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The effects of permanent monetary shocks on exchange rates and uncovered interest rate differentials[★]

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ABSTRACT

This paper shows that in a new Keynesian model of the open economy with portfolio adjustment costs a permanent increase in the nominal interest rate causes in the short run a depreciation of the nominal and real exchange rates and a deviation from uncovered interest rate parity against the tightening country. These effects have the opposite sign than those associated with transitory increases in the nominal interest rate. The paper then estimates an empirical model of exchange rates and uncovered interest rate differentials with permanent and transitory U.S. monetary policy shocks on post-Bretton-Woods data from the United States, the United Kingdom, Japan, and Canada. The estimated impulse responses to permanent monetary shocks are shown to be qualitatively consistent with the predictions of the theoretical model.

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1. Introduction

After years of exceptionally low policy rates central banks around the world are beginning to contemplate lifting them to historically more normal levels. For open economies this raises the question of whether and how interest rate normalization affects exchange rates, cross-country return differentials, inflation, and aggregate activity. A common fear among policy makers is that interest rate normalization carries the risk of currency appreciation, hot-money capital inflows, deflation, and economic contraction. In this regard, a limitation of the existing literature on open economy monetary economics is that to a large extent it restricts attention to transitory monetary shocks and is therefore ill suited to analyze the effects of permanent movements in policy rates like the ones that policy normalization would demand. The present paper aims to overcome this limitation by studying the effects of temporary and permanent monetary shocks in open economies.

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The analysis is both empirical and theoretical. The empirical framework is an open-economy extension of the latent-variable model with permanent and temporary monetary shocks introduced by Uribe (forthcoming). The domestic country is taken to be the United States and the foreign country the United Kingdom, Japan, or Canada. The U.S. permanent monetary shock is identified by assuming that it is cointegrated with U.S. inflation and the U.S. nominal interest rate. In addition to U.S. transitory and permanent monetary shocks, the empirical model features a foreign permanent monetary shock. Like in the United States, in the foreign country the nominal interest rate and inflation are assumed to be cointegrated. Unlike in the United States, however, in the foreign country the common permanent component of inflation and interest rates is a linear combination of the U.S. and foreign permanent monetary shocks. This assumption defines the U.S. central bank as a monetary authority with potentially a global impact. Its impact on each country is estimated. This specification nests as polar cases one in which there is a single global permanent monetary shock (originating in the United States) and one in which the permanent component of inflation and nominal rates in the foreign country is independent of the U.S. permanent monetary shock. The model is estimated using Bayesian methods on data covering the period 1974Q1 to 2018Q1.

The paper finds that transitory increases in the U.S. nominal interest rate cause short-run appreciation of the domestic currency, which is in line with the results of earlier studies. By contrast, monetary shocks that increase U.S. interest rates and inflation in the long run are found to cause a nominal and real depreciation of the U.S. dollar already in the short run. This suggests that information on whether movements in nominal interest rates are driven by permanent or transitory monetary shocks is key to predicting the direction in which the exchange rate will move. Further the empirical analysis suggests that a transitory increase in the interest rate lowers inflation and output, whereas a permanent increase in rates is inflationary and non-contractory. This last result echoes earlier findings in closed economy versions of the present model by Uribe (forthcoming) and Azevedo et al. (2019).

The distinction between transitory and permanent monetary shocks also has important consequences for the dynamics of uncovered interest rate differentials. As in the related empirical literature, a transitory increase in the nominal interest rate causes a short-run departure from uncovered interest rate parity in favor of domestic assets. By contrast, a permanent increase in the nominal interest rate causes a departure from uncovered interest rate parity against domestic assets. This result suggests that carry-trade speculation conditional on monetary shocks may have different pay-offs than is implied by estimates that do not distinguish permanent from transitory shocks.

The estimated empirical model predicts that domestic and foreign permanent monetary shocks jointly explain a significant fraction of the forecast error variance of the nominal and real exchange rate and uncovered interest rate differentials at horizons of 1 to 4 years, while transitory monetary shocks are found to matter less, playing an insignificant role in most estimations.

A further contribution of the paper is to show that the sharp differences in the responses of exchange rates and uncovered interest rate differentials to transitory and permanent monetary shocks predicted by the estimated empirical model can be rationalized by an optimizing open economy model with nominal rigidities and financial frictions. Nominal rigidities allow for monetary shocks to have effects not only on nominal but also on real exchange rates. Financial frictions allow for equilibrium deviations from uncovered interest rate parity. In the theoretical model we consider, nominal rigidities take the form of Calvo-type price stickiness as in Galí and Monacelli (2005) and financial frictions take the form of portfolio adjustment costs as in Schmitt-Grohé and Uribe (2021).

The intuition for why a monetary shock that leads to an increase in the nominal interest rate in the long run depreciates the nominal exchange rate already in the short run is that it is a harbinger of higher future inflation. Being a forward looking asset price, the current exchange rate factors in these inflationary expectations as they arrive. The prediction that a rise in the policy rate is associated with a depreciation of the exchange rate in the short run represents an open economy manifestation of the neo Fisher effect. By contrast, a purely transitory monetary tightening causes an appreciation of the nominal exchange rate by the standard Dornbusch (1976) mechanism. We show, however, that the appreciation in response to a transitory monetary shock turns into a depreciation when the shock becomes sufficiently persistent.

In the theoretical model, the effects of transitory and permanent monetary policy shocks on the uncovered interest rate differential are determined by a tradeoff between intertemporal and intratemporal consumption substitution. When the intratemporal elasticity exceeds the intertemporal elasticity of consumption substitution, which is the case most commonly studied in international business cycle analysis, permanent monetary tightenings lead to uncovered interest rate differentials against the high interest rate currency and transitory tightenings move them in favor of the high interest rate currency. These effects are in line with those predicted by the empirical model. However, the theoretical model predicts the opposite when the intertemporal elasticity of consumption substitution exceeds the intratemporal one.

This paper is related to a large body of work on the effects of monetary policy shocks on exchange rates and cross-country return differentials. Monetary policy shocks have been identified in the context of international empirical models using a variety of methods including recursive identification (Eichenbaum and Evans, 1995), structural vector autoregression models (Kim and Roubini, 2000; Faust and Rogers, 2003; Bjørnland, 2009), sign restrictions (Scholl and Uhlig, 2008; Kim et al., 2017), high-frequency identification (Faust et al., 2003; Inoue and Rossi, 2019), and the Romer and Romer narrative approach (Eichenbaum and Evans, 1995; Hettig et al., 2019). The two main conclusions that have emerged from this body of work are: First, the domestic currency appreciates in response to a tightening in domestic monetary policy. Second, a domestic monetary tightening causes a persistent deviation from uncovered interest rate parity in favor of domestic interest-bearing assets. This paper contributes to this literature by showing that the response of exchange rates and uncovered interest rate differentials to a monetary shock depends crucially on whether the shock is transitory or permanent.

A related paper that also considers the effects of permanent monetary disturbances on the exchange rate is De Michelis and Iacoviello (2016). These authors find, consistent with the empirical results reported in the present paper, that in response to an increase in the U.S. inflation target, the U.S. real exchange rate temporarily depreciates. Unlike the present study, this paper does not analyze the effects of monetary policy shocks on nominal exchange rates or uncovered interest rate differentials. In addition, it does not jointly estimate the effects of temporary and permanent monetary disturbances. To the best of our knowledge the present study represents the first attempt to implement this distinction in the context of an international empirical and theoretical model and to document that it has significant consequences for the dynamics of exchange rates and excess returns.

More broadly, the present paper is also related to empirical papers on foreign exchange risk premia. Engel (2016) estimates a vector error correction system in the nominal exchange rate, the cross country price-level differential, and the nominal interest-rate differential and extracts the permanent component of the nominal exchange rate. Hassan and Mano (2019) find that correcting for uncertainty about future mean interest rates yields that the hypothesis that high interest rate currencies are expected to depreciate cannot be rejected. Mueller et al. (2017) document that daily returns on currency portfolios increase on FOMC announcement days. Zhang (2020) and Wiriadinata (2020), respectively, document that the shares of dollar-invoiced imports and dollar-denominated external debt are significant determinants of spillovers of U.S. monetary shocks on exchange rates.

The remainder of the paper is organized as follows. Section 2 characterizes theoretically the effects of temporary and permanent monetary shocks in a new-Keynesian open economy model with deviations from uncovered interest rate parity. Section 3 presents the empirical model and the identification scheme. Section 4 explains the estimation procedure. Section 5 presents the estimated responses of exchange rates and interest rate differentials to permanent and transitory monetary shocks. Section 6 performs forecast error variance decompositions to document the importance of permanent monetary shocks as drivers of nominal and real exchange rates and uncovered interest rate differentials. Section 7 concludes.

2. An open economy model with permanent monetary shocks and deviations from UIP

What should we expect to happen with exchange rates and uncovered interest rate differentials once central banks begin to lift rates away from their current near-zero or negative levels and toward historically more normal levels? In this section, we investigate theoretically how permanent monetary disturbances affect nominal and real exchange rates and deviations from uncovered interest rate parity and compare these effects to those caused by transitory monetary shocks. The effects of transitory monetary policy shocks on exchange rates in new Keynesian models of the open economy are well studied. This class of model predicts that transitory monetary tightenings depress output and inflation in the short run and appreciate the domestic currency (see, for example, Galí, 2015). There is less work on the effects of permanent monetary policy shocks in new Keynesian models. In the context of a closed economy model, Uribe (forthcoming) and Azevedo et al. (2019) show that monetary shocks that lead to an increase in the nominal interest rate and inflation in the long run are in the short run associated with increases in interest rates, inflation and output, which is the opposite of what happens in the short run in response to a transitory tightening. There is also little work on understanding the way in which transitory or permanent monetary policy shocks affect deviations from uncovered interest parity. Addressing this issue requires the introduction of some form of financial friction in international asset markets.

To shed light on how monetary shocks (permanent and transitory) affect exchange rates and uncovered interest-rate differentials, we modify the Galí and Monacelli (2005) model to include permanent monetary shocks, incomplete asset markets, and portfolio adjustment costs as in Schmitt-Grohé and Uribe (2003). The latter two modifications allow the model to produce deviations from uncovered interest rate parity. The presentation that follows describes the main building blocks of the proposed model. The online appendix (Schmitt-Grohé and Uribe, 2021) provides a detailed derivation of the equilibrium conditions, shows how to cast the model in stationary variables, and discusses the calibration and numerical solution method.

The economy is populated by a large number of identical households who choose consumption, C_t , and hours worked, N_t , to maximize the utility function

$$E_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{C_t^{1-\sigma} - 1}{1-\sigma} - \frac{N_t^{1+\phi}}{1+\phi} \right),$$

where $\beta \in (0, 1)$ denotes the subjective discount factor, $\sigma > 0$ denotes the inverse of the intertemporal elasticity of consumption substitution, $\phi > 0$ denotes the inverse of the Frisch elasticity of labor supply, and E_t denotes the expectations operator conditional on information available in period t .

Consumption is a composite of domestically produced consumption goods, $C_{H,t}$, and foreign (imported) consumption goods, $C_{F,t}$, with the aggregation technology

$$C_t = \left[(1-\nu)^{\frac{1}{\eta}} C_{H,t}^{1-\frac{1}{\eta}} + \nu^{\frac{1}{\eta}} C_{F,t}^{1-\frac{1}{\eta}} \right]^{\frac{1}{1-\frac{1}{\eta}}},$$

where $1-\nu \in (0, 1)$ is a measure of home bias. The larger $1-\nu$ is, the larger the home bias in consumption will be. The parameter $\eta > 0$ is the elasticity of substitution between home and foreign goods.

