Delayed Overshooting: The Case for Information Rigidities

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We provide evidence that the delayed overshooting puzzle reflects a slow adjustment of exchange-rate expectations to monetary policy shocks, rather than a failure of uncovered interest parity. Consistent with this evidence, we put forward a New Keynesian model in which uncovered interest parity holds but there are information rigidities: Investors do not observe monetary policy shocks, but learn rationally from unanticipated shifts in monetary policy about the state of the economy. We estimate the model and find it can account for the joint responses of the spot exchange rate, forward exchange rates and excess currency returns to monetary policy shocks.
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Almost 50 years ago, Dornbusch (1976) put forward a seminal account of exchange rate dynamics. In response to a contractionary monetary policy shock, he 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 modern, micro-founded DSGE models also predict the exchange to overshoot in response to monetary policy shocks (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 tends to appreciate further in subsequent periods and starts to depreciate only much later, a pattern that has been dubbed the "delayed overshooting puzzle" (Eichenbaum and Evans, 1995; Scholl and Uhlig, 2008).

Delayed overshooting is sometimes understood as evidence against uncovered interest parity (UIP). In contrast to this notion, in this paper we first provide evidence that delayed overshooting reflects a sluggish adjustment of investors' exchange-rate expectations to monetary policy shocks, rather than a failure of UIP. Second, consistent with this empirical finding, we provide a small-scale New

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Keynesian open economy model in which UIP is satisfied, but investors' expectations adjust sluggishly due to information rigidities. Despite its simplicity, we find that the model is remarkably successful at replicating the impulse responses of the spot exchange rate, of forward exchange rates and of excess currency returns to monetary policy shocks. We conclude that information rigidities are important for understanding the impact of monetary policy on the foreign exchange market.

In the first part of the paper, we study the response of the US dollar - UK pound bilateral exchange rate following narratively identified, contractionary US monetary policy shocks (Romer and Romer, 2004).[1] In line with much of the previous literature, we find there is delayed overshooting: The dollar appreciates steadily for about a year after the shock, before it starts to depreciate. Because the shock also induces a positive interest rate differential, the dollar yields positive excess returns during the phase when it appreciates. We also study how forward exchange rates across horizons respond in the period of the monetary policy shock. We find that in the forward market, the dollar appreciates slightly at the short end (that is, for short horizons), but the response becomes quickly negligible for longer horizons. In other words, the gradual appreciation of the spot exchange rate is not apparent from the response of the forward market in the period of the shock.

In order to understand what drives these results, we turn to a direct measure of market participants' expectations about the future level of the exchange rate. Specifically, we rely on data compiled by fx4casts based on monthly surveys of professional investors' exchange-rate expectations 3, 6 and 12-months ahead. We obtain two additional results. First, by regressing these expectations on our measure of monetary policy shocks we find they respond very similar to forward exchange rates. We therefore interpret the weak response of the forward market in the period of the shock as evidence for a sluggish adjustment of investors' expectations. Second, using expectation data, we also compute *expected* excess currency returns on the dollar and estimate their response to monetary policy shocks. We find the response of expected excess returns to be insignificant, suggesting that delayed overshooting is not due to a failure of UIP. In sum, the evidence we put forward indicates that delayed overshooting is a reflection of persistent expectation errors of market participants in the foreign exchange market.

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 adjusts short-term interest rates following changes in inflation and in order to track the natural rate of interest—but subject to errors, that is, monetary policy shocks. The private sector does neither directly observe the natural rate nor monetary policy shocks but learns rationally from central bank actions. Whenever investors observe the central bank to adjust interest rates beyond what is implied by the observed level of inflation, they update their belief

[1]We rely on the hybrid VAR model of Coibion (2012) to purge the shock series of any remaining endogenous business cycle components (Ramey, 2016).

about the state of the economy. 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, "signaling" or "information effects" have featured prominently in empirically successful accounts of the monetary transmission mechanism in closed-economy models (Melosi, 2017; Nakamura and Steinsson, 2018). In line with our empirical findings, we assume that UIP holds in the model, that is, we assume that investors expect the exchange rate to depreciate when the interest rate differential is positive.

To understand why our model can account for the evidence, consider first what happens *absent* information rigidities. Following a rise in the natural rate, the exchange rate depreciates but following a contractionary monetary policy shock, the exchange rate appreciates (and overshoots). Now recall that, in the presence of information rigidities, the private sector cannot distinguish natural rate changes and monetary policy shocks on impact. This implies that the impact response of the exchange rate is muted relative to the full information benchmark. Moreover, consistent with the evidence, this also implies that on impact the response of forward exchange rates is flat across horizons because, on impact, it is ambiguous whether the exchange rate is going to appreciate or depreciate in the future. As the private sector updates its beliefs over time, it starts to realize the true nature of the shock and hence attaches gradually more probability weight to the fact that the exchange rate is eventually 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. The fact that the exchange rate appreciates going forward despite a positive interest rate differential implies a series of excess returns on domestic currency. Finally, once the learning is complete excess returns disappear and the exchange rate starts to depreciate—consistent with delayed overshooting.

In our model, the natural rate is driven by changes in the growth rate of potential output. But our mechanism applies to other drivers of the natural rate as well. To name only one, Del Negro et al. (2017) find that changes in the natural rate reflect to a considerable extent changes in the convenience yield which, in turn, matters greatly for the dynamics of the exchange rate and excess returns (Engel, 2016; Valchev, 2020; Engel and Wu, 2022). What is needed for our results is that the natural rate and monetary policy shocks are unobserved, and that the exchange rate depreciates following a rise in the natural rate. In this case, the resulting inference problem for private agents gives rise to the dynamics following monetary policy shocks that we document.

In a last part of the paper, we confront our model with an external validity check as we assess if it captures well the information effect of unconditional interest-rate surprises. Specifically, we simulate the model to generate a series of interest-rate surprises which reflect both monetary policy shocks and changes in the natural rate. We use simulated data to estimate the impulse responses of several variables of interest following these surprises. To obtain an empirical counterpart to these impulse responses, we use actual interest-rate surprises computed on the basis of high-frequency data. We obtain two results. First, the empirical impulse responses following interest-rate surprises differ fundamentally from those triggered by monetary policy shocks. For example, while monetary policy shocks trigger delayed overshooting of the dollar, interest-rate surprises do not, a finding consistent with earlier work by Rüth (2020). Second, our model can—at least qualitatively—predict the empirical impulse responses of the variables of interest following interest-rate surprises.

The rest of the paper is structured as follows. In the remainder of this section we place this paper in the context of the literature, highlighting its distinct contribution. In Section I we establish our empirical results. Section II describes the model and how we bring it to the data. Section III inspects the mechanism that operates at the heart of the model. Section IV discusses the implications of our analysis for the effects of unconditional interest-rate surprises. A final section concludes. Additional results are collected in an Online Appendix.

Related literature. In addition to the literature on the information effect of monetary policy, referenced above, our paper relates to a large literature on various puzzles regarding the relationship between exchange rates and interest rate parity, see Engel (2014) for a survey. It helps to distinguish between the puzzles that arise unconditionally and the puzzles that arise conditional on shocks. The delayed overshooting puzzle belongs to the second category, because it is concerned with the behavior of the exchange rate conditional on monetary policy shocks.

In contrast, the most well known puzzles are part of the first group, notably the Fama puzzle (also known as the UIP puzzle or the forward premium puzzle)—see Fama (1984).[2] The Fama puzzle states that countries with a positive interest rate differential tend to see their currencies appreciate, generating positive excess returns on those countries' currencies. It represents an *unconditional* puzzle, because the underlying regression framework does not specify what drives the interest rate differential. The literature has not agreed on whether the Fama puzzle does or does not reflect a failure of UIP. Many authors take the perspective that UIP fails and offer explanations based on either financial frictions (Gabaix and Maggiori, 2015; Bacchetta and van Wincoop, 2010) or currency risk premiums (Benigno et al., 2012; Lustig and Verdelhan, 2007). Other accounts, however, rely on systematic expectation errors to account for the Fama puzzle, without assuming that UIP fails. An early study by Froot and Frankel (1989) uses survey data on exchange rate expectations to decompose the Fama puzzle into portions

[2]Another puzzle in this group is the predictability reversal puzzle, which states that excess currency returns following positive interest rate differentials switch sign at longer horizons (see Bacchetta and van Wincoop 2010, Engel 2016, Valchev 2020, Candian and de Leo 2021, Kalemli-Özcan and Varela 2021). Yet another one is the Engel puzzle (high interest rate currencies are stronger than implied by UIP), see Engel (2016).

attributable to the risk premium and expectation errors. They find that most of the puzzle is due to expectation errors, a finding which has been confirmed by later studies (e.g., Bacchetta et al., 2009; Bussiere et al., 2022; Chinn and Frankel, 2020; Candian and de Leo, 2021). Recently, Kalemli-Özcan and Varela (2021) bridge the two views by providing evidence that the Fama puzzle can be explained by expectation errors in advanced economies, but by a failure of UIP in emerging markets. Our analysis is not taking a stand in this debate. In fact, our model cannot account for unconditional exchange rate puzzles because we assume UIP holds and investors are fully rational. This, in turn, implies that excess currency returns are equal to zero on average.[3] In other words, we account for delayed overshooting without modelling frictions which can account for unconditional exchange rate puzzles.[4]

This brings us to the second group of papers, those that study conditional exchange rate puzzles and notably the delayed overshooting puzzle.[5] As in the previous group, the literature is divided on whether delayed overshooting reflects a failure of UIP or not. For instance, Lindé et al. (2009) and Bacchetta and van Wincoop (2021) explain the puzzle using a model in which UIP fails due to currency risk premiums and costly portfolio adjustment, respectively. In contrast, Gourinchas and Tornell (2004) develop a model in which UIP holds, but where investors' expectations are not rational. At an empirical level, Kim et al. (2017) put forward evidence suggesting that delayed overshooting of the dollar is a phenomenon of the 80s and take this, in turn, as evidence for a failure of UIP in the Volcker period. We see our contribution to this literature as twofold. First, we find empirically that one may indeed observe delayed overshooting in the absence of any apparent failure of UIP. Specifically, our evidence suggests that delayed overshooting reflects expectation errors by investors in the foreign exchange market. Second, we show that a model in which UIP holds, investors are rational, but monetary policy impacts their expectations through information effects can account for the evidence. This model class is not only well aligned with recent work in the monetary economics literature; it can also rationalize the seemingly surprising response of the exchange rate (and other variables of interest) to unconditional interest-rate surprises (Stavrakeva and Tang, 2019; Rüth, 2020; Gürkaynak et al., 2021).

