Monetary Policy Surprises and Exchange Rate Behavior*

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Abstract

Central banks unexpectedly tightening policy rates often observe the exchange value of their currency depreciate, rather than appreciate as predicted by standard models. We document this for Fed and ECB policy days using event studies and ask whether an information effect, where the public attributes the policy surprise to an unobserved state of the economy, may explain the abnormality. It turns out that many informational assumptions make a standard two-country New Keynesian model match this behavior. To identify the particular mechanism, we condition on multiple asset prices in the event study and model implications for these. We find that there is heterogeneity in this dimension in the event study and no model with a single regime can match the evidence. Further, even after conditioning on possible information effects driving longer term interest rates, there appear to be other drivers of exchange rates. Our results show that existing models have a long way to go in reconciling event study analysis with model-based mechanisms of asset pricing.

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1 Introduction

We have become adept at measuring asset price responses to monetary policy surprises, and indeed, measuring those surprises themselves using changes in asset prices. This is due to increased data availability and conceptual advances that led to better empirical methodology. These monetary policy event studies are useful in themselves, helping relate changes in a broad array of financial markets to policy actions and announcements; and are also useful in VAR identification where the surprises are used as instruments.

In a large and expanding literature, a recent strand is focusing on asymmetries in financial market responses to policy surprises, when an asset price moves in an unexpected direction given the policy event. This may be stock prices or breakeven inflation rates increasing when there is a surprise tightening, or long-term forward interest rates decreasing in response to the same. "Unexpected" in this context is based on the canonical model of monetary policy, where tighter policy decreases stock prices and inflation, and leaves long-term forward interest rates unchanged. The observed effects require a deviation from the canonical model, and that is often found in relaxing the informational assumptions. If the central bank has a different information set than market participants, policy surprises may also signal this private information, without precluding genuine policy shocks.

Our focus in this paper is on the behavior of exchange rates on policy dates. We first show that similar unexpected behavior is prevalent in exchange rate reactions to monetary policy surprises as well, and then discuss why this may be so. In presenting the discussion we will make use of a standard two country open economy model taking into account implications for yield curves, which allows jointly analyzing policy surprises' effects on the exchange rate and the shapes of the home and foreign yield curves simultaneously.

Our study helps accomplish several goals. We are quickly able to show that looking at one moment, such as the covariance of the shortest end of the yield curve—the policy surprise—and the exchange rate, does not uniquely identify the possible mechanism. There are multiple informational assumptions that are consistent with a single moment condition. Second, we can then argue that bringing in other moments, such as covariances with changes in longer-term points on the yield curve, may narrow down the set of plausible models. Importantly, we will show that conditioning on path (forward guidance) surprises helps explain the exchange rate puzzle on almost all dates in the US but poses its own problems in terms of the possible information effects that drive this surprise. We discuss several noteworthy policy dates where this becomes apparent.

Using estimated versions of models with different informational assumptions, we then ask which model fits the observed macro-finance data best, on average. "On average" is very consequential here as information asymmetries inherently include regime switching where information of one or another kind may be received by the public on any policy date. But fitting a regime switching model to the data is not possible because each period may be in a different regime, this is not a slowly regime switching world. Thus, only the model that fits best on average can be chosen and that is certainly a misspecified model. The exercise we carry out allows us to discuss these issues and relay what we learn from the best fitting model, which is an imperfect information model.

We conclude by observing that given the canonical model we are employing, the two country open economy Clarida et al. (2002) [CGG] model, there exists a set of policy dates where no variant of the model matches the signs of all asset price changes. In that regard, this paper is a call for action on open economy macro-finance modeling.

2 What We Build On

This paper is motivated by high frequency event studies. This methodology studies asset prices, which are forward looking jump variables, at times of arrival of news to achieve identified effects of news on asset prices. This literature goes back to Fama et al. (1969) but the strand we belong to, monetary policy event studies, date to the 1989 paper of Cook and Hahn. A seminal paper is the work of Kuttner (2001) who recognized that conditioning on days of monetary policy announcements and changes in policy rates imparts considerable measurement error as market participants at least partly anticipate policy decisions and therefore these by themselves do not constitute news. Kuttner spearheaded the use of Federal Funds Futures contracts in measuring policy news.