Households are assumed to have access to one-period, nominally risk free, domestic- and foreign-currency debt instruments, D_t and D_t^* , paying the interest rates i_t and i_t^* , respectively. Foreign-currency debt is subject to portfolio adjustment costs. The sequential budget constraint of the household is given by

$$P_{H,t}C_{H,t} + P_{F,t}C_{F,t} + (1 + i_{t-1})D_{t-1} + \mathcal{E}_t(1 + i_{t-1}^*)D_{t-1}^* = W_tN_t + \Pi_t + D_t + \mathcal{E}_tD_t^* - \mathcal{E}_t\psi(D_t^*),$$

where $P_{H,t}$ and $P_{F,t}$ denote the domestic-currency prices of the home and foreign goods, W_t denotes the nominal wage rate, Π_t denotes profit income from the ownership of domestic firms, and \mathcal{E}_t denotes the nominal exchange rate, defined as the domestic-currency price of foreign currency. The object $\psi(\cdot)$ is the portfolio adjustment cost function, which is assumed to be strictly convex and to satisfy $\psi(0) = \psi'(0) = 0$.

The presence of portfolio adjustment costs implies that the effective gross interest rate on foreign-currency debt is $(1 + i_t^*)/(1 - \psi'(D_t^*))$. Because the portfolio adjustment cost function is strictly convex, the effective interest rate is increasing in D_t^* . This feature of the model introduces deviations from uncovered interest rate parity. It can be shown that up to a first-order approximation around a nonstochastic steady state with zero foreign currency debt ($D^* = 0$) the uncovered interest rate differential,

$$uid_t \equiv i_t - i_t^* - E_t(\mathcal{E}_{t+1}/\mathcal{E}_t - 1),$$

is given by

$$uid_t = \psi''(0)D_t^*. \tag{1}$$

This means that the response of the uncovered interest rate differential to any shock depends on the response of foreign-currency debt. In particular, if the uncovered interest-rate differential is to respond differently to transitory and permanent monetary shocks, foreign-currency debt must also respond differently to these two types of shock.

Portfolio adjustment costs is not the only way to allow for deviations from uncovered interest-rate parity. In an early contribution, Kollmann (2002, 2005) introduces a country risk premium with an endogenous component, which depends on the country's net foreign debt position, as well as on an exogenous and stochastic component. In other formulations the exogenous component of the country premium is linked to the level of the world interest rate to capture, for example, variations in the level of risk aversion of global investors (Uribe and Yue, 2006; Akinci and Queralto, 2019; Kalemli-Özcan, 2019). A recent approach to microfounding deviations from uncovered interest rate parity is the work of Gabaix and Maggiori (2015), Fanelli and Straub (2019), and Itskhoki and Mukhin (2019), who introduce segmentation in the foreign exchange market. Yakhin (2020) shows that the segmented market model is up to first order isomorphic to a model with portfolio adjustment costs of the type introduced in Schmitt-Grohé and Uribe (2003) and adopted here.

Output of the home good, $Y_{H,t}$, is a composite of a continuum of domestically produced intermediate goods, $Y_{H,t}(i)$, for $i \in [0, 1]$. The aggregation technology is of the form

$$Y_{H,t} = \left[\int_0^1 Y_{H,t}(i)^{1-\frac{1}{\epsilon}} di \right]^{\frac{1}{1-\frac{1}{\epsilon}}},$$

where $\epsilon > 1$ denotes the elasticity of substitution between varieties of domestically produced intermediate inputs. The implied demand function for variety i is given by

$$Y_{H,t}(i) = \left(\frac{P_{H,t}(i)}{P_{H,t}} \right)^{-\epsilon} Y_{H,t},$$

$$\text{and } P_{H,t} = \left[\int_0^1 P_{H,t}(i)^{1-\epsilon} di \right]^{\frac{1}{1-\epsilon}}.$$

Each variety i of the domestic intermediate input is produced by a monopolistically competitive firm via the production technology $N_t(i)$, where $N_t(i)$ is employment in firm i . Prices are assumed to be sticky à la Calvo-Yun. Each period t , a random fraction $1 - \theta$ of firms gets to set its price optimally. The remaining firms index their price to past domestic-price inflation, denoted $\pi_{H,t-1} \equiv P_{H,t-1}/P_{H,t-2} - 1$. A firm that gets to reoptimize in period t picks the price $\tilde{P}_{H,t}$. Profits in period $t + j$ of a firm i that last optimized its price in period t is given by

$$\Pi_{t+j}(i) = \tilde{P}_{H,t} \Psi_{t,t+j} \left(\frac{\tilde{P}_{H,t} \Psi_{t,t+j}}{P_{H,t+j}} \right)^{-\epsilon} Y_{H,t+j} - W_{t+j} N_{t+j}(i),$$

where $\Psi_{t,t+j} \equiv \prod_{k=0}^{j-1} (1 + \pi_{H,t+k})$. Also, at the posted price, the firm must satisfy demand

$$N_{t+j}(i) \geq \left(\frac{\tilde{P}_{H,t} \Psi_{t,t+j}}{P_{H,t+j}} \right)^{-\epsilon} Y_{H,t+j}. \tag{2}$$

A firm that gets to optimize in period t chooses $\tilde{P}_{H,t}$ and $N_t(i)$ to maximize the present discounted value of profits,

$$E_t \sum_{j=0}^{\infty} Q_{t,t+j} \theta^j \Pi_{t+j}(i),$$

subject to Eq. (2), where $Q_{t,t+j}$ is a nominal pricing kernel. In period $t + j$, a firm i that last optimized in t picks $N_{t+j}(i)$ to satisfy Eq. (2) with equality.

Market clearing in the domestic goods market requires that output of the domestic good be equal to the sum of the domestic and foreign demand for the domestically produced good,

$$Y_{H,t} = C_{H,t} + C_{H,t}^*,$$

where $C_{H,t}^*$ denotes the foreign demand for domestically produced goods and is assumed to be equal to

$$C_{H,t}^* = \nu \left(\frac{P_{H,t}^*}{P_t^*} \right)^{-\eta} C_t^*.$$

In this expression, $P_{H,t}^*$ is the foreign price of the domestic good expressed in foreign currency, P_t^* is the foreign consumer price level, and C_t^* is the level of foreign aggregate demand. The law of one price is assumed to hold for domestic and foreign goods,

$$P_{H,t} = \mathcal{E}_t P_{H,t}^*$$

and

$$P_{F,t} = \mathcal{E}_t P_{F,t}^*.$$

The variables P_t^* , $P_{F,t}^*$, and C_t^* are assumed to be exogenous.

The real exchange rate, denoted e_t , is given by

$$e_t = \frac{\mathcal{E}_t P_t^*}{P_t},$$

where P_t denotes the nominal price of the domestic composite consumption good, C_t , and is given by $P_t = \left[(1-\nu)P_{H,t}^{1-\eta} + \nu P_{F,t}^{1-\eta} \right]^{\frac{1}{1-\eta}}$.

The central bank sets the interest rate according to the following Taylor-type interest-rate feedback rule

$$1 + i_t = \beta^{-1} (1 + \pi_{H,t})^{\alpha_\pi} \left(\frac{Y_{H,t}}{Y_H} \right)^{\alpha_y} e^{z_t^m + (1-\alpha_\pi)X_t^m}, \tag{3}$$

where z_t^m is a stationary monetary disturbance and X_t^m is a nonstationary monetary disturbance, which can be interpreted as a permanent inflation target shock. The parameters $\alpha_\pi > 1$ and $\alpha_y > 0$ are the coefficients of the Taylor rule. In equilibrium, both the nominal interest rate and inflation are cointegrated with X_t^m . The monetary disturbances z_t^m and X_t^m are the focus of the present analysis. We assume that z_t^m and $\Delta X_t^m \equiv X_t^m - X_{t-1}^m$ follow univariate AR(1) processes with serial correlations ρ_{zm} and ρ_{xm} . The constant Y_H denotes the steady-state value of $Y_{H,t}$.

We characterize the predictions of the model numerically. The calibration of the structural parameters of the model follows to a large extent Galí (2015, Chapter 8). The time unit is a quarter. The parameter values are $\sigma = 1$, $\beta = 0.99$, $\theta = 0.75$, $\varepsilon = 9$, $\nu = 0.4$, $\phi = 5$, $\eta = 1.5$, $\psi''(0) = 1$, $\alpha_\pi = 1.5$, $\alpha_y = 0.125$, $\rho_{zm} = 0$, and $\rho_{xm} = 0$. The value assumed for the intratemporal elasticity of substitution between home and foreign goods, η , deviates from the value of unity assumed by Galí (2015). The reason for this change is that, as is well known, when this elasticity is equal to unity and equal to the intertemporal elasticity of substitution, $1/\sigma$, then the model economy displays no variations in external debt, which, in turn, would imply no deviations from uncovered interest-rate parity (see Eq. (1)). The value of 1.5 assigned to η lies in the range of values commonly used in trade and international business cycle analysis (e.g., Whalley, 1985; Backus et al., 1995). The portfolio adjustment cost parameter, $\psi''(0)$, which does not feature in the Galí and Monacelli model, is set to unity, for illustrative purposes.

Fig. 1 presents the impulse responses to a permanent monetary policy shock (ΔX_t^m) that increases inflation and the nominal interest rate in the long run by 1 annual percentage point together with the impulse responses to a temporary monetary policy shock (z_t^m) that increases the nominal interest rate on impact by 1 annual percentage point. To highlight the endogenous dynamics of the model, ΔX_t^m and z_t^m are assumed to follow i.i.d. processes ($\rho_{zm} = \rho_{xm} = 0$). The figure shows that in response to a temporary monetary policy shock the model delivers the standard dynamics. The increase in the domestic interest rate raises the real interest rate, which induces agents to save more and spend less. Faced with lower demand, firms reduce prices. Thus, in equilibrium inflation and output both fall. The domestic tightening makes the domestic currency more attractive, which results in an

