)p_t + \omega(s_t + p^*). \tag{B.8}$$

It is given by a weighted average between the price of domestically produced goods and imported goods.

Third, in the presence of complete international financial markets, domestic consumption is linked to the level of prices via the condition

$$\theta(c_t - y^*) = (1-\omega)(s_t + p^* - p_t). \tag{B.9}$$

This is the so-called risk sharing condition implied by the assumption of complete financial markets (Backus and Smith, 1993).

Market clearing. Goods market clearing is given by (B.7). Labor market clearing implies $y_t = \mathbb{E}_t^{\mathcal{P}} a_t + h_t$. Asset market clearing follows residually.

Equilibrium conditions from the text. We now show how to obtain the equilibrium conditions presented in Section 3 in the main text.

We first derive a relationship between consumption and output. Combining (B.7)-(B.9) yields

$$y_t = \frac{1}{1-\omega}(\varpi c_t + (1-\omega-\varpi)y^*),$$

where we define $\varpi \equiv 1 + \omega(2-\omega)(\sigma\theta - 1)$. In what follows, we assume that $\sigma = \theta^{-1}$, the so-called Cole-Obstfeld condition. In this case, the previous equation simplifies

$$c_t = (1-\omega)y_t + \omega y^*. \tag{B.10}$$

To derive the Phillips curve, **equation** (3.1), from the main text, we first express the real wage $w_t - p_t$ in terms of economic activity. Using equations (B.5), (B.8), (B.9) and labor market clearing $y_t = \mathbb{E}_t^{\mathcal{P}} a_t + h_t$, we can write

$$w_t - p_t = \frac{\theta}{1-\omega}c_t + \varphi(y_t - \mathbb{E}_t^{\mathcal{P}} a_t) - \frac{\theta\omega}{1-\omega}y^*.$$

Inserting (B.10) to replace c_t, this becomes

$$w_t - p_t = (\varphi + \theta) y_t - \varphi \mathbb{E}_t^{\mathcal{P}} a_t. \tag{B.11}$$

We next define potential output as the level of output when prices are flexible and in the presence of complete information. Under these two assumptions, (B.4) implies that

$$w_t - p_t = \log \left(\frac{\epsilon - 1}{\epsilon} \right) + a_t.$$

Combining this with (B.11), we obtain

$$y_t^n = \frac{1}{\varphi + \theta} \left(\log \left(\frac{\epsilon - 1}{\epsilon} \right) + (1 + \varphi) a_t \right). \tag{B.12}$$

Inserting (B.11) in the Phillips curve (B.4) yields

$$\pi_t = \beta \mathbb{E}_t^{\mathcal{P}} \pi_{t+1} + \lambda \left((\varphi + \theta) y_t - \varphi \mathbb{E}_t^{\mathcal{P}} a_t - \log \left(\frac{\epsilon - 1}{\epsilon} \right) - \mathbb{E}_t^{\mathcal{P}} a_t \right).$$

Taking conditional expectations in (B.12) to replace $\mathbb{E}_t^{\mathcal{P}} a_t$ yields the Phillips curve (3.1) from the main text, where we define $\kappa \equiv \lambda(\varphi + \theta)$.

To derive **equation** (3.2) in the main text, simply combine equations (B.9) and (B.10).

Equation (3.3) in the main text merely defines the real exchange rate q_t.

To derive the uncovered interest parity (UIP) condition, **equation** (3.4), from the main text, first combine (B.8) and (B.9) to obtain a relationship between c_t, p_t^C and s_t

$$\theta(c_t - y^*) = s_t + p^* - p_t^C.$$

Inserting this in the Euler equation (B.6), and using that $\rho = i^*$ directly yields the result.

To derive the forward exchange rate, **equation** (3.5), from the main text, note that the Euler equation on an h-period bond in foreign currency is given by

$$c_t = \mathbb{E}_t^{\mathcal{P}} c_{t+h} - \theta^{-1} \left(i^* + \mathbb{E}_t^{\mathcal{P}} \Delta s_{t+h} - \mathbb{E}_t^{\mathcal{P}} \pi_{t+h}^C - \rho \right).$$

In turn, the Euler equation on an h-period forward contract on foreign currency is given by

$$c_t = \mathbb{E}_t^{\mathcal{P}} c_{t+h} - \theta^{-1} \left(i^* + f_t^h - s_t - \mathbb{E}_t^{\mathcal{P}} \pi_{t+h}^C - \rho \right).$$

Combining both yields equation (3.5).

Equation (3.6) is the combination of equations (2.5) and (3.5). We may use equation (2.5) to define the excess return, because covered interest parity is satisfied in our model.

The Taylor rule, **equation** (3.7), is given by the linear expression defined in the main text.

We assume that u_t and y_t^n, where y_t^n is defined in equation (B.12), follow the stochastic processes given in **equations** (3.8) **and** (3.9).

To define the natural interest rate, **equation** (3.10), in the main text, we derive the dynamic IS curve of the model. First combine the Euler equation (B.6) and market clearing (B.10)

$$y_t = \mathbb{E}_t^{\mathcal{P}} y_{t+1} - \frac{1}{(1-\omega)\theta}\left(i_t - \mathbb{E}_t^{\mathcal{P}} \pi_{t+1}^C - \rho\right).$$

Next, use equation (B.8) to replace p_t^C

$$y_t = \mathbb{E}_t^{\mathcal{P}} y_{t+1} - \frac{1}{(1-\omega)\theta}\left(i_t - \mathbb{E}_t^{\mathcal{P}}((1-\omega)\pi_{t+1} + \omega\Delta s_{t+1}) - \rho\right).$$

Using the UIP condition, equation (3.4) (which we derived earlier above), and using that $i^* = \rho$, this can be written as

$$y_t = \mathbb{E}_t^{\mathcal{P}} y_{t+1} - \theta^{-1}\left(i_t - \mathbb{E}_t^{\mathcal{P}} \pi_{t+1} - \rho\right).$$

The natural interest rate is defined as the real rate when prices are fully flexible and there is complete information. In this case, output equals potential output $y_t = y_t^n$. Using this in the previous equation, and rearranging for $i_t - \mathbb{E}_t^{\mathcal{F}} \pi_{t+1}$, yields

$$r_t^n = \rho + \theta \mathbb{E}_t^{\mathcal{F}} \Delta y_{t+1}^n.$$

The signal $\varsigma_{1,t}$, which is **equation** (3.11) in the main text, is given by combining equations (B.3) and (B.12)

$$\tilde{\varsigma}_{1,t} = \frac{1+\varphi}{\varphi+\theta} a_t + \eta_t = y_t^n - \frac{1}{\varphi+\theta}\log\left(\frac{\epsilon-1}{\epsilon}\right) + \eta_t.$$

Defining $\varsigma_{1,t} \equiv \tilde{\varsigma}_{1,t} + (1/(\varphi+\theta))\log((\epsilon-1)/\epsilon)$ yields the result.

Finally, the signal $\varsigma_{2,t}$, which is **equation** (3.12) in the main text, is a direct implication of combining equations (3.7) and (3.10), both of which we derived before.

This completes the description of the equilibrium conditions of the model.