In closely related work, Candian (2019) builds an open economy model with

[3]Theoretical attempts to account for the Fama puzzle while maintaining the assumption that UIP holds typically rely on departures from rational expectations, see Gourinchas and Tornell (2004), Burnside et al. (2011), Ilut (2012) and Candian and de Leo (2021). For instance, in Candian and de Leo (2021), the authors build a model with under- and overreactions to changes in fundamentals to account for the Fama puzzle (and for the predictability reversal puzzle that we mention in footnote 2).

[4]In an earlier version of this paper we explicitly considered financial frictions. While such frictions induce an unconditional failure of UIP, they do not impair the mechanism which operates at the heart of our analysis conditional on monetary policy shocks.

[5]Another conditional exchange rate puzzle is the forward guidance exchange rate puzzle (Galí, 2020). This puzzle states that the exchange rate is more strongly affected by expected monetary policy shocks in the near future compared to the distant future—while in typical models, the exchange rate response is horizon-invariant. This puzzle is closely linked to the forward guidance puzzle in closed-economy models.

information frictions similar to ours. However, his paper is concerned with *real* exchange rate dynamics, both unconditionally and conditional on nominal shocks (which are not necessarily monetary policy shocks). Also, in Candian's model the information friction is on the firm side, while the households side (investors) is frictionless. This implies it cannot account for the persistent excess returns following monetary policy shocks that we document.

I. 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 bilateral USD-GBP (USD denoting the US dollar, GBP denoting the British pound) exchange rate following US monetary policy shocks, narratively identified by Romer and Romer (2004).[6] We obtain three main results. We find, first, that a contractionary monetary policy shock induces delayed overshooting of the USD: It appreciates gradually for about one year before it starts to depreciate. Second, consistent with delayed overshooting we find a sequence of excess returns to be earned on the USD, which disappear gradually over time. Third, we find no evidence that delayed overshooting is caused by a failure of UIP. Rather, we find that excess returns are unanticipated and reflect expectation errors.

A. Data and empirical strategy

For our baseline specification, we use monthly data for the period 1976M1 to 2007M12, that is, our sample starts after the Bretton Woods system had been completely abandoned and ends before the financial crisis and the low interest-rate period that followed afterwards.

In what follows, we use s_t to denote the log of the spot exchange rate and define it as the price of GBP in USD, such that a decline of s_t represents an appreciation of the USD. In addition to the spot exchange rate, we study the adjustment of the forward exchange rate to monetary policy shocks. Let f_t^h denote the log of the tenor-h forward exchange rate at time t, that is, the USD-price in period t of one GBP 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 use two sources for forward exchange rates. First, for the period up to 1978 we obtain one and three months-ahead forward exchange rates from Thomson Reuters. For the remainder of our sample period, we use forward rates for horizons $h \in \{1, 3, 6, 12\}$ provided by the Bank of England.[7]

We also use the forward exchange rate to obtain a measure of the interest rate differential that is relevant to the marginal investor in the foreign exchange

[6] In an earlier version of this paper, we also consider other bilateral exchange rates as well as the effective dollar exchange rate and generally find very similar results (Hettig et al., 2019). Below we focus on the USD-GBP exchange rate, because the data coverage is most comprehensive in this case.

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

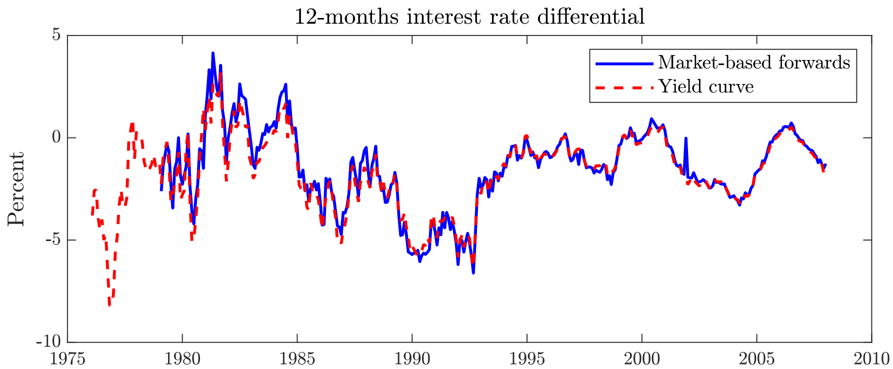

FIGURE 1. COMPARING MARKET-BASED AND YIELD-CURVE-IMPLIED FORWARDS.

Note: Solid (blue) line shows interest rate differential implied by forward discount ("market-based forwards"); dashed (red) line shows interest rate differential implied by yield curve data. Shown is the 12-months interest rate differential, results for 1, 3, and 6-months interest rate differentials are in the Online Appendix.

market. Specifically, assuming that covered interest rate parity (CIP) holds, we obtain the implied interest rate differential from the "forward discount":

$$i_t^h - i_t^{h,£} = f_t^h - s_t, \tag{1}$$

where i_t^h denotes the period-t interest rate of an investment in USD with horizon h, and $i_t^{h,£}$ the counterpart of an investment 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 holds well in the period before the global financial crisis. Deviations from CIP only start to emerge after 2007, a period which we exclude from our sample.

In our analysis below we also use forward rates for horizons $h \in \{1, \dots, 24\}$ for which market-based price quotes are not generally available. To do so, we resort to estimates of the yield curves of GBP-denominated and USD-denominated Treasury bonds to obtain a proxy for the interest rate differential in condition (1).[8] We then "reverse-impute" the price of the forward exchange rate for each horizon. In principle, the marginal investor in the foreign exchange market might not be able to borrow and lend at the government's interest rate. Moreover, the USD and GBP Treasury bonds might have different liquidity, convenience or risk properties. Still, as we contrast the 12-months interest rate differential of the Treasury rates and the one implied by the market-based forwards in Figure 1

[8]For the US yield curve, updates of the estimates of Gürkaynak et al. (2007) 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 find that the two series align rather well in periods where both measures are available. In what follows, we use the imputed forward exchange rates to complement market-based data for forward exchange rates in periods where the latter are unavailable.

Our measure of monetary policy shocks is based on Romer and Romer (2004). Here we summarize briefly how these shocks are constructed and skip the details which are provided in the original paper. In a first step, Romer and Romer (or RR, for short) 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 RR 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 captures non-systematic shifts in policy, that is, monetary policy shocks. In order to cover our entire sample period, we rely on the update of RR's shock series compiled by Coibion et al. (2017).

To assess the response of the economy to monetary policy shocks, we follow Coibion (2012) and incorporate the RR shocks in an otherwise conventional VAR model. This "hybrid VAR" features time series for US industrial production (in logs), ip_t, the unemployment rate, ur_t, the consumer price index and a commodity price index (both in logs), cpi_t and cp_t, respectively, as well as the cumulative RR shock series, u_t. Monetary policy shocks are identified recursively as innovations to the RR shock series (ordered after the other variables). In this way, as explained in detail by Ramey (2016), we cleanse the RR shocks of a potentially endogenous response by the FOMC to information that is contained in the VAR's variables but not fully reflected in the Fed's Greenbook forecast. In addition to the variables included in Coibion's original specification, our VAR model features the interest rate differential and the USD-GBP spot exchange rate. In total, we estimate the VAR on seven time series, ordered as follows: $\{ip_t, cpi_t, ur_t, cp_t, u_t, i_t^3 - i_t^{3,£}, s_t\}$. We consider 12 lags (one year) in the estimation.

In our analysis below, we also estimate the responses of additional variables to monetary policy shocks. For this purpose, we run local projections on the cleansed RR shock series that we obtain from our recursively identified VAR: $\tilde{u}_t$. Formally, letting x_{t+h} denote the realization of a variable of interest h months after the shock, we estimate the following relation:

$$x_{t+h} = c^h + \sum_{j=1}^{J} \alpha_j^h x_{t-j} + \sum_{k=0}^{K-1} \beta_k^h \tilde{u}_{t-k} + \varepsilon_{t+h}. \tag{2}$$

Here, c^h is a constant for each horizon and ε_{t+h} is an iid error term with zero mean. The estimated impulse response of interest is given by the vector $[\hat{\beta}_0^0, ..., \hat{\beta}_0^{24}]$. As in the VAR, we include 12 lags in the local projection ($J = K = 12$).

B. The exchange rate response to monetary policy shocks

Figure 2 shows selected impulse responses to a contractionary US monetary policy shock, while the responses of the remaining variables included in the VAR are shown in the Online Appendix. The shock is normalized so that the annualized 3-months interest rate differential increases initially by one percentage point. Here and in what follows, the solid lines represent the point estimate, while shaded areas indicate 90 percent confidence bands.[9] The horizontal axis measures time in months. The vertical axis measures deviations from the pre-shock level, in percentage points for the interest rate differential and in percent for the other variables.

The upper-left panel shows the response of the interest rate differential. It increases by 1 percentage point on impact, then it slowly falls back to its pre-shock level. The upper-right panel shows the response of the spot exchange rate. Recall that a decline represents an appreciation of the USD. The USD appreciates immediately by approximately 1 percent in response to the shock. However, the appreciation continues over time. Half a year after the shock, the USD has gained some 5 percent in value. Only after about one year does the USD start to depreciate. This is the delayed overshooting result, established in earlier work (Eichenbaum and Evans, 1995; Scholl and Uhlig, 2008).

The combination of a positive interest rate differential and a slowly-appreciating USD implies a sequence of excess returns to be earned on the USD. We denote the excess return over horizon h by λ_t^h and define it as

$$\lambda_t^h \equiv i_t^h - i_t^{h,£} - (s_{t+h} - s_t). \tag{3}$$

Hence, the excess return is given by the USD-GBP horizon-h interest rate differential net of the actual (or realized) depreciation of the USD over that horizon. When the interest rate differential is positive and in addition the dollar appreciates over time, then $\lambda_t^h > 0$: holding dollars over the next h periods earns positive excess returns.

Based on the estimated impulse response function of the (3-months) interest rate differential and the spot exchange rate, we can compute the implied impulse response function of the excess return λ_t^3 on the basis of equation (3). The result is shown in the lower-left panel of Figure 2. As expected, the excess return conditional on monetary policy shocks is initially positive, and persistently so for about 4 months. Only after this period does the excess return become insignificant, reflecting that the USD no longer appreciates. Bootstrapping confidence bands on the basis of our estimated VAR model allows us to establish that the

[9]For the variables included in the VAR model, we boostrap confidence bounds; in case we run local projections, we compute standard errors as in Newey and West (1987).