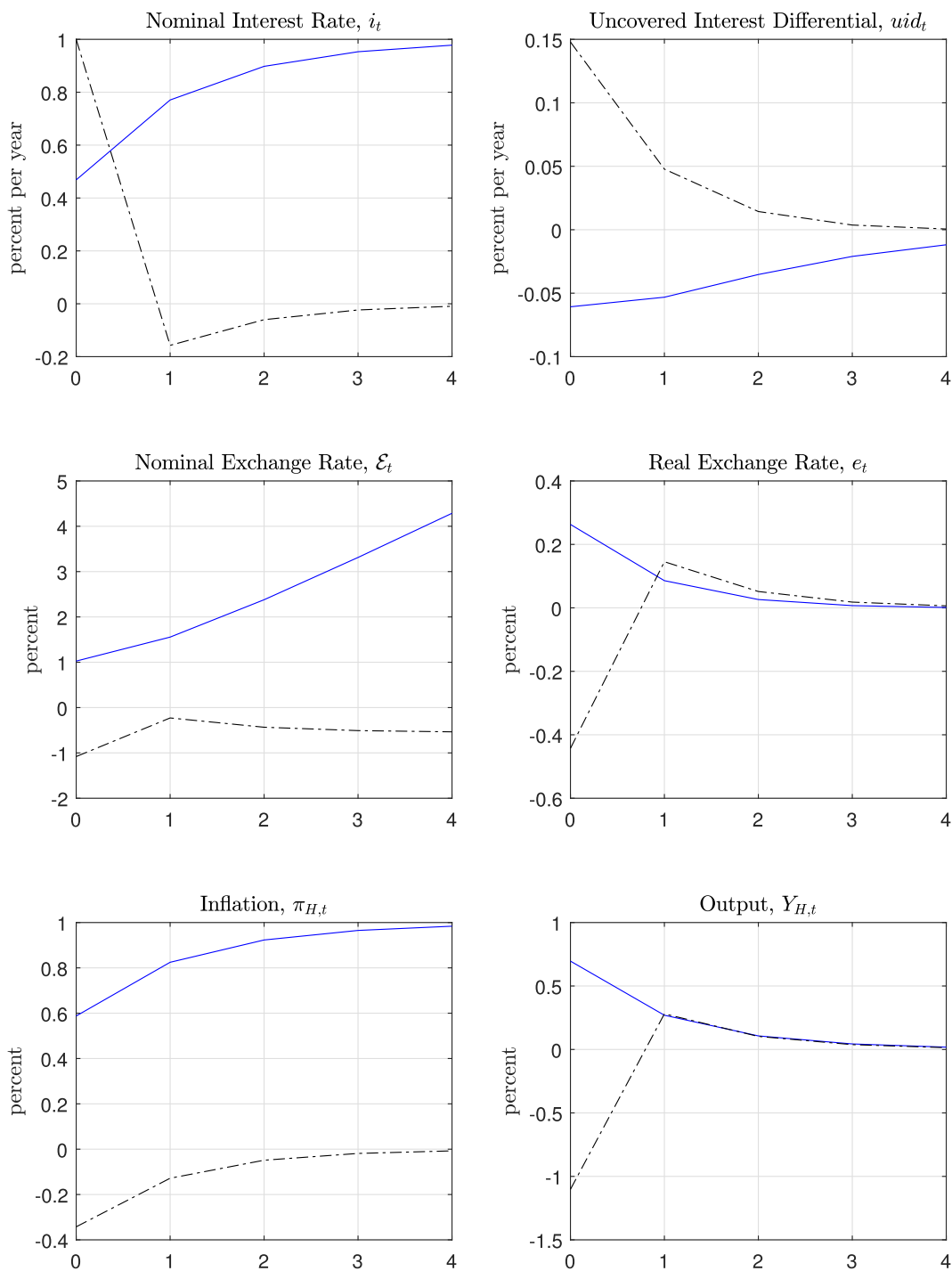


Fig. 1. Impulse responses to a permanent and a transitory monetary policy shock in the theoretical model. Notes. Solid lines display impulse responses to a permanent monetary shock that increases the nominal interest rate by 1 annual percentage point in the long run (an increase in X_t^m). Dash-dotted lines display impulse responses to a transitory monetary shock that increases the nominal interest rate by 1 annual percentage point on impact (an increase in Z_t^m).

appreciation of the domestic currency (a fall in \mathcal{E}_t). Since nominal prices are sticky, the short-run response of the real exchange rate (e_t) mimics that of its nominal counterpart.

The dynamics are quite different after a permanent monetary policy shock. In line with the predictions of closed economy new Keynesian models, in response to a shock that increases the nominal interest rate in the long run by 1 percentage point (see, Uribe, forthcoming; Azevedo et al., 2019), the present open-economy model predicts that in the short run the monetary authority

raises interest rates and that inflation increases by more than the nominal rate. This is because firms who get to change their price in the period of the inflation target shock (X_t^m) know that in the future prices of their competitors as well as nominal wages will grow at a faster rate. Therefore, to avoid making losses in the future by having to sell below cost (recall that output is demand determined), firms raise prices aggressively when they get a chance. Because inflation rises faster than the nominal interest rate, the real interest rate declines, which causes an expansion in aggregate demand.

The novel result is that in response to a permanent increase in the interest rate, the nominal and real exchange rates depreciate in the short run. That is, while temporary tightenings appreciate the currency in the short run, permanent tightenings depreciate it in the short run. The intuition behind why a permanent tightening depreciates the domestic currency is that, being a forward-looking variable, the exchange rate incorporates on impact the current and expected future higher cross-country inflation differentials (recall that a permanent increase in the nominal interest rate is inflationary in the short and the long runs).

The prediction of the model that a transitory increase in the nominal interest rate generates an appreciation of the exchange rate is not independent of the assumed persistence of the monetary shock, z_t^m . In particular, under the current calibration, the nominal and real exchange rates appreciate in response to a transitory tightening if the serial correlation of the transitory monetary shock (ρ_{zm}) is less than a threshold value close to but below 0.7, but depreciate for values greater than this threshold.

The top right panel of Fig. 1 displays the response of the uncovered interest-rate differential, uid_t , to a permanent and a transitory monetary policy shock. In response to a transitory monetary shock (z_t^m) that increases the nominal interest rate by 1 annual percentage point on impact, deviations from uncovered interest rate parity are positive. This means that the high interest-rate currency exhibits excess returns.

As shown in Eq. (1), the uncovered interest-rate differential is governed by the behavior of the net foreign debt position, D_t^* . There are two opposing effects of an increase in the interest rate on D_t^* . One is an intertemporal effect whereby the transitory increase in i_t raises the real interest rate in the short run. In turn, the increase in the real interest rate encourages saving. This reduces the country's net debt position, D_t^* , and hence the uncovered interest rate differential. The strength of the intertemporal effect depends on the size of the intertemporal elasticity of substitution, $1/\sigma$.

The intertemporal effect competes with an intratemporal effect, whereby the appreciation of the exchange rate induced by the interest rate hike appreciates the terms of trade. This lowers the demand for the country's export good and increases the domestic demand for imports, resulting in a deterioration of the trade balance. The deterioration in the trade balance is financed by foreign borrowing, that is, an increase in D_t^* . Because of the portfolio adjustment costs the increase in foreign debt raises the country's effective interest rate on foreign bonds and therefore also raises the uncovered interest rate differential, uid_t . The strength of the intratemporal effect depends on the intratemporal trade elasticity η . Thus, the sign of the response of uid_t to a temporary monetary tightening depends on the relative sizes of the intra- and intertemporal elasticities of substitution. In the special case that $\eta = 1/\sigma = 1$, these two effects exactly cancel and uncovered interest rate parity holds. However, under the present calibration, with $\eta = 1.5$ and $\sigma = 1$, the intratemporal channel dominates so that the temporary tightening is associated with an increase in uid_t .

By contrast, in response to a permanent monetary shock (X_t^m) that increases the nominal interest rate by 1 annual percentage point in the long run short-run deviations from uncovered interest rate parity are predicted to be negative. This means that the high interest rate currency exhibits negative excess returns. The intuition behind this result is similar to that given above for the temporary monetary shock. As explained earlier, when the increase in the interest rate is driven by a permanent monetary policy shock, the real interest rate falls and the domestic currency depreciates. These two effects have the opposite sign to those triggered by a temporary monetary tightening and as a result also generate the opposite effect on uid_t .

In sum, a transitory increase in the nominal interest rate appreciates the nominal and real exchange rates and generates a deviation in the uncovered interest differential in favor of domestic bonds. By contrast, a permanent increase in the interest rate has the opposite short-run effects: the nominal and real exchange rates depreciate and the uncovered interest rate differential moves against the domestic bond. Put differently, these theoretical results suggest that a policymaker thinking about normalizing rates from near zero to historically normal levels should not fear exchange rate appreciation or hot-money capital inflows. The following sections provide empirical support to these findings.

3. The empirical model

The empirical model adapts the closed-economy model of temporary and permanent monetary shocks developed in Uribe (forthcoming) to include a foreign bloc. This formulation allows for the presence of more structural shocks than observable time series, as in DSGE models, and more flexible identification restrictions than SVAR models. Here we present a self-contained description of the resulting empirical model. The model is cast in six variables: the logarithm of real domestic output, denoted y_t , domestic inflation, denoted π_t , the domestic nominal interest rate, denoted i_t , the foreign interest rate, denoted i_t^* , the foreign inflation rate, denoted π_t^* , and the depreciation rate of the domestic currency, denoted $\epsilon_t \equiv \ln(\mathcal{E}_t/\mathcal{E}_{t-1})$, where \mathcal{E}_t denotes the nominal exchange rate, defined as the price of one unit of foreign currency in terms of units of domestic currency in period t . The variables π_t , i_t , π_t^* , i_t^* , and ϵ_t are expressed in percent per year. The domestic economy is meant to be the United States, and the foreign economy either the United Kingdom, Japan, or Canada.

All six variables are assumed to be nonstationary: y_t is assumed to be cointegrated with the exogenous variable X_t , which can be interpreted as a stochastic output trend; i_t and π_t are assumed to be cointegrated with the exogenous variable X_t^m , which is the permanent domestic monetary policy shock; i_t^* and π_t^* are assumed to be cointegrated with $\alpha X_t^m + X_t^{m*}$, where X_t^{m*} is an

exogenous variable capturing the foreign permanent monetary policy shock and α is a parameter to be estimated. This formulation allows the domestic and foreign interest rates and inflation rates to share a permanent component. Since both α and the parameters governing the stochastic process for X_t^{m*} are estimated, two polar cases are nested: $\alpha = 0$, in which inflation and interest rates have different permanent components across countries, and $\text{var}(X_t^{m*}) = 0$, in which these variables have the same permanent component. Finally, ϵ_t is assumed to be cointegrated with $(1-\alpha)X_t^m - X_t^{m*}$. This assumption implies that the real depreciation rate, $\epsilon_t + \pi_t^* - \pi_t$, is stationary. The real exchange rate is not restricted to be stationary. The formulation of the model lets the data tell how big the random walk component of the real exchange rate will be. In the special case $\alpha = 1$ and $\text{var}(X_t^{m*}) = 0$, the nominal depreciation rate, ϵ_t , is also stationary. One can then define the following vector of stationary variables

$$\begin{bmatrix} \hat{y}_t \\ \hat{\pi}_t \\ \hat{i}_t \\ \hat{\epsilon}_t \\ \hat{i}_t^* \\ \hat{\pi}_t^* \end{bmatrix} \equiv \begin{bmatrix} y_t - X_t \\ \pi_t - X_t^m \\ i_t - X_t^m \\ \epsilon_t - (1-\alpha)X_t^m + X_t^{m*} \\ i_t^* - \alpha X_t^m - X_t^{m*} \\ \pi_t^* - \alpha X_t^m - X_t^{m*} \end{bmatrix}.$$

This vector is assumed to evolve according to the following autoregressive process¹:

$$\begin{bmatrix} \hat{y}_t \\ \hat{\pi}_t \\ \hat{i}_t \\ \hat{\epsilon}_t \\ \hat{i}_t^* \\ \hat{\pi}_t^* \end{bmatrix} = \sum_{i=1}^L B_i \begin{bmatrix} \hat{y}_{t-i} \\ \hat{\pi}_{t-i} \\ \hat{i}_{t-i} \\ \hat{\epsilon}_{t-i} \\ \hat{i}_{t-i}^* \\ \hat{\pi}_{t-i}^* \end{bmatrix} + C \begin{bmatrix} \Delta X_t^m \\ z_t^m \\ \Delta X_t \\ z_t \\ \Delta X_t^{m*} \\ z_t^* \\ w_t^* \end{bmatrix}, \tag{4}$$

where the exogenous variable z_t^m is a stationary domestic monetary shock, and the exogenous variable z_t is interpreted as a combination of nonmonetary stationary shocks affecting the variables in the system, which we do not wish to identify individually. The exogenous variables z_t^* and w_t^* are interpreted as foreign stationary shocks. These interpretations will become clear in Section 3.1, which discusses the identification scheme. The objects B_i for $i = 1, \dots, L$ and C are matrices of coefficients, and L denotes the number of lags. The driving forces are assumed to follow univariate AR(1) processes of the form

$$\begin{bmatrix} \Delta X_{t+1}^m \\ z_{t+1}^m \\ \Delta X_{t+1} \\ z_{t+1} \\ \Delta X_{t+1}^{m*} \\ z_{t+1}^* \\ w_{t+1}^* \end{bmatrix} = \rho \begin{bmatrix} \Delta X_t^m \\ z_t^m \\ \Delta X_t \\ z_t \\ \Delta X_t^{m*} \\ z_t^* \\ w_t^* \end{bmatrix} + \psi \begin{bmatrix} \nu_{t+1}^1 \\ \nu_{t+1}^2 \\ \nu_{t+1}^3 \\ \nu_{t+1}^4 \\ \nu_{t+1}^5 \\ \nu_{t+1}^6 \\ \nu_{t+1}^7 \end{bmatrix}, \tag{5}$$

where $\nu_t^i \sim \text{i.i.d. } \mathcal{N}(0, 1)$ for $i = 1, \dots, 7$ and ρ and ψ are diagonal matrices.