Gürkaynak et al. (2005a) then showed that monetary policy announcements are perceived to be multi-dimensional, with one factor capturing the surprise in the policy action (target) and another the surprise in the policy communication (path). The monetary policy event-study literature took off, with a large number of papers that we will not survey here using these surprise measures as independent variables and studying the responses of a wide variety of asset prices.

More recently, the event study literature, with its measure of policy surprises, met the VAR literature, with its measure of shocks. High frequency event study surprises are innovations in market participants' information sets, whereas lower frequency VAR shocks are innovations conditional on the actual state of the economy. These two measures would overlap under full information (Gürkaynak and Wright, 2013) but even under partial information surprises may be a good instrument for identified shocks in VARs, where identification is notoriously difficult. Faust et al. (2004) took the first step in formally identifying monetary VARs using event study data and Gertler and Karadi (2015) introduced the use of monetary policy surprises as instruments for shocks in a proxy VAR.

As noted by Gertler and Karadi and discussed in detail by Ramey (2016), some of the findings of Gertler and Karadi are consistent with the event study surprise not satisfying the exclusion restriction. For example, if the central bank correctly forecasts output to go down and cuts interest rates for this reason and the forecast is private to the central bank, the rate cut will be surprise in the event study sense (market participants received new information) but not a shock in the VAR sense (the policy rule was followed exactly given the state). Central banks may indeed have superior information on some aspects of macroeconomic processes, as argued by Romer and Romer (2000) and Peek et al. (1999). This observation has led to a growing literature in central bank information effects.

Event studies are again the starting point, as some asset price reaction will look "abnormal" under the presence of asymmetric information. Abnormality is, of course, in the eye of the beholder and the beholder is the model one has in mind. For example, Gürkaynak et al. (2005b) have argued that the reaction of the long-end of the yield curve is not consistent with models of fixed steady states and instead proposed a model where the inflation target is time-varying and unknown to the public, as was the case in the US before 2012. This is a case where the information asymmetry is about the preferences of the central bank, as in the theoretical work of Ellingsen and Soderstrom (2001).

The influential paper of Campbell et al. (2012) provided the nomenclature of information effects, with Delphic forward guidance providing signals about the central bank's forecast itself and Odyssean forward guidance being about the future path of interest rates given the macroeconomic forecast. More recently, event study papers focusing on the long-end of the yield curve (Nakamura and Steinsson, 2018), stock prices (Jarociński and Karadi, 2020; Lunsford, 2020; Kerssenfischer, 2019), break-even inflation rates (Andrade and Ferroni, 2016) have found similar puzzling behavior from the perspective of standard models and have proposed central bank information-based explanations. These papers suggest central banks may have superior information on the steady state growth rate of output or the current state of the business cycle and use asset price behavior to disentangle standard monetary policy surprises from information surprises.

Two papers that stand out in this literature are Miranda-Agrippino and Ricco (2017) and Bauer and Swanson (2020). The former paper conditions on Greenbook forecasts of the Fed (which are released with a five year delay) to see whether the contemporaneous market-based surprise correlates with the internal forecast. In essence, this paper asks whether there was actually information the Fed had, rather than the market participants behaving as if it did. There is evidence of information effects but only a small proportion of the surprise is attributable to Greenbook forecasts. The latter paper asks this question outright in a survey, which finds that market participants do not think the Fed has consistently superior information about cyclical dynamics. Bauer and Swanson note that central bank preferences, as in Gürkaynak et al. (2005b) are likely candidates for information effects.

There is also a large literature on exchange rate reactions to monetary policy. The relevant strand for our purposes goes back to Engel and Frankel (1984) who observed the unexpected behavior of exchange rates in response to monetary policy actions, with the local currency depreciating when policy is tightened. Their explanation rested on policy reversals. As relevant are works that focus on non-monetary policy data releases and exchange rate reactions, relating these to monetary policy rules. In particular, Clarida and Waldman (2008) and Clarida (2009) nicely argue that inflation surprises (inflation higher than expected) may lead to local currency appreciations if inflation is a persistent process and monetary policy is sufficiently attuned to inflation stabilization. Clarida (2009) employs the Clarida et al. (2002) model to make that point and is the rare paper that provides a formal model to make an argument based on event study evidence.