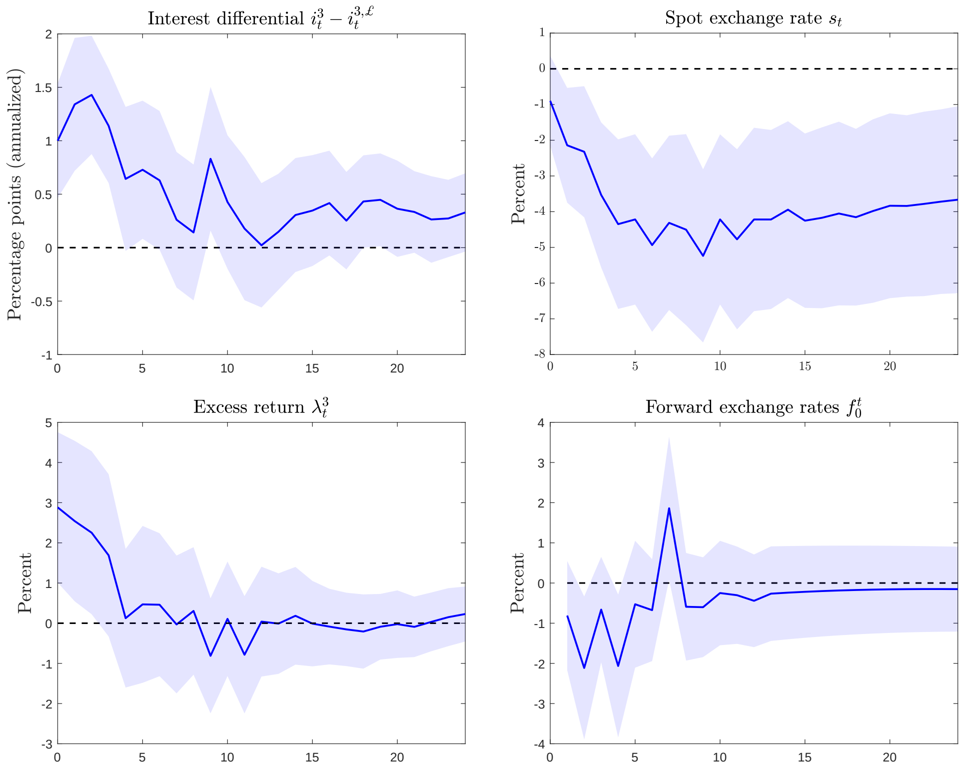

FIGURE 2. RESPONSES TO US MONETARY POLICY SHOCKS

Note: Sample: 1976:M1–2007:M12. Identification based on Romer-Romer shocks within a hybrid VAR, see Section I.A for details. Solid lines represent point estimates, shaded areas indicate 90 percent confidence bands. Horizontal axis measures time in months. Vertical axis measures deviation from pre-shock level in percentage points (interest rate differential) or in percent (for the other variables).

initial response of the excess return is statistically different from zero.[10]

In the lower-right panel we show the response of forward exchange rates *across horizons* in the period of the monetary policy shock, f_0^t.[11] We find that forward exchange rates appreciate only at the short end, by about 1-2 percent. In contrast, the response of forward exchange rates is much weaker and not significantly different from zero for longer horizons. This is in sharp contrast to the response of the spot exchange rate, which appreciates on impact and continues to appreciate over time. Thus, the gradual appreciation of the USD is not visible in

[10]A recent literature has found the dynamic response of excess currency returns to switch sign at longer horizons—the predictability reversal puzzle (for instance, Engel, 2016). However, as we stress in the introduction, the predictability reversal puzzle is an *unconditional* exchange rate puzzle, as it involves regressing excess returns λ_{t+k}^h on the interest rate differential $i_t^h - i_t^{h,*}$, rather than on monetary policy shocks as we do in our analysis. Hence, the fact that we do not find a reversal of excess returns at longer horizons is not at odds with the literature.

[11]To estimate this response, we replace x_{t+h} by f_t^h and x_{t-j} by f_{t-j}^h in the local projection (2).

the forward exchange market in the period of the shock. There is an equivalent statement of this result in terms of excess returns. Combine the CIP condition (1) and equation (3) to obtain

$$\lambda_t^h = f_t^h - s_{t+h}. \tag{4}$$

Therefore, as long as CIP holds, the excess return for horizon h represents the difference between the forward exchange rate and the realized spot rate h periods after the forward rate is quoted. The fact that f_0^t hardly responds to the shock whereas s_t appreciates over time then implies that $\lambda_0^h > 0$: The impact response of excess returns is positive across horizons. Stated differently, our analysis considers the response of excess returns λ_t^h to monetary policy shocks along two distinct dimensions. First, we find that excess returns are positive for some time after the shock, keeping the horizon constant (recall the response of λ_t^3 in the lower-left panel). Second, we find that in the impact period of the shock ($t = 0$), excess returns are positive across horizons h as well.

C. Excess returns are unanticipated

Delayed overshooting and excess returns after monetary policy shocks are sometimes taken as evidence against the uncovered interest parity (UIP) condition. However, a failure of UIP is not necessarily implied by delayed overshooting, because UIP is an ex ante relationship that makes a statement about market participants' *expectations*. In order to assess whether UIP fails, we therefore complement our empirical results with results based on exchange rate forecasts (or expectations). And indeed, in what follows, we do not find evidence that UIP fails following monetary policy shocks. Instead, our results suggest that excess returns triggered by monetary policy shocks are unanticipated.

To organize the discussion, we explicitly consider the possibility that UIP fails:

$$\gamma_t^h = i_t^h - i_t^{h,£} - (E_t^{\mathcal{P}} s_{t+h} - s_t), \tag{5}$$

where γ_t^h represents a possible failure of UIP (for instance, a currency risk premium). In turn, $E_t^{\mathcal{P}} s_{t+h}$ are investors' expectations of the spot exchange rate h periods ahead. Combine this equation with the definition of the excess return (3) to see that

$$\lambda_t^h = \gamma_t^h - (s_{t+h} - E_t^{\mathcal{P}} s_{t+h}). \tag{6}$$

Excess returns are thus either caused by a failure of UIP or by expectation errors, $s_{t+h} - E_t^{\mathcal{P}} s_{t+h}$ (see Gourinchas and Tornell (2004) for a similar decomposition of excess returns). Taking expectations of (6) shows that a failure of UIP implies that excess returns are expected to be earned by investors:

$$E_t^{\mathcal{P}} \lambda_t^h = \gamma_t^h. \tag{7}$$

In addition, from expression (4) it follows that expected excess returns can also be written as follows: $E_t^{\mathcal{P}} \lambda_t^h = f_t^h - E_t^{\mathcal{P}} s_{t+h}$. Expected excess returns, in other words, emerge when forward exchange rates and expectations about future exchange rates diverge.

These insights motivate a further experiment for which we resort to a direct measure of exchange rate expectations maintained by market participants, $E_t^{\mathcal{P}} s_{t+h}$. Specifically, we rely on survey data from fx4casts. These data are available since 1986 and reflect the consensus forecast about major currencies at a global level. On a monthly basis, participants in the foreign exchange market such as HSBC or Citigroup are surveyed about their expectations of major exchange rates several months ahead. We use data for horizons 3, 6 and 12 months, again for the USD-GBP exchange rate to estimate again the local projection (2).[12]

Figure 3 shows the results. The upper-left panel shows the impact response of the forward market across horizons (as in Figure 2, lower right-panel). Even though the sample is now shorter, the response of the forward market looks similar to our baseline. We contrast this response with the impact response of 3, 6 and 12 months exchange-rate expectations (vertical lines in red). We find that the impact response of exchange-rate expectations is not materially different from the response of the forward market. But this implies that, at least in the impact period, expected excess returns are close to zero. Using our expectation data, we can also estimate the response of expected excess returns to a monetary policy shock over time. The remaining three panels of the figure show these for the three horizons for which expectation data are available. In no case do we find that expected excess returns differ markedly from zero.

Our evidence thus suggests that excess returns on the USD conditional on monetary policy shocks are unanticipated by market participants. Put differently, we do not find evidence that delayed overshooting reflects a failure of UIP, see again equation (7). Rather, in light of equation (6), our evidence suggests that excess returns caused by monetary policy shocks reflect expectation errors of market participants.

A number of recent papers have used survey data to assess if exchange rate puzzles are due to expectation errors or due to a failure of UIP. These papers are typically concerned with unconditional exchange rate puzzles, such as the Fama puzzle (see Bussiere et al. (2022) and Kalemli-Özcan and Varela (2021) and other papers referenced in the introduction). Like our results, the evidence emerging from these studies suggests that systematic expectation errors are indeed important for understanding exchange rate puzzles. What sets our analysis apart from these studies is that we are concerned with a *conditional* puzzle: the delayed-

[12] fx4casts also provide data for 1 and 24-months expectations but only from 2008M7 onwards.

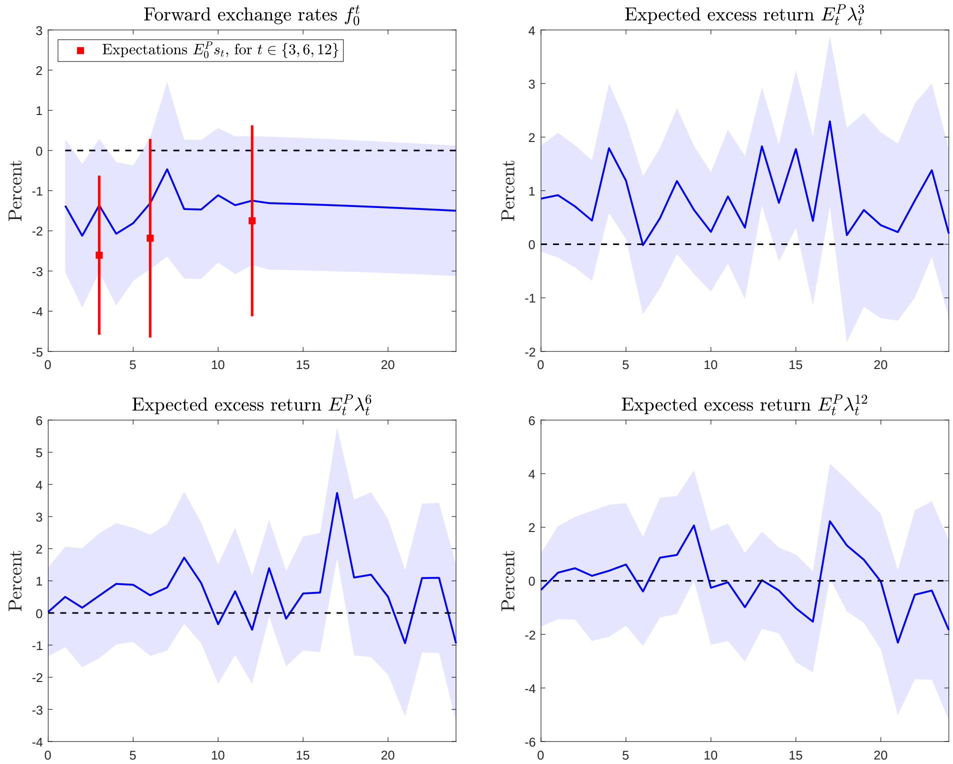

Figure 3. Response of Forecast Data to US Monetary Policy Shocks

Note: Sample constrained by data on exchange rate expectations: 1986:M8–2007:M12. Local projection on cleansed RR shocks. Solid lines represent point estimate, shaded areas indicate 90 percent confidence bands. In the upper-left panel, the vertical red lines indicate 90 percent confidence bands. Horizontal axis measures time in months. Vertical axis measures deviation from pre-shock level in percent.

overshooting response of the exchange rate following monetary policy shocks. To the best of our knowledge, ours is the first paper to study if UIP fails in this conditional sense.