The system consisting of Eqs. (4) and (5) is unobservable, because neither the detrended endogenous variables nor the driving forces are observed. Thus, one can think of that system as describing the evolution of latent state variables in a state-space representation. The estimation strategy exploits the fact that the above system of latent variables has precise predictions for variables that are observable. Formally, the estimation procedure adds equations linking the unobservable variables to variables with an empirical counterpart. The included observable variables are the growth rate of real output, Δy_t , the domestic interest-rate inflation differential, $r_t \equiv \hat{i}_t - \hat{\pi}_t$, the changes in the domestic and foreign nominal interest rates, Δi_t and Δi_t^* , the change in the nominal depreciation rate, $\Delta \epsilon_t$, and the real depreciation rate, denoted $\epsilon_t^r \equiv \epsilon_t + \pi_t^* - \pi_t$. These variables are linked to the unobservable variables by the following identities:

$$\begin{aligned} \Delta y_t &= \hat{y}_t - \hat{y}_{t-1} + \Delta X_t, \\ r_t &= \hat{i}_t - \hat{\pi}_t, \\ \Delta i_t &= \hat{i}_t - \hat{i}_{t-1} + \Delta X_t^m, \\ \Delta \epsilon_t &= \hat{\epsilon}_t - \hat{\epsilon}_{t-1} + (1-\alpha)\Delta X_t^m - \Delta X_t^{m*}, \end{aligned} \tag{6}$$

¹ The exposition of the model omits intercepts.

$$\begin{aligned} \Delta i_t^* &= \hat{i}_t^* - \hat{i}_{t-1}^* + \Delta X_t^{m*} + \alpha \Delta X_t^m, \\ \epsilon_t^r &= \hat{\epsilon}_t + \hat{\pi}_t^* - \hat{\pi}_t. \end{aligned}$$

The first identity says that output growth is the sum of the growth rate of detrended output and the growth rate of the output trend. The second identity says that the interest rate-inflation differential equals the difference between the cyclical components of the interest rate and inflation. This is so because these two variables are assumed to have a common permanent component. Note that r_t does not represent the real interest rate because it measures the difference between the nominal interest rate and current inflation rather than expected future inflation. The remaining identities have similar interpretations.

As is customary in Bayesian estimation, the variables on the left-hand sides of the above expressions are assumed to be observed with measurement error. Specifically, it is assumed that the econometrician observes the vector o_t defined as

$$o_t = \begin{bmatrix} \Delta y_t \\ r_t \\ \Delta i_t \\ \Delta \epsilon_t \\ \Delta i_t^* \\ \epsilon_t^r \end{bmatrix} + \mu_t, \tag{7}$$

where μ_t is a vector of measurement errors distributed i.i.d. $\mathcal{N}(\emptyset, R)$, and R is a diagonal variance-covariance matrix. The vector of measurement errors μ_t is restricted to explain no more than 10 percent of the variance of the observables.

3.1. Identification

The objective of the present investigation is to understand the effects of permanent and temporary U.S. monetary policy shocks (X_t^m and z_t^m) on nominal and real dollar exchange rates and uncovered interest rate differentials. The assumed formulation of the model introduces restrictions that allow for the identification of the permanent sources of uncertainty. Specifically, the assumptions that y_t is cointegrated with X_t , that i_t and π_t are cointegrated with X_t^m , that i_t^* and π_t^* are cointegrated with $X_t^{m*} + \alpha X_t^m$, and that ϵ_t is cointegrated with $(1-\alpha)X_t^m - X_t^{m*}$, allow for the identification of the three permanent shocks. We introduce additional restrictions that allow us to identify the transitory U.S. monetary shocks following the approach of Eichenbaum and Evans (1995). Specifically, we assume that the two U.S. monetary shocks, X_t^m and z_t^m , have zero impact effects on output and inflation. Transitory U.S. monetary shocks have a zero impact effect on output and inflation provided that

$$C_{12} = C_{22} = C_{62} = 0,$$

where C_{ij} denotes element (i, j) of the matrix C that appears in Eq. (4).

The permanent U.S. monetary shock, X_t^m , has a zero impact effect on output and domestic and foreign inflation if, respectively,

$$C_{11} = 0, C_{21} = -1, \text{ and } C_{61} = -\alpha.$$

To see why the second restriction is required for X_t^m to have a zero impact effect on π_t , note that element C_{21} determines the impact effect of an innovation in ΔX_t^m on $\hat{\pi}_t \equiv \pi_t - X_t^m$. To see why the third restriction guarantees that the impact effect of X_t^m on π_t^* is nil, note that C_{61} determines the impact effect on $\hat{\pi}_t^* \equiv \pi_t^* - X_t^{m*} - \alpha X_t^m$.

Similarly, the foreign permanent monetary shock, X_t^{m*} , is assumed to have a zero impact effect on output and inflation. This requires that

$$C_{15} = C_{25} = 0, \text{ and } C_{65} = -1.$$

In addition, we assume that X_t^{m*} does not affect U.S. interest rates on impact, that is,

$$C_{35} = 0.$$

In line with the discussion in Faust and Rogers (2003), we leave unconstrained the contemporaneous response of the foreign interest rate to U.S. monetary policy, C_{51} and C_{52} , thus allowing the foreign monetary authority to respond within the period to U.S. monetary policy shocks. The UIP shock, w_t^* , is assumed to affect on impact only the depreciation rate, ϵ_t , thus, we set

$$C_{17} = C_{27} = C_{37} = C_{57} = C_{67} = 0.$$

The shock z_t^* represents a second foreign stationary shock distinct from w_t^* by the fact that it is allowed to affect contemporaneously not only the exchange rate but also the foreign interest rate, i_t^* . Accordingly, we impose

$$C_{16} = C_{26} = C_{36} = C_{66} = 0.$$

Without loss of generality, we normalize the impact effect of a unit innovation in the transitory U.S. monetary shock, z_t^m , on the U.S. nominal interest rate to unity. Similarly, we normalize to unity the impact effect of a unit innovation in the foreign transitory shock, z_t^* , on the foreign interest rate, i_t^* , the impact effect of the transitory shock, z_t , on U.S. output, y_t , and the impact effect of the UIP shock, w_t^* , on the depreciation rate, ε_t . We therefore set

$$C_{32} = C_{56} = C_{14} = C_{47} = 1.$$

A related issue has to do with the identifiability of the parameters of the model. We check for identifiability by applying the test proposed by Iskrev (2010). In essence the Iskrev test checks whether the derivatives of the predicted autocovariogram of the observables with respect to the vector of estimated parameters has rank equal to the length of the vector of estimated parameters. After estimating the model as described in Section 4, we find that, regardless of whether the foreign country is the United Kingdom, Japan, or Canada, the derivative of the vectorized predicted autocovariogram of the vector of observables with respect to the parameters has full column rank when evaluated at the posterior mean of the Bayesian estimate. Full column rank obtains starting with the inclusion of covariances of order 0 to 6. According to this test, therefore, for all three country pairs the parameter vector is identifiable in the neighborhood of the mean of the posterior estimate. Specifically, the test result indicates that in the neighborhood of the estimate all values of the vector of parameters different from the estimated one give rise to autocovariograms that are different from the one associated with the posterior mean estimate.

4. Estimation

For the purpose of estimating the model, it is convenient to express it in a first-order state-space form. To this end let

$$\begin{aligned} \hat{Y}_t &\equiv \left[\hat{y}_t \quad \hat{\pi}_t \quad \hat{i}_t \quad \hat{\varepsilon}_t \quad \hat{i}_t^* \quad \hat{\pi}_t^* \right]', \\ u_t &\equiv \left[\Delta X_t^m \quad z_t^m \quad \Delta X_t \quad z_t \quad \Delta X_t^{m*} \quad z_t^* \quad w_t^* \right]', \\ \nu_t &\equiv \left[\nu_t^1 \quad \nu_t^2 \quad \nu_t^3 \quad \nu_t^4 \quad \nu_t^5 \quad \nu_t^6 \quad \nu_t^7 \right]', \end{aligned}$$

and

$$\xi_t \equiv \left[\hat{Y}_t' \quad \hat{Y}_{t-1}' \quad \dots \quad \hat{Y}_{t-L+1}' \quad u_t' \right]'$$

Then the system Eqs. (4)–(7) can be written as

$$\xi_{t+1} = F\xi_t + P\nu_{t+1}, \tag{8}$$

and

$$o_t = H'\xi_t + \mu_t, \tag{9}$$

where the matrices F , P , and H are known functions of the matrices B_i for $i = 1, \dots, L$, C , ρ , and ψ and are shown in Appendix A. This representation allows for the use of the Kalman filter to calculate the likelihood of the data $\{o_1 \ o_2 \ \dots \ o_T\}$, where T is the number of observations. The model is estimated using Bayesian techniques. The specification includes 4 lags in Eq. (4), $L = 4$.

4.1. Priors

Table 1 describes the assumed prior distributions of the estimated parameters. Normal prior distributions are imposed on all elements of B_i , for $i = 1, \dots, L$. In the spirit of the Minnesota prior, it is assumed that at the mean of the prior parameter distribution the elements of \hat{Y}_t follow univariate autoregressive processes. So when evaluated at their prior mean, only the main diagonal of B_1 takes nonzero values and all other elements of B_i for $i = 1, \dots, L$ are nil. An autoregressive coefficient of 0.95 is assumed in all equations, so that all elements along the main diagonal of B_1 take a prior mean of 0.95. The prior standard deviation of the diagonal elements of B_1 is equal to 0.5, which implies a coefficient of variation close to one half (0.5/0.95). Lower prior standard deviations of 0.25 are imposed on all other elements of the matrices B_i for $i = 1, \dots, L$.

All estimated elements of the matrix C are assumed to have normal prior distributions with mean zero and unit standard deviation, with the following exceptions: First, element C_{31} , which governs the response of $\hat{i}_t \equiv i_t - X_t^m$ to an innovation in ΔX_t^m , is assumed to have a prior mean of -1 . This means that a shock that increases the U.S. nominal rate in the long run by 1 percentage point, under the prior, has a zero impact effect on the nominal interest rate. Second, C_{55} is assumed to have a prior mean of -1 .

Table 1
Prior distributions.

Parameter	Distribution	Mean.	Std. Dev.
Main diagonal elements of B_1	Normal	0.95	0.5
All other elements of $B_i, i = 1, \dots, L$	Normal	0	0.25
C_{31}, C_{55}	Normal	-1	1
C_{45}	Normal	1	1
C_{41}, C_{51}	Uniform[-1, .0]	-0.5	0.2887
All other estimated elements of C	Normal	0	1
α	Uniform[0, .1]	0.5	0.2887
$\psi_{ii}, i = 1, \dots, 7$	Gamma	1	1
$\rho_{ii}, i = 1, .2, .3, .5, .6, .7$	Beta	0.3	0.2
ρ_{44}	Beta	0.7	0.2
$R_{ii}, i = 1, \dots, 7$	Uniform $\left[0, \frac{\text{var}(o_t)}{10}\right]$	$\frac{\text{var}(o_t)}{10 \times 2}$	$\frac{\text{var}(o_t)}{10 \times \sqrt{12}}$
Elements of A	Normal	mean(o_t)	$\sqrt{\frac{\text{var}(o_t)}{T}}$

Notes. T denotes the sample length. The vector A denotes the mean of the vector o_t , and is defined in Appendix A.

This implies that a foreign permanent monetary shock that increases the foreign nominal interest rate in the long run by 1 percentage point has a prior mean impact effect on the foreign nominal interest rate of zero. Third, C_{45} , which governs the response of $\hat{\epsilon}_t \equiv \epsilon_t - (1 - \alpha)X_t^m + X_t^{m*}$ to an innovation in ΔX_t^{m*} is assumed to have a prior mean of 1. This implies that a foreign monetary shock that increases the foreign interest rate in the long run by 1 percentage point has a zero impact effect on the nominal exchange rate under the prior. Fourth, the prior means of C_{41} and C_{51} , which govern the response of $\hat{\epsilon}_t \equiv \epsilon_t - (1 - \alpha)X_t^m + X_t^{m*}$ and $\hat{i}_t^* \equiv i_t^* - \alpha X_t^m - X_t^{m*}$ to an innovation in ΔX_t^m , are assumed to be equal to $-(1 - \alpha)$ and $-\alpha$, respectively. This implies that under the prior, the impact effects on the depreciation rate, ϵ_t , and the foreign nominal interest rate, i_t^* , in response to a permanent U.S. monetary policy shock, X_t^m , that increases the U.S. interest rate in the long run by 1 percentage point, are both 0. Furthermore, the cointegration parameter α is assumed to have a uniform prior distribution over the interval $[0, 1]$. The parameters ψ_{ii} , for $i = 1, \dots, 7$, representing the standard deviations of the seven exogenous innovations in the AR(1) process (5) are all assigned Gamma prior distributions with mean and standard deviation equal to one. The serial correlations of the exogenous shocks (ρ_{ii} for $i = 1, \dots, 7$) are restricted to be positive and to have Beta prior distributions. The prior serial correlations of all disturbances other than z_t are assumed to have a relatively small mean of 0.3. The prior serial correlation of the stationary nonmonetary shock (z_t) is assumed to have a relatively high prior mean of 0.7, as it is meant to represent the effects of productivity shocks and other real stationary shocks that are typically estimated to be persistent. The prior distributions of all serial correlations are assumed to have a standard deviation of 0.2. The variances of all measurement errors, R_{ii} , are assumed to have a uniform prior distribution with lower bound 0 and upper bound of 10 percent of the sample variance of the corresponding observable indicator. Although not explicitly discussed thus far, the estimated model includes constants. These constants appear in the observation Eq. (9), for details see Appendix A. The unconditional means of the observables are assumed to have normal prior distributions with means equal to their sample means and standard deviations equal to their sample standard deviations divided by the square root of the length of the sample period.

To draw from the posterior distribution of the estimated parameters, we apply the Metropolis-Hastings sampler. We construct a Monte-Carlo Markov chain (MCMC) of two million draws and burn the initial one million draws. Posterior means and error bands around the impulse responses shown in later sections are constructed from a random subsample of the MCMC chain of length 100 thousand with replacement.

4.2. Data

The estimation uses quarterly data from 1974:Q1 to 2018:Q1 from the United States, the United Kingdom, Japan and Canada. Output, y_t , is measured by real GDP per capita. Inflation, π_t , is proxied by the growth rate of the GDP deflator. The measure of the nominal interest rate, i_t , depends on the country considered. For the United States it is the federal funds rate, for the United Kingdom it is the Official Bank Rate of the Bank of England, for Japan it is the call rate of the Bank of Japan, and for Canada it is the overnight rate. The nominal depreciation rate of the U.S. dollar, $\epsilon_t \equiv \ln \mathcal{E}_t - \ln \mathcal{E}_{t-1}$, is measured by the growth rate of the nominal exchange rate (dollar price of one unit of foreign currency). Thus, $\epsilon_t > 0$ corresponds to a depreciation of the U.S. dollar against the foreign currency and $\epsilon_t \ll 0$ to an appreciation. The dollar real depreciation rate, ϵ_t^r , is computed as $\epsilon_t^r = \epsilon_t + \pi_t^* - \pi_t$, where π_t^* indicates the inflation rate in the foreign country, which is either the United Kingdom, Japan, or Canada.

5. Permanent monetary shocks, exchange rates, and uncovered interest rate differentials

The central focus of this paper is to characterize the effects of permanent monetary shocks in the United States on exchange rates and uncovered interest rate differentials. Fig. 2 addresses this issue through the lens of the empirical model. It presents the

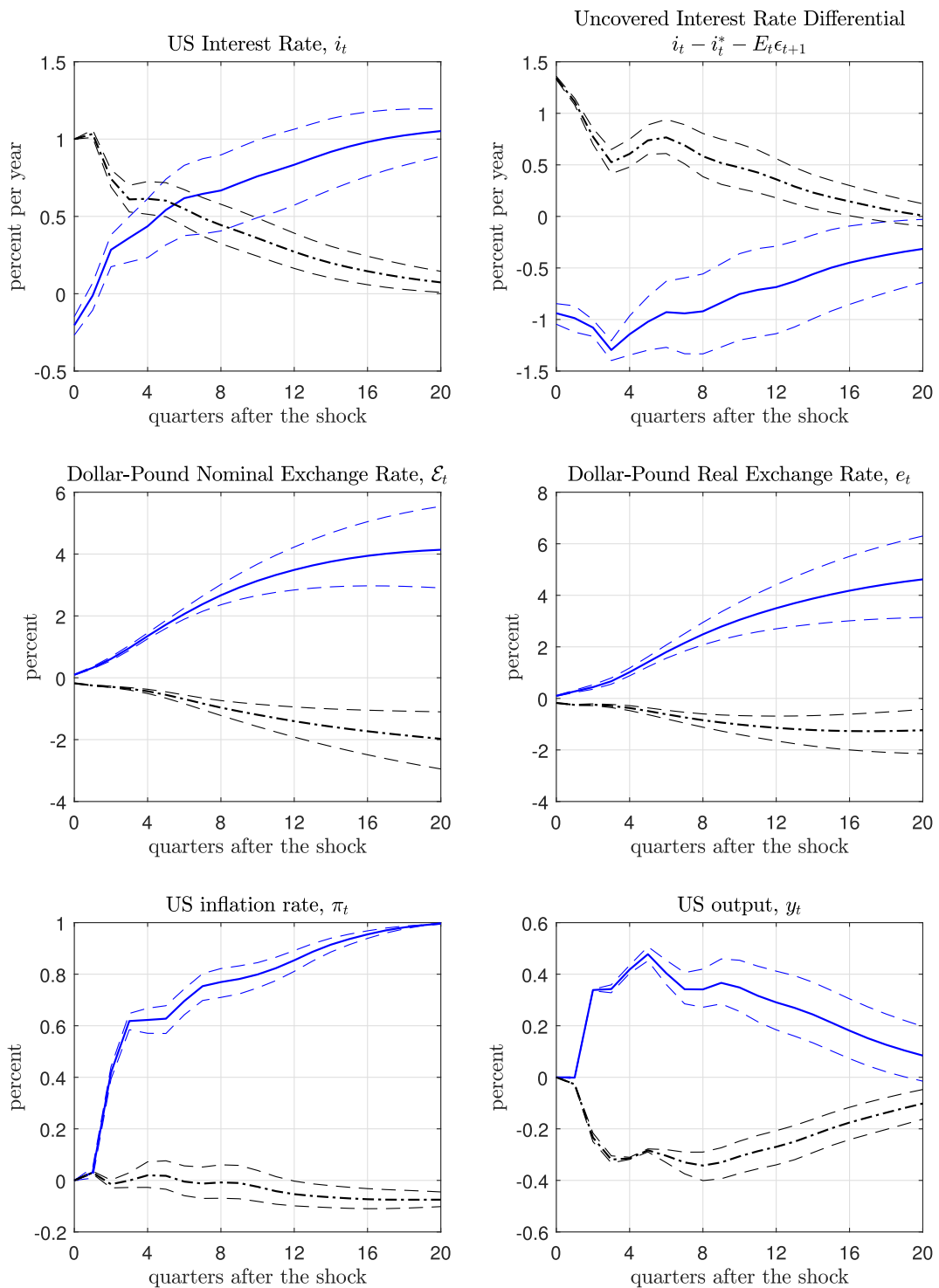


Fig. 2. Impulse responses to permanent and transitory U.S. monetary shocks: united kingdom. Notes. Solid lines display the posterior mean response to a permanent monetary shock that increases the U.S. nominal interest rate by 1 annual percentage point in the long run (an increase in X_t^n). Dash-dotted lines display the posterior mean response to a transitory monetary shock that increases the U.S. nominal interest rate by 1 annual percentage point on impact (an increase in z_t^n). Broken lines are asymmetric 95-percent confidence bands computed using the Sims and Zha (1999) method.

estimated impulse responses of variables of interest to temporary and permanent U.S. monetary shocks. In the figure, the foreign country is taken to be the United Kingdom.

A transitory increase in the U.S. nominal interest rate (a unit increase in z_t^m), shown with a dash-dotted line, leads to a decline in output and inflation in the United States. This finding is consistent with results obtained in the related empirical literature and supports the interpretation of z_t^m as a transitory monetary shock. More central to the focus of this paper, the figure shows that a temporary tightening in the U.S. causes a short-run appreciation of the U.S. dollar, \mathcal{E}_t . Again, this is a familiar and expected result. It is in line with the predictions of the New Keynesian model discussed in Section 2 and with the existing empirical literature that has focused on the effects of transitory monetary disturbances on exchange rates (e.g., Eichenbaum and Evans, 1995). Intuitively, when the U.S. monetary authority makes the dollar more scarce, its price relative to other currencies goes up.

The responses of exchange rates and uncovered interest rate differentials are quite different when the monetary shock is of a more permanent nature. Fig. 2 shows that a monetary shock that increases the U.S. nominal interest rate by one percentage point in the long run (an increase in X_t^m), shown with a solid line, produces a persistent depreciation of the U.S. dollar. Since the cointegration parameter α is estimated to be less than one, the increase in X_t^m must depreciate the dollar in the long run. The important feature of the impulse response of \mathcal{E}_t to a positive innovation in X_t^m is therefore the predicted depreciation of the U.S. dollar at business cycle horizons, 0 to 20 quarters.

The results obtained for the response of the nominal exchange rate extend to the real exchange rate, $e_t \equiv \mathcal{E}_t P_t^{UK} / P_t^{US}$. Fig. 2 shows that, as in the case of the nominal exchange rate, the dollar-pound real exchange rate appreciates in response to a transitory monetary tightening but depreciates in response to a shock that increases the U.S. nominal interest rate in the long run. This finding is in line with the high correlation between the nominal and the real exchange rate observed in raw post-Bretton Woods data as stressed in the literature on the Mussa puzzle (see, for example, Mussa, 1986; Kollmann, 2005; Itskhoki and Mukhin, 2019). Thus these results suggest that the Mussa puzzle extends to correlations conditional on identified transitory and permanent monetary shocks. The fact that permanent monetary shocks have effects on the real exchange rate at relatively long horizons (20 quarters) suggests that the source of monetary nonneutrality may go beyond nominal price rigidity.

We note that neither the temporary nor the permanent monetary shock produces overshooting of the nominal or the real exchange rate, as their responses are weaker in the short run than at any point in the future. The lack of overshooting in response to temporary monetary shocks is in contrast with the existing body of empirical studies, which have found the existence of overshooting either immediately (Kim and Roubini, 2000; Faust and Rogers, 2003; Kim et al., 2017), or in a delayed fashion (Eichenbaum and Evans, 1995; Scholl and Uhlig, 2008).