We conclude this section with a qualification. The evidence established here relies on a fairly small survey of exchange rate expectations. Moreover, we observe only the average of a potentially heterogeneous group of forecasters. For this reason, our results are suggestive only and further evidence may be considered necessary to support our interpretation that delayed overshooting does not reflect a failure of UIP. That said, we find it reassuring that the model we put forward in the next section can, despite its simplicity, account very well for delayed overshooting—without relying on a failure of UIP.

II. The model

Our point of departure is a standard New Keynesian open-economy model. Consistent with our empirical findings, we assume that UIP holds at all times in the model. At the same time, the model may account for delayed overshooting in response to monetary policy shocks because it features information rigidities. As a result, excess returns arise due to persistent expectation errors by market participants. We estimate the model and show that it can account for the evidence not only qualitatively but also quantitatively.

A. Setup

We extend the New Keynesian small-open economy model due to Galí and Monacelli (2005) 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. While we maintain the assumption of rationality, we depart from full-information rational expectations (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 (Melosi, 2017; Nakamura and Steinsson, 2018). The private sector learns about fundamentals only gradually as new information arrives, in line with recent insights about the way expectations are formed following macroeconomic shocks (Coibion and Gorodnichenko, 2012, 2015).

Such a framework appears adequate because our measure for monetary policy shocks employed above is not directly observable by market participants: The Fed's Greenbook, on which the construction of these shocks is based, is published only with a five-year delay. For this reason, we assume in the model that monetary policy shocks are likewise unobserved (as is the natural rate of interest).

Except for the information friction, our model setup is standard. The domestic country is small such that domestic developments have no bearing on the rest of the world. A unit mass of monopolistically competitive firms produce a variety of goods which are consumed domestically and 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 temporarily 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 household and firm problem to the Online Appendix. In what follows, we provide a compact exposition of the approximate equilibrium conditions and discuss expectation formation in detail.

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:

$$\pi_t = \beta E_t^{\mathcal{P}} \pi_{t+1} + \kappa(y_t - E_t^{\mathcal{P}} y_t^n), \tag{8}$$

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, $E_t^{\mathcal{P}} y_t^n$, rather than on potential output y_t^n itself. The superscript $\mathcal{P}$ of the expectation operator $E_t^{\mathcal{P}}$ 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 follows as we combine market clearing for domestically produced goods with the condition for international risk sharing (Backus and Smith, 1993). It establishes a link between domestic output and the real exchange rate:

$$\theta(y_t - y^*) = s_t + p^* - p_t. \tag{9}$$

Here θ^{-1} denotes the elasticity of intertemporal substitution, 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 (9) 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

$$q_t = (1-\omega)(s_t + p^* - p_t), \tag{10}$$

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.

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

$$E_t^{\mathcal{P}} \Delta s_{t+1} = i_t - i^*. \tag{11}$$

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 $E_t^{\mathcal{P}} \Delta s_{t+1}$ is conditional on the information available to investors at time t.

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

$$i_t = r_t^n + \phi \pi_t + u_t. \tag{12}$$

Here the central bank responds to inflation, with $\phi > 1$, 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. From the perspective of market participants, 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.

In order to confront the model predictions with the evidence established in Section I, 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

$$f_t^h = E_t^{\mathcal{P}} s_{t+h}. \tag{13}$$

Intuitively, the fact that both covered and uncovered interest parity hold at all times in our model implies that the forward rate equals market-based expectations of the spot rate in period $t+h$. The excess return on domestic currency at horizon h can then be defined as in equation (4) above:

$$\lambda_t^h = f_t^h - s_{t+h} = -(s_{t+h} - E_t^{\mathcal{P}} s_{t+h}), \tag{14}$$

where the second equality uses equation (13). The excess return reflects (the negative of) the expectation error in the foreign exchange market. Taking expectations of the last equation, we see that $E_t^{\mathcal{P}} \lambda_t^h = 0$. Hence, expected excess returns are zero at all times in the model.

We now turn to the shock processes which generate the model dynamics. We assume that the monetary policy shock follows an autoregressive process of order one:

$$u_t = \rho_u u_{t-1} + \varepsilon_t^u, \quad \varepsilon_t^u \sim \mathcal{N}(0, \sigma_u^2), \tag{15}$$

with $0 \leq \rho_u < 1$. 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:

$$\Delta y_t^n = \rho_y \Delta y_{t-1}^n + \varepsilon_t^y, \quad \varepsilon_t^y \sim \mathcal{N}(0, \sigma_y^2), \tag{16}$$

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

$$r_t^n \equiv (i_t - E_t^{\mathcal{F}} \pi_{t+1})|_{\kappa=\infty} = \bar{r} + \theta E_t^{\mathcal{F}} \Delta y_{t+1}^n = \bar{r} + \theta \rho_y \Delta y_t^n, \tag{17}$$

where $\bar{r} = -\log(\beta) > 0$ and where $E_t^{\mathcal{F}}$ is the expectation operator under full information (in which case potential output is perfectly observed by private agents: $E_t^{\mathcal{F}} y_t^n = y_t^n$). Equation (17) reveals that the natural rate is a function of potential output y_t^n. It shows that when potential output rises, the natural rate increases temporarily, as this foreshadows a growing economy.[13]

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, potential output y_t^n and hence the natural rate (see equation (17)) are *not* directly observed by private agents. However, in each period t private agents learn about potential output in two ways.

[13]The fact that we model natural output as a growth process is motivated by the findings in Nakamura and Steinsson (2018). They document a positive correlation between unconditional interest-rate surprises and changes in private-sector expectations about future output growth—a finding which our model can replicate (see Section IV). In contrast, by specifying natural output as an autoregressive process in *levels*, a higher natural rate would reflect a drop in current natural output and hence our model would produce the opposite correlation. It turns out that this also matters for the ability of our model to match the evidence regarding the behavior of exchange rates. As we illustrate in Section III, our model can account for the evidence because a rise in the natural rate is associated with an exchange rate depreciation (ultimately caused by rising natural output). In contrast, the specification in levels would imply that a rise in the natural rate is associated with an exchange rate appreciation (because natural output is temporarily reduced). More generally, our insights apply to any specification in which a rise in the natural rate is associated with an exchange rate depreciation, independent of the underlying driver of the natural rate.

First, there is a signal given by

$$\varsigma_{1,t} = y_t^n + \eta_t, \tag{18}$$

where $\eta_t \sim_{iid} \mathcal{N}(0, \sigma_\eta^2)$ represents stochastic noise. In the micro-foundation that we present in the Online 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. Intuitively, 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 (18).

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

$$\varsigma_{2,t} = r_t^n + u_t = \bar{r} + \theta \rho_y \Delta y_t^n + u_t. \tag{19}$$

The interpretation of this signal is straightforward: The private sector, by observing the policy rate and inflation, observes the sum of the natural rate and u_t, given the interest rate rule (12). For the private sector, the monetary policy shock u_t can thus be viewed as stochastic noise in the signal it receives by observing the central bank. The key feature of our setting is that, whenever private agents observe a rise in the policy rate i_t, they do not know whether this represents a monetary policy shock or a rise in the natural rate of interest.

Formally, the expectation operator $E_t^{\mathcal{P}}$ can be written as $E(\cdot|\mathcal{I}_t)$, 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 in y_t^n and u_t, and because we assume that expectations are rational, private agents solve the signal extraction problem by using the Kalman filter.[14] 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 the FIRE benchmark. Both of these features are consistent with empirical evidence on how expectations adjust to macroeconomic shocks (Coibion and Gorodnichenko, 2012). The Kalman filter is represented by

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

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 an observation equation

$$\begin{pmatrix} \varsigma_{1,t} \\ \varsigma_{2,t} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ \theta\rho_y & -\theta\rho_y & 1 \end{pmatrix} \begin{pmatrix} y_t^n \\ y_{t-1}^n \\ u_t \end{pmatrix} + \begin{pmatrix} \eta_t \\ 0 \end{pmatrix} = H \begin{pmatrix} y_t^n \\ y_{t-1}^n \\ u_t \end{pmatrix} + \begin{pmatrix} \eta_t \\ 0 \end{pmatrix}. \tag{20}$$

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

$$E_t^{\mathcal{P}} \begin{pmatrix} y_t^n \\ y_{t-1}^n \\ u_t \end{pmatrix} = F E_{t-1}^{\mathcal{P}} \begin{pmatrix} y_{t-1}^n \\ y_{t-2}^n \\ u_{t-1} \end{pmatrix} + K_t \left(\begin{pmatrix} \varsigma_{1,t} \\ \varsigma_{2,t} \end{pmatrix} - H F E_{t-1}^{\mathcal{P}} \begin{pmatrix} y_{t-1}^n \\ y_{t-2}^n \\ u_{t-1} \end{pmatrix} \right). \tag{21}$$

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.

B. *Estimation*

We estimate key model parameters by matching impulse response functions, as in Rotemberg and Woodford (1997) and Christiano et al. (2005). 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.

Because our empirical analysis is based on monthly observations, we let a period in the model represent one month. We set $\beta = 0.9966$, implying that the annualized real interest rate in steady state equals four percent. We assume that $\theta^{-1} = 0.25$ for the elasticity of intertemporal substitution, in line with recent evidence (Havránek, 2015; Best et al., 2019). We use the conventional value for the interest-rate rule coefficient and set $\phi = 1.5$. For the degree of openness we assume $\omega = 0.15$, because imports account for roughly 15% of GDP in the US in the last decades.

The parameters to be estimated are κ—the slope of the Phillips curve—and the persistence and standard deviation of the shock processes which govern the extent of information rigidities. We estimate the slope of the Phillips curve, because the response of the nominal exchange rate is very sensitive to the degree of nominal rigidity in the model. We collect the parameters to be estimated in the vector $\varphi = [\kappa, \rho_u, \rho_y, \sigma_y, \sigma_\eta]'$. Note that φ does not include the standard deviation of monetary innovations σ_u because what matters for the Kalman filter (21) are the variance (signal-to-noise) *ratios*. Therefore, without loss of generality, we may normalize one of the standard deviations and set $\sigma_u = 0.1$. Notice that the full-information case is nested as a special case in our model: When $\sigma_\eta = 0$, the signal $\varsigma_{1,t}$ is perfectly informative about the level of potential output (see equation (18)).