Consider now the response of the uncovered interest-rate differential, $i_t - i_t^* - E_t \epsilon_{t+1}$. In line with results documented in the related empirical literature (see, for instance, the papers just cited), Fig. 2 shows that a temporary increase in the U.S. nominal interest rate causes a deviation from uncovered interest-rate parity (UIP) in favor of U.S. assets. The novel result is that, contrary to what happens under a temporary shock, a monetary shock that increases the U.S. interest rate in the long run causes a deviation from UIP against U.S. assets. This is so for two reasons. First, as we already saw, the dollar appreciates in response to a temporary monetary shock but depreciates in response to a permanent monetary shock. Second, both shocks cause an increase in the cross-country interest rate differential, $i_t - i_t^*$, (not shown). However, the increase in the interest rate differential is larger in response to the temporary increase in the domestic interest rate. This finding suggests that deviations from uncovered interest rate parity might give an edge to investors that have the ability to tell apart permanent from transitory monetary shocks as they take place.²

As mentioned earlier, consistent with the existing closed-economy literature on the effects of transitory monetary policy shocks, see, for example, Christiano et al. (2005), Fig. 2 shows that a temporary tightening causes a contraction in aggregate activity and a fall in inflation. By contrast, the figure shows that a permanent increase in the nominal interest rate causes an increase in inflation and an expansion in aggregate activity, in line with the findings of Uribe (forthcoming). Thus, the neo-Fisher effect, whereby a monetary policy shock that raises the nominal interest rate in the long run causes an increase in inflation already in the short run, appears to be present not only in closed economy empirical models, but also in models that allow for a foreign bloc.

The effects of permanent U.S. monetary shocks obtained when the foreign country is taken to be the United Kingdom continue to hold when the foreign country is assumed to be either Japan or Canada. This is shown in Figs. 3 and 4. In particular, a monetary policy shock that increases the U.S. policy rate in the long run by one percentage point (an increase in X_t^m) causes a depreciation of the dollar vis-à-vis both the Japanese yen and the Canadian dollar already in the short run and a deviation from UIP against U.S. assets. The opposite results obtain when the monetary tightening in the United States is temporary, although in the case of Canada the responses of the nominal and real exchange rates are a muted depreciation. The responses of U.S. inflation and U.S. output are also broadly in line with the results reported when the model is estimated on U.S. and U.K. data, that is, a temporary monetary tightening in the United States has the conventional contractionary effects on real activity and prices, whereas a U.S. monetary shock that increases interest rates in the long run is associated with neo-Fisherian dynamics, that is, an increase in U.S. inflation and output.

As a robustness check, the model is also estimated jointly on data from the United States, the United Kingdom, Japan, and Canada. This case is of interest because it ensures that the same permanent and transitory U.S. monetary shocks, X_t^m and z_t^m , affect the three other countries. The results are presented in Fig. 5. The figure shows that a monetary shock that increases the U.S.

² For unconditional, risk-based analyses of violations of uncovered interest rate parity see, for example, Lustig and Verdelhan (2007), Hassan (2013), and Richmond (2019).

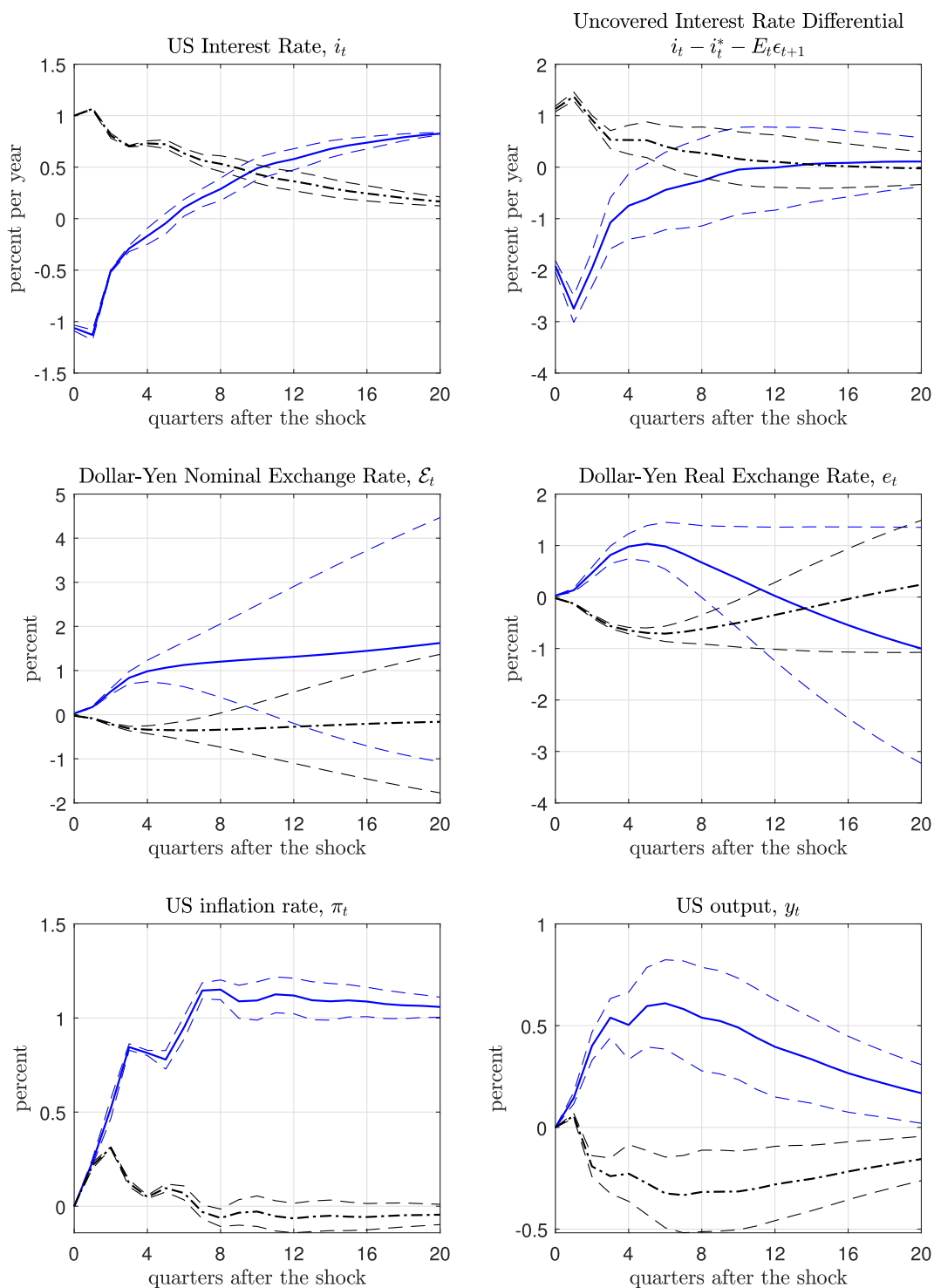


Fig. 3. Impulse responses to permanent and transitory U.S. monetary shocks: Japan. Notes. Solid lines display the posterior mean response to a permanent monetary shock that increases the U.S. nominal interest rate by 1 annual percentage point in the long run (an increase in X_t^m). Dash-dotted lines display the posterior mean response to a transitory monetary shock that increases the U.S. nominal interest rate by 1 annual percentage point on impact (an increase in z_t^m). Broken lines are asymmetric 95-percent confidence bands computed using the Sims and Zha (1999) method.

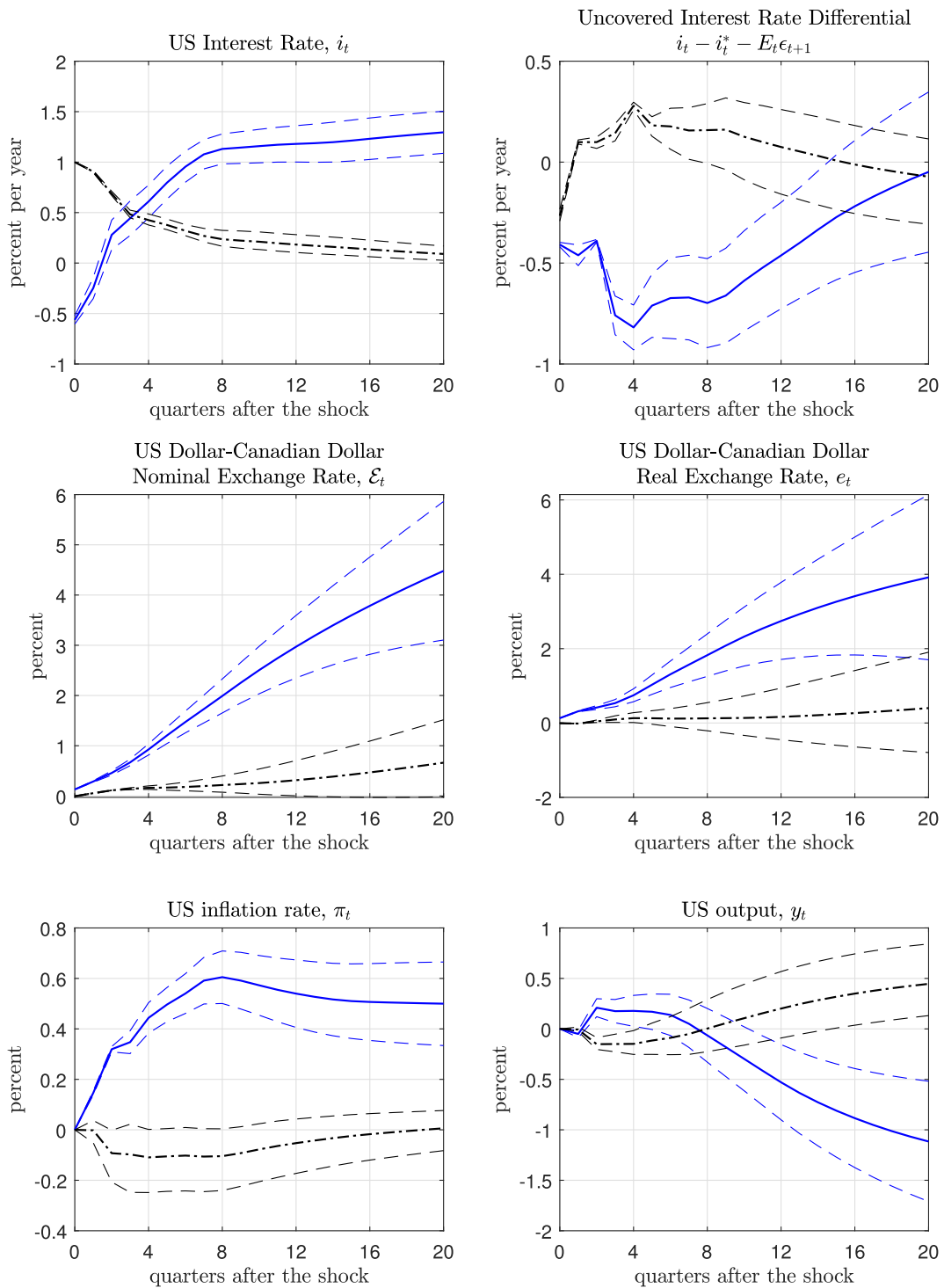


Fig. 4. Impulse responses to permanent and transitory U.S. monetary shocks: Canada. Notes. Solid lines display the posterior mean response to a permanent monetary shock that increases the U.S. nominal interest rate by 1 annual percentage point in the long run (an increase in X_t^m). Dash-dotted lines display the posterior mean response to a transitory monetary shock that increases the U.S. nominal interest rate by 1 annual percentage point on impact (an increase in z_t^m). Broken lines are asymmetric 95-percent confidence bands computed using the Sims and Zha (1999) method.

nominal interest rate in the long run (an increase in X_t^m) causes a depreciation of the U.S. dollar vis-à-vis all other currencies in nominal and real terms already in the short run. Furthermore, an increase in X_t^m leads to a deviation from uncovered interest rate