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

$$\hat{\varphi} = argmin_{\varphi} \; (\hat{\Lambda}^{emp} - \Lambda^{model}(\varphi))'\hat{\Sigma}^{-1}(\hat{\Lambda}^{emp} - \Lambda^{model}(\varphi)). \tag{22}$$

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 4 shows the result of the estimation. It shows the 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 spot exchange rate very 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 I. Second, the estimated model tracks the impact response of forward exchange rates very well, too. In particular, the model predicts 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 positive excess return 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 I. Absent information rigidities, instead, the model has a hard time matching the empirical impulse responses. In this case, in fact, the spot rate response is characterized by overshooting as in

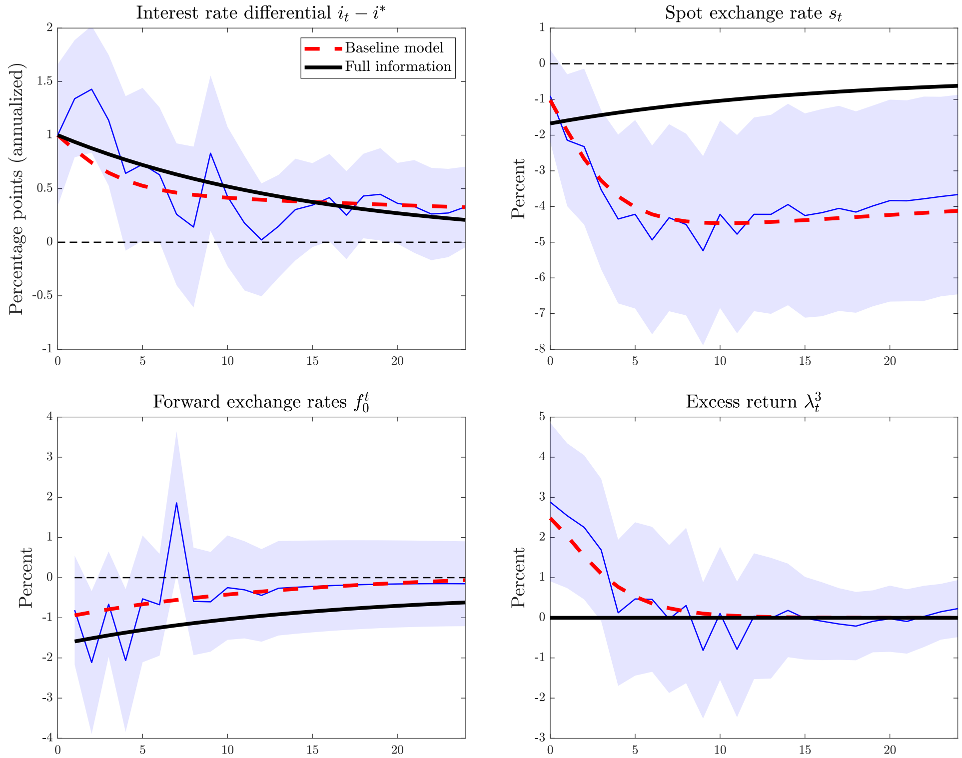

FIGURE 4. RESPONSES TO MONETARY POLICY SHOCK: MODEL V DATA

Note: 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 months. Vertical axis measures deviation from pre-shock level in percentage points (interest rate differential) or in percent (for the other variables).

Dornbusch (1976). Moreover, the impact response of the forward rate predicts perfectly the future path of the spot rate. Last, under full information, the excess return in response to the shock is equal to zero.

In Table 1 we report the implied parameter estimates, including standard errors in parentheses.[15] The Phillips curve is estimated to be very flat, with $\kappa = 0.0006$. Yet, recall that we calibrate our model to monthly frequency—the annual slope coefficient would be correspondingly higher. Also, our estimate is in the ballpark of recent estimates of a very flat Phillips curve in the US (Hazell et al.,

[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.

Table 1—Parameter Estimates

Parameter	κ	ρ_y	ρ_u	σ_y	σ_η
Estimate	0.0006 (0.0001)	0.91 (0.066)	0.98 (0.002)	0.21 (0.257)	0.10 (0.031)

Note: Estimates based on impulse response matching approach. Standard errors in parentheses.

2022). The shock process for potential output growth features an autocorrelation of $\rho_y = 0.91$, 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 different normalization for σ_u would also imply that σ_y is estimated to be different. As for the monetary policy shock, we estimate a high degree of autocorrelation ($\rho_u = 0.98$). This reflects that, to keep the analysis simple, we have abstracted from interest rate smoothing in the Taylor rule. Therefore, the persistence of the interest rate differential 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 $\sigma_\eta = 0.1$, and is highly statistically significant. Recall that the full information model corresponds to the case $\sigma_\eta = 0$. Our estimates therefore reject the full information version of the model.

C. 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 (21) describes the perceived evolution of the monetary policy shock, $E_t^{\mathcal{P}} u_t$. Under full information, it holds that $E_t^{\mathcal{P}} u_t = u_t$. The last row of the Kalman gain matrix K then implies two parametric restrictions. Formally, the last row of K becomes

$$\varepsilon_t^u = \begin{pmatrix} K_{3,1} & K_{3,2} \end{pmatrix} H \begin{pmatrix} \varepsilon_t^y \\ 0 \\ \varepsilon_t^u \end{pmatrix} = \begin{pmatrix} K_{3,1} & K_{3,2} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ \theta\rho_y & -\theta\rho_y & 1 \end{pmatrix} \begin{pmatrix} \varepsilon_t^y \\ 0 \\ \varepsilon_t^u \end{pmatrix}, \tag{23}$$

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, $K_{3,1} = K_{3,2} = 0$.[16]

We can quantify the degree of information frictions that is 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 $-\hat{K}_{3,1}/(\theta\rho_y) = 0.172$ and $\hat{K}_{3,2} = 0.199$. Note that the second statistic is a measure of the information content of the signal from the central bank.[17] It implies that when private agents observe a policy rate increase, they attach a probability weight of about 20 percent to this representing 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 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.

III. 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.

A. Full information benchmark

As explained above, our model nests the FIRE case 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. When solving the model numerically, we use the estimated parameters obtained in 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 interest rate differential $i_t - i^*$ rises and slowly converges back to zero. The right panel shows that the nominal exchange rate s_t appreciates, both on impact and (very modestly) in the long run. Yet, after the impact period, the exchange rate depreciates as it converges to its new long-run level from below.

[16] 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 $\sigma_y^2 = \infty$.

[17] To see this, note from equation (23) that $K_{3,2}$ multiplies the second row of H, which, from the observation equation (20), captures the signal from the central bank.

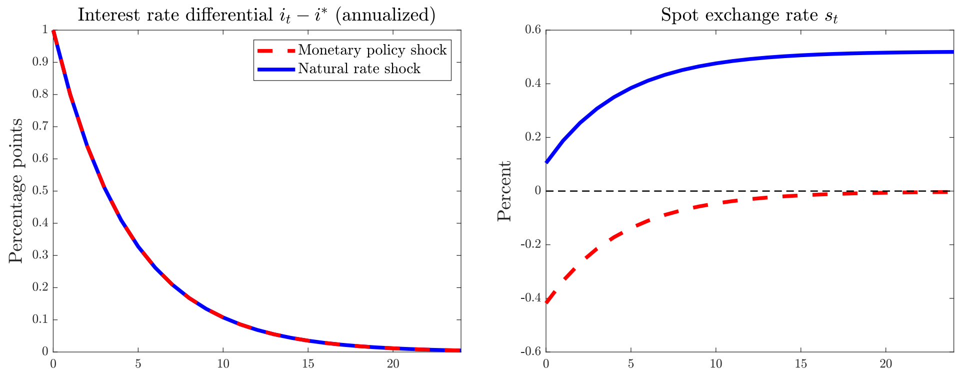

FIGURE 5. IMPULSE RESPONSES UNDER FULL INFORMATION

Note: Responses 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 II.B.

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 (9), 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, $s_\infty < s_{-1}$.[18]

The second equation is the UIP condition (11), 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

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

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

A monetary contraction implies a surprise increase of the interest rate differential at time 0, $i_0 - i^* > 0$. After this period, all uncertainty is resolved. This implies $E_t^{\mathcal{F}} \Delta s_{t+1} = \Delta s_{t+1}$, because under FIRE, agents are not making expectation errors absent fundamental surprises. Hence, we can write $i_t - i^* = \Delta s_{t+1}$,

[18]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. In our estimated model, the long-run levels p_∞ and s_∞ are not far below zero because we have estimated the Phillips curve to be very flat.

for $t \geq 0$. A positive interest rate 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 therefore overshoots.

Focus next on the natural rate shock. According to equation (16), 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 equation (17). According to the interest rate rule (12), 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 (9). 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.[19]

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.[20]

B. *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 rise in inflation. In Figure 6, we illustrate the extent of misperception 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 0.095 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 of the economy following a monetary policy shock, the actual response of the natural rate is equal to zero.

[19]Empirical evidence that growing countries experience a real depreciation through a worsening of their terms of trade is provided by Acemoglu and Ventura (2002).

[20]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.

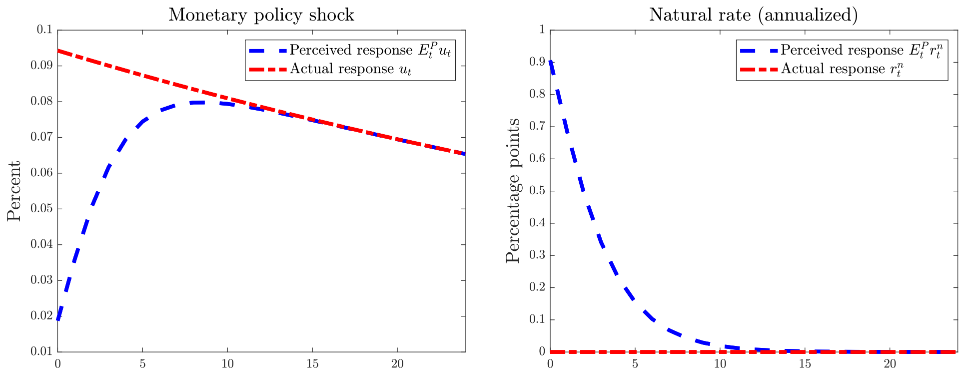

FIGURE 6. PERCEIVED V ACTUAL SHOCKS

Note: Dashed (blue) line is perceived monetary policy shock (left) and natural rate (right) in the estimated model with information rigidities. Dashed-dotted (red) line is the actual shock in both instances.

As Figure 6 shows, agents initially attach a small probability weight to a monetary policy shock, as $E_t^{\mathcal{P}} u_t$ rises only by 0.019 percent on impact—about one fifth the actual rise of u_t.[21] In turn, 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 interest rate differential to a mix of a monetary policy shock and a natural rate increase. By observing the response of the economy, agents update their beliefs over time. According to our estimates, the learning process is completed about 12 months after the shock.

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

$$s_0 = -E_0^{\mathcal{P}} \sum_{j=0}^{\infty} (i_j - i^*) + E_0^{\mathcal{P}} s_\infty. \tag{24}$$

This expression shows that the impact response of the exchange rate is governed by the expected interest rate differential and the expected long-run value of the exchange rate. The interest rate differential evolves similarly under monetary policy shocks and natural rate shocks, as we have argued before. However, the

[21] Recall that the probability weight attached to a monetary policy shock following a signal by the central bank is about 20 percent, see Section II.C.

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, $E_0^{\mathcal{P}} s_\infty > 0$. 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 (13)). Iterating forward the UIP condition (11) 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:

$$f_0^t = E_0^{\mathcal{P}} s_t = -E_0^{\mathcal{P}} \sum_{j=0}^{\infty} (i_{t+j} - i^*) + E_0^{\mathcal{P}} s_\infty. \tag{25}$$

Since the expected long-run value of the exchange rate $E_0^{\mathcal{P}} s_\infty$ 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 equation (24). 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 to market participants.[22]

We next explore how the exchange rate evolves dynamically over time. Evaluating equation (11) in a generic period $t > 0$ and $t + h > 0$, where $h > 0$, yields

$$s_t = -E_t^{\mathcal{P}} \sum_{j=0}^{\infty} (i_{t+j} - i^*) + E_t^{\mathcal{P}} s_\infty \tag{26}$$

and

$$s_{t+h} = -E_{t+h}^{\mathcal{P}} \sum_{j=0}^{\infty} (i_{t+h+j} - i^*) + E_{t+h}^{\mathcal{P}} s_\infty. \tag{27}$$

Assume now that $E_{t+h}^{\mathcal{P}} s_\infty < E_t^{\mathcal{P}} s_\infty$, such that agents have updated their expectations regarding the long-run value of the exchange rate. Specifically, in period $t + h$ they consider a long-run appreciation more likely compared to period t, because they have revised upwards the probability that a monetary policy shock has hit the economy (see Figure 6). Combining equations (26) and (27) reveals

[22]Note from equation (25) that, to the extent that the interest rate differential $i_{t+j} - i^*$ is positive, f_0^t is monotonically rising in t, reaching $E_0^{\mathcal{P}} s_\infty$ as $t \to \infty$. The fact that f_0^t monotonically rises in theory is also borne out empirically, see Figure 4.

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.

Finally, these dynamics imply that excess currency returns conditional on monetary policy shocks are positive. Formally, we can write

$$\lambda_t^h = -(s_{t+h} - E_t^{\mathcal{P}} s_{t+h}) = E_t^{\mathcal{P}} \sum_{j=0}^{h-1} (i_{t+j} - i^*) - (s_{t+h} - s_t) > 0. \tag{28}$$

The first equality is equation (14). The second equality takes time-t conditional expectations in (27) and uses equation (26) and the law of iterated expectations to replace $E_t^{\mathcal{P}} s_{t+h}$. The excess return is the horizon-h expected interest rate differential (the h-period long-term interest rate) net of the actual depreciation of the exchange rate over that horizon. The inequality sign then results from combining $s_{t+h} < s_t$ (the exchange rate has appreciated dynamically over time, see above) and the fact that $E_t^{\mathcal{P}} \sum_{j=0}^{h-1} (i_{t+j} - i^*) > 0$, that is, the interest rate differential is positive.

IV. External validation: The effect of interest-rate surprises

We now make an attempt to validate our model-based account on the basis of evidence that we have not used to estimate the model. We do so by looking at unconditional interest-rate surprises and their effect on the economy. According to our model, such interest-rate surprises are related to but conceptually distinct from monetary policy shocks. However, a number of recent contributions have used interest-rate surprises either as a direct measure or as a proxy for monetary policy shocks, following the pioneering work by Kuttner (2001), Gürkaynak et al. (2005) and Gertler and Karadi (2015).

In line with common practice in the literature, we define interest-rate surprises as an adjustment of expectations about future interest rates, of the form

$$\phi_t \equiv E_t^{\mathcal{P}} i_{t+h} - E_{t-1}^{\mathcal{P}} i_{t+h}, \tag{29}$$

where $h \geq 0$. Stated differently, interest-rate surprises represent the change of an h-months interest-rate futures contract following the arrival of new information. As in Jarociński and Karadi (2020), we set $h = 3$ thereby capturing an update of interest-rate expectations based on a three-month future. Results are robust for different values of h.

Because the central bank changes interest rates in response to both monetary policy shocks and changes in the natural rate in our model, interest-rate surprises are endogenous and generally reflect both a monetary policy shock and a natural rate component. As discussed above, the notion that interest-rate surprises are not necessarily fundamental shocks but may convey information about the state of the economy has already been highlighted by a number of influential contributions (see also Jarociński and Karadi, 2020; Miranda-Agrippino and Ricco, 2021).

Recall that our model accounts for delayed overshooting, because interest-rate surprises give rise to a signal extraction problem as private agents try to infer their underlying components. To confirm that our model captures well this signal extraction problem, in what follows we show that our model replicates the impulse responses to an empirical measure of unconditional interest-rate surprises. We obtain model responses through simulations based on the same set of parameter values that we have estimated in Section II.B. By not reestimating the model, we therefore seek to validate our model with external evidence along a key dimension of our theory.

To obtain empirical impulse responses to interest-rate surprises, we rely on the time-series of surprises compiled by Jarociński and Karadi (2020). They measure the change in the three months fed funds future in a narrowly defined window around FOMC announcements.[23] The time series of surprises is available since 1990 only, such that our sample is now shorter than in Section I. Based on this shorter sample (1990:M1–2007:M12), we estimate the impulse responses to interest-rate surprises using again the local projection (2), while replacing $\tilde{u}_t$ with ϕ_t. We estimate the response of the USD-GBP nominal exchange rate as well as the response of two macroeconomic indicators: US industrial production and the consumer price index (CPI). For the sake of comparison, we also reestimate on the new sample the responses of the same variables to our measure of monetary policy shocks, $\tilde{u}_t$. Figure 7 shows the results. As in Figure 2 above, the blue solid lines represent the point estimate while shaded areas are confidence bands. The left column shows the impulse responses to a monetary policy shock, the right column shows the responses to an interest-rate surprise.[24]

Focus first on the response of the exchange rate shown in the top panels. Even though the sample is now different, the USD still displays delayed overshooting following the monetary policy shock, as in our baseline. In sharp contrast, the response of the USD following an interest-rate surprise is quite different, not only quantitatively but also qualitatively. After an impact-appreciation, the USD depreciates over time and displays no sign of delayed overshooting. This is consistent with the results by Rüth (2020), who finds that the USD overshoots following an

[23]Jarociński and Karadi (2020) estimate a VAR model with sign restrictions to identify monetary policy shocks on the basis of these unconditional interest-rate surprises. Interestingly, this methodology likely uncovers a different type of monetary policy shock than the true shock u_t in our model. This happens because their sign restrictions impose the received wisdom about the effects of monetary policy shocks on macro variables (such as a decline in the stock market), whereas the u_t in our model triggers quite non-standard responses of macro variables due to the information rigidity. For instance, if the information rigidity is severe enough, a rise in u_t may actually lead to a rise in the stock market in our model, as market participants initially mistake the associated rise in the central bank's policy rate for a rise in the natural rate of interest.

[24]Throughout, we normalize the size of the impulse responses so that i) the interest rate differential (annualized) equals one percentage point on impact in the model and ii) the cumulative increase of the interest rate differential is the same in model and data. We use the cumulative rather than the impact response of the interest rate differential to scale the empirical responses in order to account for differences in the persistence of the interest rate differential responses across model and data.

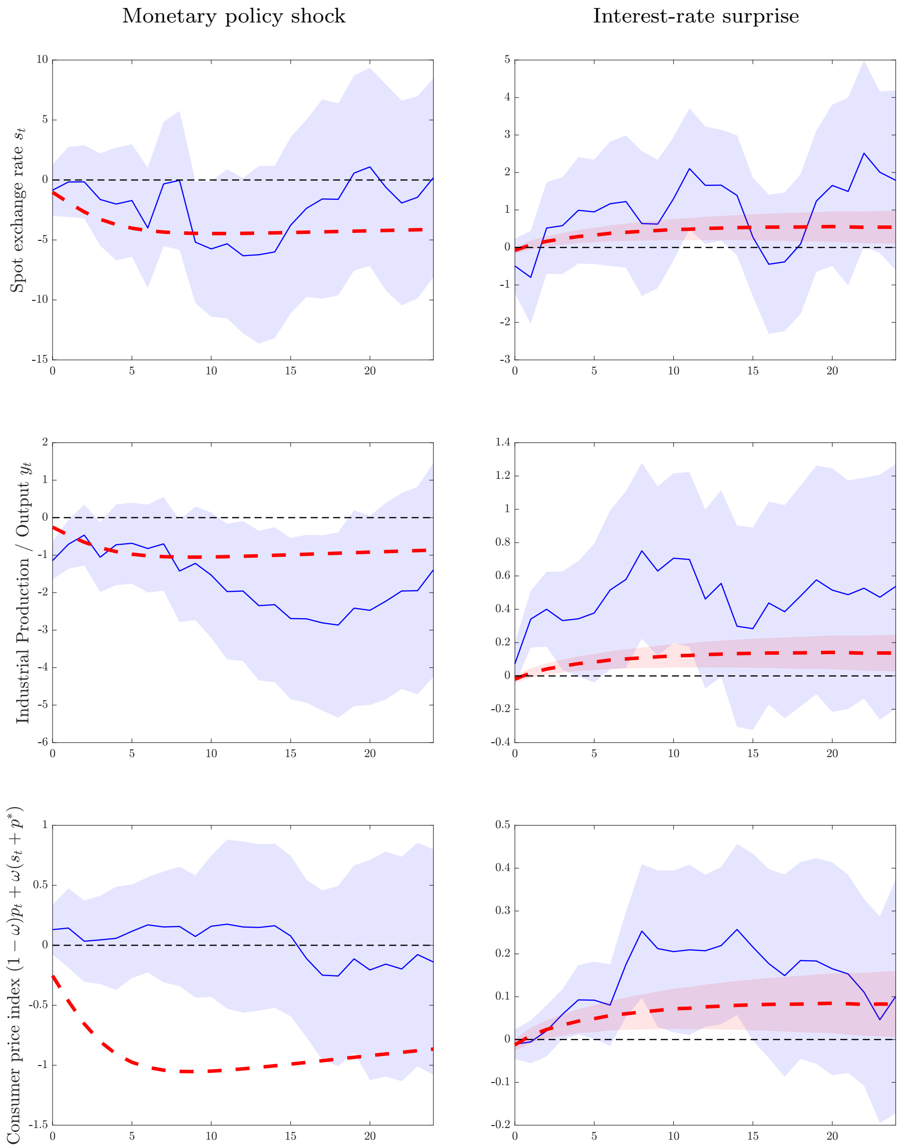

FIGURE 7. MONETARY POLICY SHOCK V INTEREST-RATE SURPRISE

Note: Impulse responses to monetary policy shocks (left) and interest-rate surprises (right). Solid (blue) line represents empirical impulse response functions (point estimate) with shaded area indicating confidence bounds. Dashed (red) line represents model-based impulse responses. The horizontal axis measures time in months. Vertical axis measures deviation from pre-shock level in percent.

interest-rate surprise. In contrast to Rüth (2020) we find that the USD depreciates so much over time that it ends up depreciating in the long term. While this result may appear puzzling, it is in line with recent evidence by Gürkaynak et al.