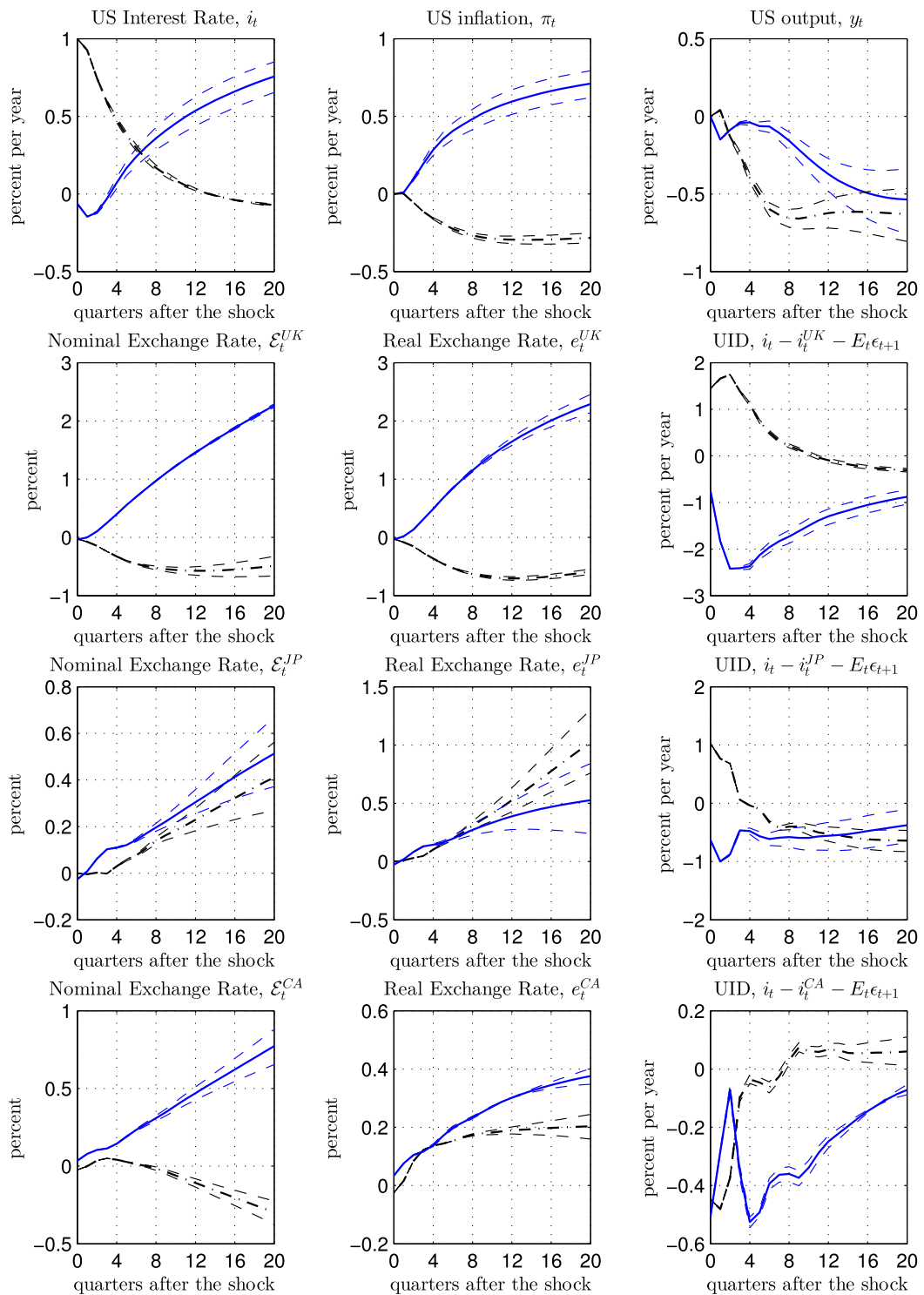


Fig. 5. Impulse responses to permanent and transitory U.S. monetary shocks: UK-Japan-Canada. Notes. Solid lines display the posterior mean response to a permanent monetary shock that increases the U.S. nominal interest rate by 1 annual percentage point in the long run (an increase in X_t^m). Dash-dotted lines display the posterior mean response to a transitory monetary shock that increases the U.S. nominal interest rate by 1 annual percentage point on impact (an increase in z_t^m). Broken lines are asymmetric 95-percent confidence bands computed using the Sims and Zha (1999) method.

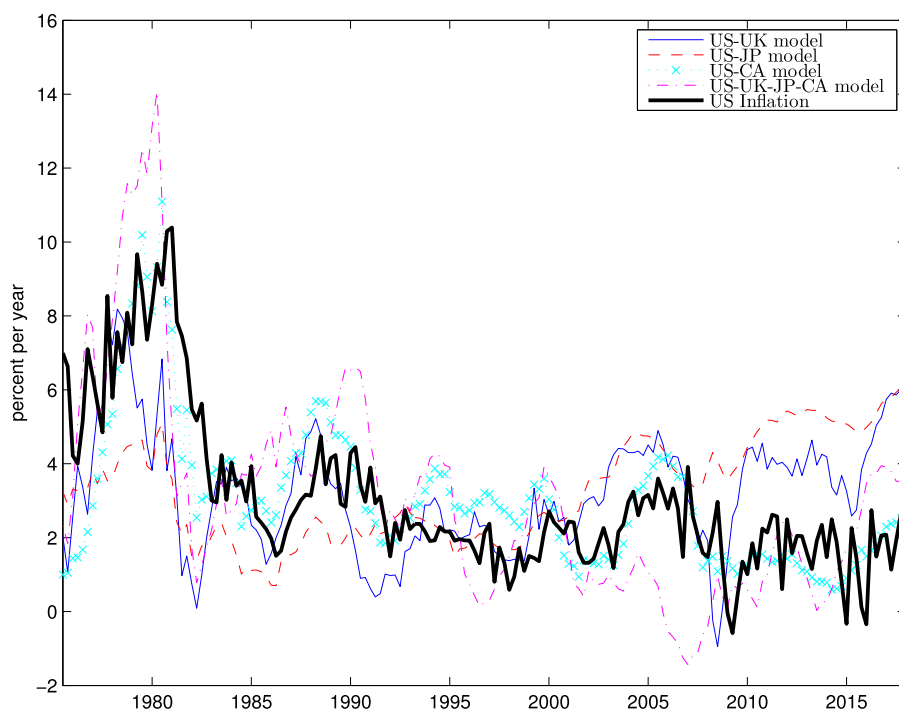


Fig. 6. U.S. inflation and its permanent component, X_t^m . Note. For each model the permanent component of U.S. inflation, X_t^m , was scaled by adding a constant so that its sample mean equals the sample mean of actual U.S. inflation.

parity against U.S. assets for all three currencies. Thus, the main results stressed in this paper emerge not only when the model is estimated on data from individual country pairs but also when it is estimated using data from all countries simultaneously.

It is of interest to ascertain the behavior of the permanent component of U.S. monetary policy, X_t^m , as viewed through the lens of the empirical model. Fig. 6 displays the estimate of the permanent U.S. monetary shock, X_t^m and actual U.S. inflation, π_t . All four estimations of the model, which use different combinations of country data, have predictions for the same object, X_t^m , which are plotted in the figure. The estimates of the permanent monetary component, X_t^m , track well low frequency movements in inflation. In particular, in all variants of the empirical model, X_t^m is high during the high inflation years of the late 1970s and falls during the Volcker disinflation of the early 1980s. Also the estimates of X_t^m suggest the presence of a significant permanent component in both the low inflation following the great contraction of 2008 and the increase in inflation that started when the Fed embarked on a gradual normalization of interest rates in late 2015.

6. The importance of permanent monetary shocks for exchange rates and UIP: variance decompositions

This section sheds light on the sources of variation in exchange rates and uncovered interest rate differentials at business cycle frequencies. Table 2 reports forecast-error variance decompositions of the nominal and real exchange rates and other variables at horizon 12 quarters, which is a standard horizon for business cycle analysis. The picture that emerges from the table is that permanent monetary shocks are important drivers of exchange rates and uncovered interest rate differentials. Jointly, the domestic and foreign permanent monetary shocks, X_t^m and X_t^{m*} , explain the vast majority of the forecast-error variance of the dollar-pound and dollar-yen exchange rates and the uncovered interest rate differentials. In the case of the dollar-pound exchange rate the forecast error variance explained by permanent monetary shocks is split in roughly equal parts between the U.S. permanent monetary shock (X_t^m) and the U.K. permanent monetary shock (X_t^{m*}). In the case of the dollar-yen exchange rates virtually all of the forecast error variance is explained by the Japanese permanent monetary shock. By contrast, the U.S. transitory monetary shock (z_t^m) plays a minor role in accounting for movements in exchange rates and uncovered interest rate differentials in the United Kingdom and Japan, with a forecast error variance share of less than five percent. For Canada permanent monetary shocks are relevant but not as prominent in explaining the forecast error variances of exchange rates and uncovered interest rate differentials. However, permanent monetary shocks continue to be the dominant source of monetary disturbance, as z_t^m is estimated to account for a negligible fraction of the variance of exchange rates and uncovered interest rate differentials.

Table 2 further shows that for a given country the nominal and real exchange rates are driven by the same shocks. This is the case for all three currencies considered. This finding is another reflection of the Mussa fact, namely, the presence of a high degree of comovement of nominal and real exchange rates post Bretton Woods at business cycle frequencies.

Table 2
Forecast error variance decomposition at horizon 12 quarters.

	A. United Kingdom						
	Δy_t	π_t	i_t	$\ln \mathcal{E}_t$	$\ln e_t$	i_t^*	$i_t - i_t^* - E_t \varepsilon_{t+1}$
Permanent Monetary Shock, X_t^m	0.29	0.88	0.47	0.43	0.39	0.37	0.14
Transitory Monetary Shock, z_t^m	0.05	0.00	0.27	0.02	0.02	0.09	0.03
Permanent Nonmonetary Shock, X_t	0.57	0.03	0.19	0.01	0.02	0.06	0.02
Transitory Nonmonetary Shock, z_t	0.02	0.00	0.00	0.00	0.00	0.02	0.00
Foreign Permanent Monetary Shock, X_t^{m*}	0.05	0.06	0.05	0.52	0.55	0.17	0.79
Foreign Transitory Shock, z_t^*	0.02	0.03	0.01	0.02	0.01	0.29	0.01
UIP Shock, w_t^*	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B. Japan							
Permanent Monetary Shock, X_t^m	0.05	0.59	0.11	0.00	0.00	0.05	0.02
Transitory Monetary Shock, z_t^m	0.03	0.02	0.23	0.00	0.00	0.03	0.01
Permanent Nonmonetary Shock, X_t	0.23	0.13	0.01	0.00	0.00	0.03	0.01
Transitory Nonmonetary Shock, z_t	0.49	0.14	0.25	0.00	0.00	0.03	0.04
Foreign Permanent Monetary Shock, X_t^{m*}	0.13	0.11	0.35	0.88	0.87	0.80	0.76
Foreign Transitory Shock, z_t^*	0.00	0.00	0.00	0.00	0.00	0.03	0.00
UIP Shock, w_t^*	0.06	0.02	0.04	0.11	0.13	0.04	0.17
C. Canada							
Permanent Monetary Shock, X_t^m	0.13	0.77	0.74	0.28	0.20	0.50	0.07
Transitory Monetary Shock, z_t^m	0.01	0.02	0.09	0.00	0.00	0.06	0.00
Permanent Nonmonetary Shock, X_t	0.27	0.11	0.08	0.65	0.67	0.09	0.86
Transitory Nonmonetary Shock, z_t	0.50	0.08	0.08	0.06	0.13	0.05	0.02
Foreign Permanent Monetary Shock, X_t^{m*}	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Foreign Transitory Shock, z_t^*	0.08	0.02	0.02	0.00	0.01	0.28	0.05
UIP Shock, w_t^*	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Notes. Notation: Δy_t , U.S. output growth; π_t , U.S. inflation; i_t , the federal funds rate; $\ln \mathcal{E}_t$, dollar-pound, dollar-yen, or dollar-CAD nominal exchange rate; $\ln e_t$, dollar-pound, dollar-yen, or dollar-CAD real exchange rate; i_t^* , U.K., Japanese, or Canadian nominal interest rate; ε_t , devaluation rate.