(2021) who find that an interest-rate surprise may very well lead to a depreciation of the exchange rate (see also Stavrakeva and Tang, 2019). And moreover, as we show below, this result is also in line with the prediction of our model.

As discussed above, delayed overshooting following monetary policy shocks implies that the dollar earns positive excess returns in the first periods after the shock. Interest-rate surprises do not give rise to delayed overshooting. Consistent with this observation, we find that excess returns are not significantly different from zero following interest-rate surprises, see Rüth (2020) as well as our Online Appendix. Our model offers a perspective why this might be the case. Excess returns in response to monetary policy shocks do not represent unexploited profit opportunities because these shocks are not observable by market participants. Interest-rate surprises, in contrast, are by their very nature immediately observable to market participants. If UIP holds, this implies the exchange rate must depreciate over time following interest-rate surprises, to rule out arbitrage opportunities.

Turning to macroeconomic indicators (shown in the second and third row of the figure), we find again that interest-rate surprises induce adjustment dynamics which differ fundamentally from those triggered by monetary policy shocks. We find that industrial production declines following monetary policy shocks, but rises following interest-rate surprises. Similarly, we find that the CPI tends to decline following monetary policy shocks (albeit not significantly for this sample), but rises following an interest-rate surprise.[25] The fact that industrial production may rise following interest-rate surprises for specific sample periods has puzzled several observers (see, for instance, Ramey, 2016).[26] Nakamura and Steinsson (2018) obtain a related (puzzling) result: They find that interest-rate surprises also tend to raise *expectations* of future output growth.

Figure 7 also contrasts the empirical impulse responses with the predictions of the model. We compute the model responses to interest-rate surprises on the basis of a Monte-Carlo simulation. Specifically, we simulate observations based on the estimated model for 216 periods (the same number of periods as months in our empirical analysis) and estimate local projection (2) on the simulated data. We repeat this analysis 100 times and report the average response (red dashed lines in the figure). The shaded area (red) indicates confidence bands, computed on the basis of the (pointwise) standard deviations across simulations. Overall, the model predictions align well with the evidence, at least qualitatively. Regarding the exchange rate response, the model predicts delayed overshooting following a monetary policy shock, but a gradual depreciation over time following an interest-

[25]For this sample period, the CPI is fairly unresponsive to the monetary policy shock, a finding that has been documented before (see, for instance, Ramey, 2016). However, the CPI declines significantly according to the VAR model which we estimate in Section I on the full sample (1976:M1 to 2007M12), see the Online Appendix.

[26]See Panel B of Figure 3 in Ramey (2016) in particular. Ramey's discussion centers around differences between VAR models and local projections. Our explanation, instead, highlights the potential natural rate component of interest-rate surprises (see below).

rate surprise. In fact, the model even predicts that the exchange rate depreciates in the long run. A similar pattern obtains for industrial production, proxied by output y_t. The model predicts a decline of output following a monetary policy shock, but a *rise* of output following an interest-rate surprise. Last, the model predicts a decline in the CPI following a monetary policy shock, but a rise in prices following an interest-rate surprise.

To understand the predictions by the model, recall from the discussion above that interest-rate surprises are endogenous and represent a "mix" of monetary policy shocks and changes in the natural rate. As we have shown in Section III, following natural rate shocks the exchange rate depreciates and output increases in our model. Because our estimation implies that a substantial part of interest-rate surprises is indeed due to natural rate shocks (see Section II.C), the model predicts that the exchange rate depreciates and output rises following interest-rate surprises. Last, the rise in the consumer price index is driven by the nominal depreciation of the exchange rate. In fact, the producer price index p_t slightly declines following an interest-rate surprise in our estimated model (not shown). Because the consumer price index contains an "import component", $\omega(s_t + p^*)$, this explains why the consumer price index actually rises following an interest-rate surprise in our model.

Last, our model can also account for the finding by Nakamura and Steinsson (2018) regarding the response of output growth expectations. In our estimated model, an interest-rate surprise that raises the one-year interest rate by one percentage point raises expectations about one-year-ahead output growth by 0.28 percentage points. This number is somewhat smaller but still comparable to the numbers reported by Nakamura and Steinsson.

In sum, we find that our model passes an important external validity check because it can account for various moments that have not been targeted in the estimation. First, it can account for the response of macroeconomic indicators following monetary policy shocks. Second and more importantly, it can also account for various impulse responses to unconditional interest-rate surprises.

V. Conclusion

The delayed overshooting puzzle is one of the most long-standing empirical puzzles in international macroeconomics. What accounts for the delayed overshooting puzzle? In this paper, we first provide new empirical evidence which suggests that delayed overshooting reflects a sluggish adjustment of exchange-rate expectations by market participants, rather than a failure of uncovered interest parity (UIP). We show, in particular, that a contractionary US monetary policy shock causes the USD to earn excess returns which, however, come as a surprise to investors.

We then show that a straightforward modification of the New Keynesian open-economy model ensures that the model predictions align well with the evidence. In the model UIP holds but there are information rigidities: Market participants do not directly observe the natural rate of interest and monetary policy shocks.

Instead, observing an interest-rate surprise they face a signal extraction problem and update their beliefs rationally. We estimate the model by matching the impulse responses to monetary policy shocks but verify that the estimated model can also account for impulse responses to unconditional interest-rate surprises, which are distinct from monetary policy shocks in the context of our analysis.

A large literature has sought to account for various exchange rate puzzles by departing from the assumption of full-information rational expectations (FIRE), typically by relying on departures from rationality (the "RE"). While there may be departures from rationality in the data, in this paper we showcase that those may not be behind the classic phenomenon of delayed overshooting in response to monetary policy shocks. Instead, we point to the inherent unobservability of monetary policy shocks, that is, to a departure from full information (the "FI") as causing delayed overshooting. We leave for future research to figure out how to connect this insight with the broader set of observations which are suggestive of a failure of RE in exchange rate data.

In concluding, we stress that our analysis is purely positive and does not study the implications for optimal policy. So far, discussions of optimal monetary policy in the context of the information effect are limited to closed-economy settings (Nakamura and Steinsson, 2018; Jia, 2019). Hence, we believe that a systematic exploration of optimal monetary policy in the presence of information rigidities which accounts for the open-economy dimension is a promising area for future research.

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Online Appendix
for "Delayed Overshooting: The Case for Information Rigidities"

Gernot J. Müller, Martin Wolf and Thomas Hettig

A1. Empirical Analaysis

In this Appendix, we complement our empirical results from the main text.

Forward and yield curve data. — In Figure A1 in this appendix, we show the counterpart of Figure 1 from the main text for the 1, 3 and 6-months horizon (see Section I.A). Again we find that the interest rate differentials based on the forward-discount and based on yield curve data, in periods where both time series are available, line up very well.

Baseline VAR. — In Figure A2 in this appendix, we report impulse responses of all variables to the monetary policy shock in our baseline VAR (see Section I.A). We find that our cleansed measure of Romer and Romer shocks produces sensible results for all variables included in the VAR. The upper-left panel shows that industrial production declines and 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 industrial production has declined approximately 0.7 percent relative to its pre-shock level. The upper-right panel shows the response of the consumer price index. Initially, prices adjust sluggishly. We observe a significant decline of prices only after about 8-10 months, again a familiar finding of earlier studies. However, the price level continues to decline markedly afterwards. The middle-left panel shows the response of the unemployment rate. Unemployment raises markedly after the shock, with a maximum effect of a 0.2 percentage points higher unemployment rate about 1 year after the shock. The middle-right panel shows the commodity price index. It declines markedly following the shock, by about 2 percent after 2 years. In turn, the panels in the last row show the responses of the interest rate differential and the spot exchange rate, and have been discussed in the main text (see Section I.B).

Excess returns following interest-rate surprises. — In Section IV we have shown that monetary policy shocks trigger delayed overshooting of the USD whereas unconditional interest-rate surprises do not. Consistent with this pattern, there are positive excess returns on the USD following monetary policy shocks, but excess returns are small following interest-rate surprises. We show this in Figure A3 in this appendix. The left panel shows excess returns following monetary policy shocks. The response is rather volatile, driven by the fact that our sample is (much) shorter than in Section I implying that the estimated response of the