Independently of whether the foreign bloc is taken to be the United Kingdom, Japan, or Canada, the U.S. permanent monetary shock is estimated to be an important driver of U.S. inflation accounting for 88, 59, and 77 percent of its forecast-error variance, respectively. This finding is similar to that obtained in Uribe (forthcoming) in the context of closed-economy empirical and optimizing models estimated on U.S. data.

The U.S. transitory monetary shock, z_t^m , plays a much smaller role than the permanent monetary shock, X_t^m , in accounting for short-run movements in all variables with the exception of the federal funds rate when the foreign bloc is Japan. This result is of interest in light of the fact that the related literature is often aimed at understanding the importance of transitory monetary shocks.

The result that permanent monetary shocks play an important role in explaining the forecast error variance of the nominal exchange rate, the real exchange rate, and uncovered interest rate differentials continues to hold in the U.K. and Japan at other horizons relevant for business-cycle analysis. Fig.B.1 in Appendix B shows forecast error variance decompositions for horizons between 1 and 16 quarters. As expected, permanent monetary shocks continue to be important at horizons longer than 12 quarters. The noteworthy result is that even at a horizon as short as 1 quarter, permanent monetary shocks explain a large fraction of the forecast-error variance of the three variables in the United Kingdom and Japan. In the case of Canada, the role of permanent monetary policy shocks falls markedly as the forecasting horizons shortens below four quarters.

To place these results in the context of the related literature, we note that a key difference with the papers cited in the introduction, for example, Eichenbaum and Evans (1995), is the distinction made here between transitory and permanent monetary disturbances. The variance decompositions reveal that permanent monetary shocks, both domestic and foreign, which are the novel source of monetary uncertainty introduced in this paper, are important. These findings suggest that if the permanent components of domestic and foreign monetary policy were to display more stability, exchange rate volatility could be greatly reduced.

7. Conclusion

Existing empirical studies have documented that a monetary shock that increases the domestic interest rate causes an appreciation of the domestic currency in nominal and real terms and a persistent deviation from uncovered interest parity in favor of the high-interest-rate currency. In this paper, we estimate an empirical model of exchange rates that allows for permanent and transitory monetary shocks. Using quarterly data from the United States, the United Kingdom, Japan, and Canada for the post Bretton-Woods period, we obtain the following three results. First, in the short run permanent monetary policy shocks depreciate the domestic currency whereas temporary ones appreciate it. Second, both transitory and permanent increases in the domestic nominal interest rate cause deviations from uncovered interest-rate parity but of opposite signs, the former in favor of the high interest rate currency and the latter against. Third, permanent monetary shocks explain an important fraction of short-run movements in nominal and real exchange rates and uncovered interest rate differentials, while transitory monetary shocks play a minor role.

A theoretical contribution of the paper is to show that the estimated impulse responses to transitory and permanent monetary policy shocks can be qualitatively explained in the context of a dynamic optimizing open economy model. The two key ingredients of the model are nominal rigidities and financial frictions. The former guarantees that monetary disturbances have an effect on real exchange rates and the latter allows the model to display deviations from uncovered interest rate parity. The sign of the response of the exchange rate to monetary tightenings depends on the persistence of the monetary innovation whereas the sign of the response of the uncovered interest rate differential depends on the relative magnitudes of the inter- and intratemporal elasticities of consumption substitution.

A possible policy implication of the findings presented in this paper has to do with the real consequences of an eventual normalization of nominal interest from near zero levels, as observed at the time of this writing in many countries around the world, to levels in line with historical averages. The empirical and theoretical findings suggest that such normalization need not cause an appreciation of the nominal and real exchange rates, a deflation, or a contraction in economic activity. This concern, which is often voiced by policymakers, is consistent with existing results on the real consequences of transitory adjustments in policy rates. However, a process of interest rate normalization is more akin to a permanent rise in rates than to a transitory one and, as the results of this paper suggest, it should therefore be expected to trigger quite different dynamics.

Appendix A

In this appendix, we present the empirical model in more detail showing explicitly its associated intercepts that we had omitted earlier to simplify the exposition. Let

$$\widehat{Y}_t \equiv \begin{bmatrix} y_t - X_t - E(y_t - X_t) \\ \pi_t - X_t^m - E(\pi_t - X_t^m) \\ i_t - X_t^m - E(i_t - X_t^m) \\ \varepsilon_t - (1 - \alpha)X_t^m + X_t^{m*} - E(\varepsilon_t - (1 - \alpha)X_t^m + X_t^{m*}) \\ i_t^* - \alpha X_t^m - X_t^{m*} - E(i_t^* - \alpha X_t^m - X_t^{m*}) \\ \pi_t^* - \alpha X_t^m - X_t^{m*} - E(\pi_t^* - \alpha X_t^m - X_t^{m*}) \end{bmatrix} \text{ and } u_t \equiv \begin{bmatrix} \Delta X_t^m - E(\Delta X_t^m) \\ z_t^m \\ \Delta X_t - E(\Delta X_t) \\ z_t \\ \Delta X_t^{m*} - E(\Delta X_t^{m*}) \\ z_t^* \\ w_t^* \end{bmatrix}.$$

The vector \widehat{Y}_t evolves over time according to

$$\widehat{Y}_t = \sum_{i=1}^L B_i \widehat{Y}_{t-i} + C u_t$$

and the vector u_t according to

$$u_t = \rho u_{t-1} + \psi v_t.$$

Then to obtain a first-order state space representation let the vector ξ_t be given by

$$\xi_t \equiv [\widehat{Y}_t \widehat{Y}_{t-1} \dots \widehat{Y}_{t-L+1} u_t']'.$$

With these definitions and notation in hand, the empirical model becomes

$$\xi_{t+1} = F \xi_t + P v_{t+1}$$

and the observation equations can be written as

$$o_t = A' + H' \xi_t + \mu_t.$$

The relationship between the matrices B_i for $i = 1, \dots, L, C, \rho$, and ψ and the matrices A, F, P , and H is as follows. Let V denote the number of variables included in the vector \widehat{Y}_t and S the number of shocks in the vector v_t . In the empirical implementation of the model $V = 6$ and $S = 7$. Further, let

$$B \equiv [B_1 \dots B_L],$$

and let I_j denote an identity matrix of order j and \emptyset_{ij} a zero matrix of order i by j . Then, for $L \geq 2$ we have

$$F = \begin{bmatrix} B & C\rho \\ [I_{V(L-1)} \ \emptyset_{V(L-1),V}] & \emptyset_{V(L-1),S} \\ \emptyset_{S,V} & \rho \end{bmatrix}, P = \begin{bmatrix} C\psi \\ \emptyset_{V(L-1),S} \\ \psi \end{bmatrix}, A' = \begin{bmatrix} E(\Delta X_t) \\ E(i_t - \pi_t) \\ E(\Delta X_t^m) \\ (1 - \alpha)E(\Delta X_t^m) - E(\Delta X_t^{m*}) \\ E(\Delta X_t^{m*} + \alpha \Delta X_t^m) \\ E(\varepsilon_t + \pi_t^* - \pi_t) \end{bmatrix}$$

and

$$H' = [M_\xi \Phi_{V,V(L-2)} M_u],$$

where the matrices M_ξ and M_u take the form

$$M_\xi = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & -1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \text{ and } M_u = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1-\alpha & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ \alpha & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

Appendix B. Variance decomposition at forecasting horizons of 1 to 16 quarters

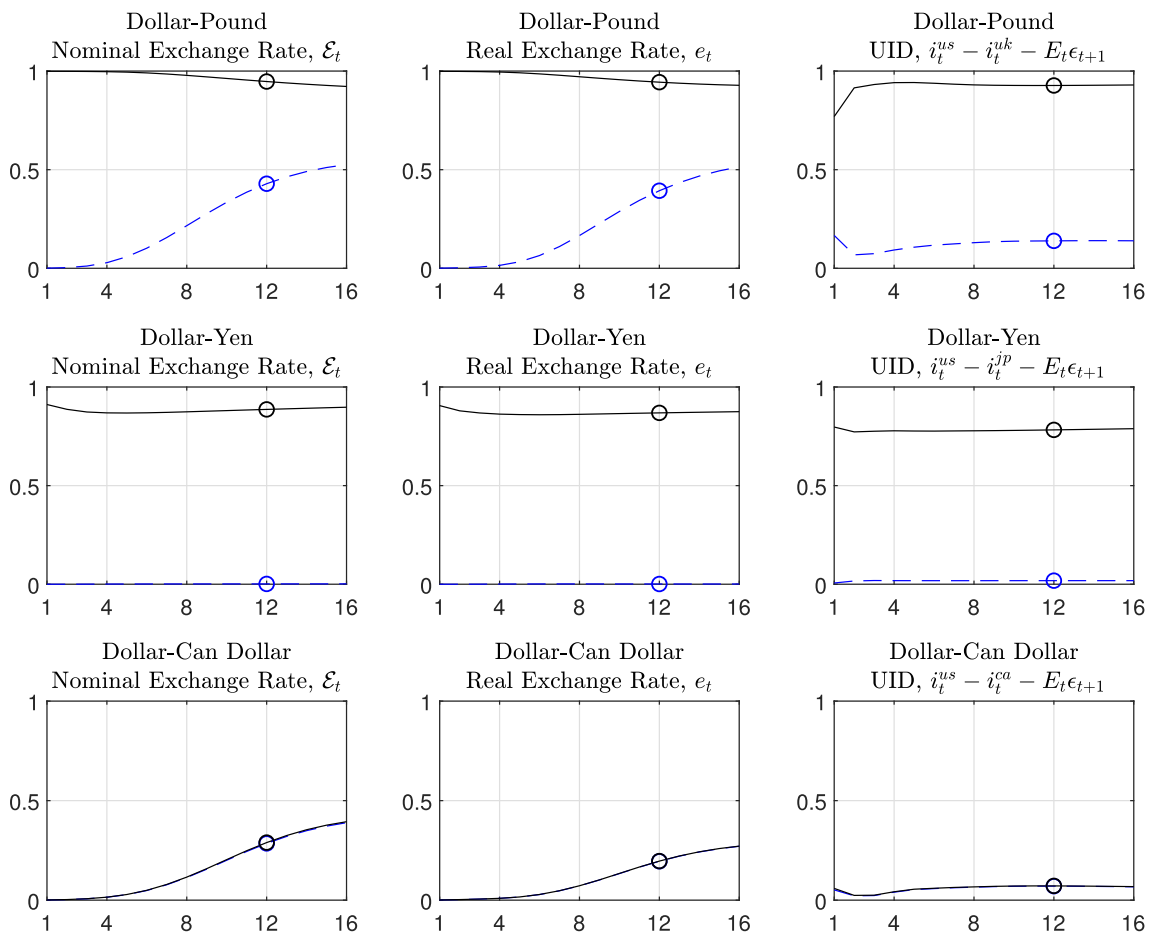


Fig. B.1. Forecast error variance decompositions of the nominal exchange rate, the real exchange rate, and uncovered interest rate differentials. Notes: The horizontal axis indicates the forecasting horizon in quarters. The vertical axis measures the fraction of the forecasting error variance explained by ΔX_t^m (broken line) and by ΔX_t^m and ΔX_t^{m*} jointly (solid line). The circle indicates the fraction of the forecast error variance at forecasting horizon 12 quarters, which is the one shown in Table 2 in the body of the paper.

Appendix C. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.jinteco.2021.103560>.

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