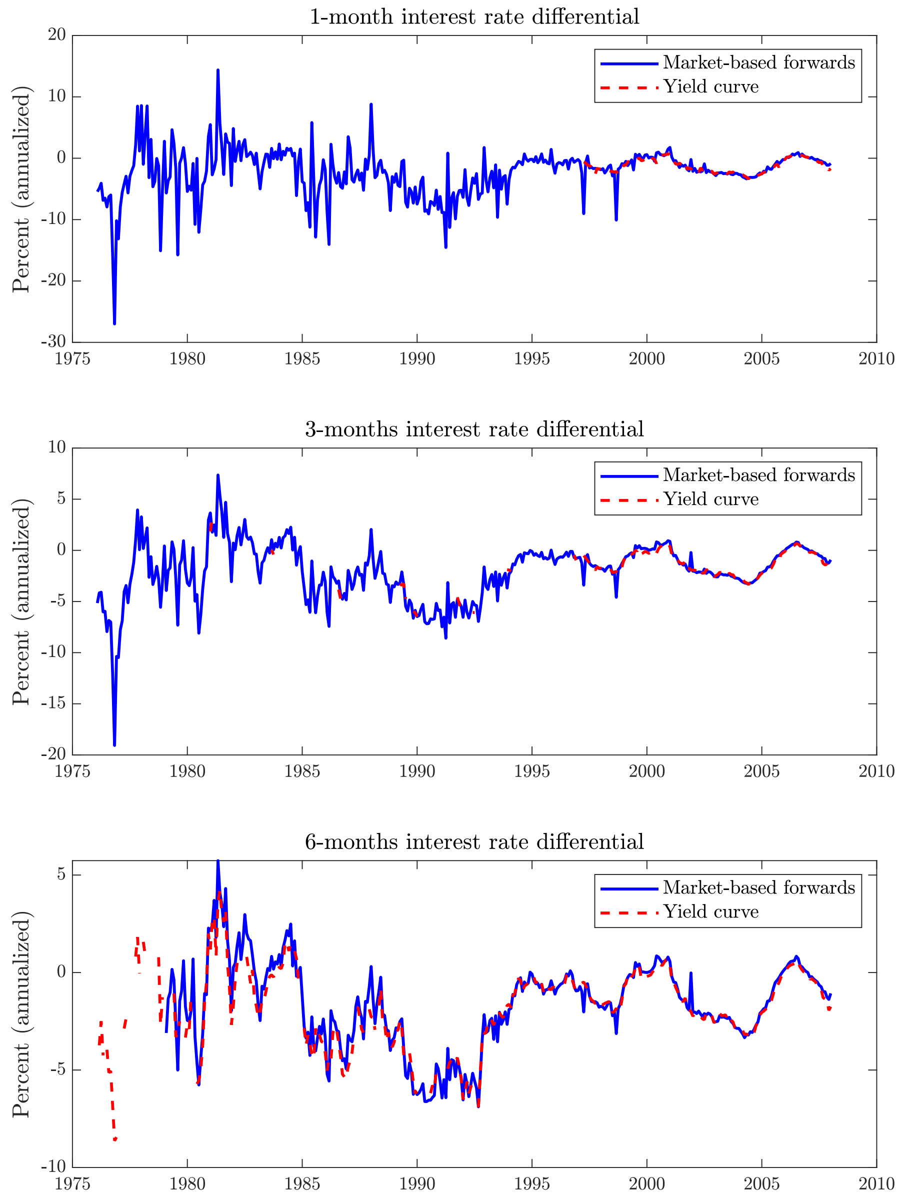

FIGURE A1. COMPARING MARKET-BASED AND YIELD-CURVE-IMPLIED FORWARDS.

Note: USD-GBP 1, 3 and 6-months interest rate differential, implied by forward exchange rate data versus implied by yield curve data.

USD is rather volatile (see Figure 7, the upper-left panel). Nonetheless, our result from our baseline sample in Figure 2 is again detectable: that excess returns are

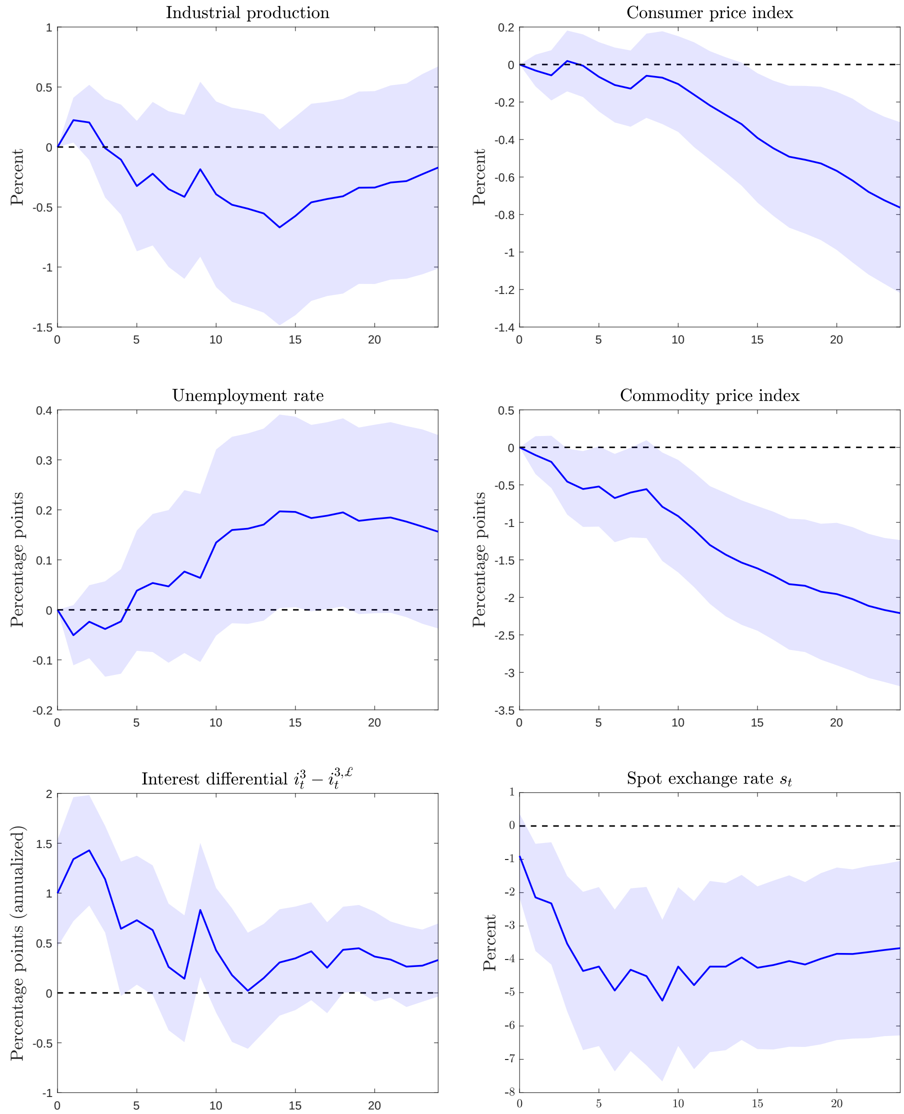

Figure A2. Responses to Monetary Policy Shocks

Note: Sample: 1976:1–2007:12. Identification based on RR shocks within hybrid VAR, see Section I.A for details. Solid lines represent point estimate, shaded areas indicate 90 percent confidence bands. Horizontal axis measures time in months. Vertical axis measures deviation from pre-shock level in percentage points (interest differential and unemployment rate) or in percent (for the other variables).

large and positive (about 2 percent) in the first periods after the shock.

In turn, the right panel in Figure A3 shows the response of excess returns following unconditional interest-rate surprises. In contrast to the response to monetary policy shocks, we find that excess returns are not different from zero in

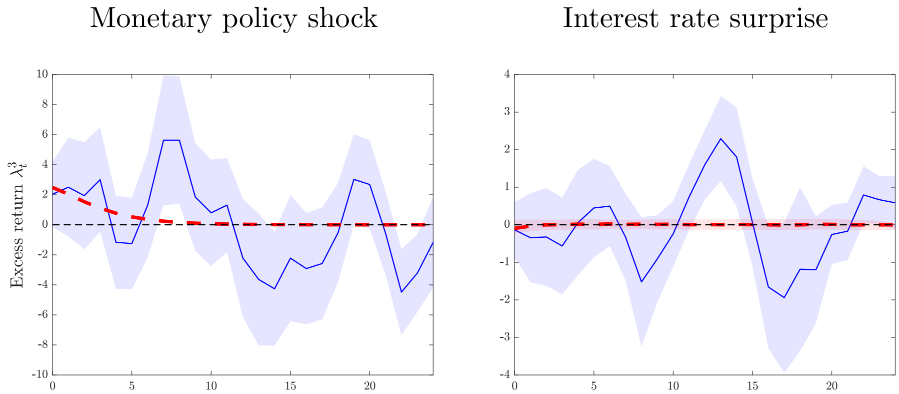

Figure A3. Response of Excess Return

Note: Monetary policy shock (left) and interest-rate surprise (right). Empirical responses given by blue solid line (point estimate) and shaded area (confidence bounds). Model prediction given by red dashed line and bounds represented by red shaded area for interest-rate surprises. The horizontal axis measures time in months. Vertical axis measures deviation from pre-shock level in percent.

the first periods after the shock. Excess returns start to fluctuate about 1 year after the shock, however, this is again driven by the fact that we estimate a very volatile USD response following interest-rate surprises on this short sample (see Figure 7, the upper-right panel).

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

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

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

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

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 $W_t / E_t^{\mathcal{P}} A_t$, where we assume that firms expect workers to work with an effort of one in each period ($E_t^{\mathcal{P}} e_{jt} = 1$).

In the second stage, production takes place. To the extent that firms misperceived the productivity of their workers ($E_t^{\mathcal{P}} A_t \neq A_t$), 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

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

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.

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

Phillips curve

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

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 disutility 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

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

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

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

where we define $\rho \equiv -\log(\beta)$. In equation (A.6), we assume that households and firms share the same information set, as expectations are given by $E_t^{\mathcal{P}}$. 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

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

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

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

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

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

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 (A.7). Labor market clearing implies $y_t = E_t^{\mathcal{P}} a_t + h_t$. Asset market clearing follows residually.

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

We first derive a relationship between consumption and output. Combining (A.7)-(A.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

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

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

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

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

$$w_t - p_t = (\varphi + \theta) y_t - \varphi E_t^{\mathcal{P}} a_t. \tag{A.11}$$

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, (A.4) implies that

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

Combining this with (A.11), we obtain

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

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

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

Taking conditional expectations in (A.12) to replace $E_t^{\mathcal{P}} a_t$ yields the Phillips curve (8) from the main text, where we define $\kappa \equiv \lambda(\varphi + \theta)$.

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

Equation (10) in the main text merely defines the real exchange rate q_t.

To derive the uncovered interest parity (UIP) condition, **equation** (11), from the main text, first combine (A.8) and (A.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 (A.6), and using that $\rho = i^*$ directly yields the result.

To derive the forward exchange rate, **equation** (13), from the main text, note that the Euler equation on an h-period bond in foreign currency is given by

$$c_t = E_t^{\mathcal{P}} c_{t+h} - \theta^{-1}\left(hi^* + E_t^{\mathcal{P}} s_{t+h} - s_t - (E_t^{\mathcal{P}} p_{t+h}^C - p_t^C) - h\rho\right).$$

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

$$c_t = E_t^{\mathcal{P}} c_{t+h} - \theta^{-1}\left(hi^* + f_t^h - s_t - (E_t^{\mathcal{P}} p_{t+h}^C - p_t^C) - h\rho\right).$$

Combining both yields equation (13).

Equation (14) is the combination of equations (4) and (13). We may use equation (4) to define the excess return, because covered interest parity is satisfied in our model.

The Taylor rule, **equation** (12), 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 (A.12), follow the stochastic processes given in **equations** (15) **and** (16).

To define the natural interest rate, **equation** (17), in the main text, we derive the dynamic IS curve of the model. First combine the Euler equation (A.6) and market clearing (A.10)

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

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

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

Using the UIP condition, equation (11) (which we derived earlier above), and using that $i^* = \rho$, this can be written as

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

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 $i_t - E_t^{\mathcal{F}} \pi_{t+1}$, yields

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

The signal $\varsigma_{1,t}$, which is **equation** (18) in the main text, is given by combining equations (A.3) and (A.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** (19) in the main text, is a direct implication of combining equations (12) and (17), both of which we derived before.

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