More recently, Stavrakeva and Tang (2018) note the appreciation of the dollar in response to easings in Fed policy during the Great Recession. They propose a combination of information (Delphic forward guidance) and exorbitant duty a la Gourinchas et al. (2018) as an explanation. Taking a similar path in event studies, we will show that the average finding in high frequency event studies is the opposite, the dollar on average depreciates when there are surprise easings by the Fed. Our interest will nonetheless will be on the many days where the dollar response was puzzling, and on that topic we will show that this behavior was not limited to the dollar and was also not limited to the Great Recession period. Another immediately relevant paper is that of Cieslak and Schrimpf (2019), who do not focus on exchange rates but do take into account multiple moments in the event study, in their case the joint behavior of the stock prices, policy action surprise, and the long-end of the yield curve. We will focus on exchange rates and yield curves in two economies, as well as bringing in a formal model to frame the interpretation.

This overview of the state of the literature helps place our contribution in context. Event studies have long been used to inform models and models form the baseline against which event study findings are seen as by-the-book or puzzling. We study the exchange rate behavior on policy days in response to Fed and ECB surprises. From the perspective of the CGG model, puzzling behavior is rampant.

If monetary policy is informative about some other, unobserved realization in the economy, then asset price reactions to monetary policy in the incomplete information setting will be the asset price reactions to that realization in the complete information setting. We therefore ask which shock in the full information model generates the observed puzzling covariance of exchange rate and the short rate. The answer turns out to be several shocks and combinations of shocks. This lack of identification is important. Asset price reactions contrary to the standard model predictions suggest something may be unobserved and signaled by the central bank but they may not uniquely pin down what.

We therefore bring in more asset prices and have a larger set of moment conditions from the event study to discipline the information structure of the model. The main body of the paper is carrying out these exercises. But before we go there an important caveat is in order.

The model is limited to information asymmetries for the variables it employs. We therefore do not speak to the Rogers et al. (2014) "saving the euro" effect where easier than expected monetary policy announcements during the European debt crisis sometimes led to appreciations of the euro as these were seen as signs that the ECB was determined to hold the euro area together. This has no counterpart in the model and we cannot analyze its effects, although we believe the effect was present. We also do not speak to market participants slowly learning about the reaction function of the ECB (i.e. the relative weight of inflation) in the early part of our sample as pointed out by Goldberg and Klein (2011). The solution algorithm used for the partial information model (applicable only to linearized models and the local approximations at the steady state where inflation and output gaps are zero) makes time-varying effects of policy smoothing parameter and relative weights of inflation versus output gap stabilization vanish. This is an important caveat, as potentially changing preferences of policy makers is a natural source of information asymmetry. The development of algorithms that allow for changing policy preferences in partial information models will lead to fruitful research in both closed and open economy macroeconomics and the study of changing preferences other than the inflation target will have to be taken up in future work using those methods.

Despite the caveats, we are able to offer the most complete model-based assessment of event study evidence in the presence of potential information effects and speak clearly about the dimensions in which the standard workhorse open economy macroeconomic model does and does not help explain the financial market data we observe.

3 Event study: First pass

We will study the USD/EUR exchange rate reaction to ECB and Fed policy surprises. The exchange rate, e, is always defined as dollars per euro, hence e going up in response to surprise ECB tightening is an appreciation of the euro (as expected) but the same happening in response to a surprise Fed tightening is a depreciation of the dollar (and is contrary to the standard model prediction).

Our data comes from the Euro Area Monetary Policy Event Study Database (Altavilla et al., 2019) and an updated version of the data used in Gürkaynak et al. (2005a). The monetary policy surprise measure is the standard one, often called target surprise, backed out using a short dated interest rate contract, Federal Funds Futures for the US, and Overnight Indexed Swap for the euro area.

Using these surprise measures, we run event study regressions for the US and the euro area to identify the effects of monetary policy surprises on the exchange rate. For the US, we use the percentage change in USD/EUR exchange rate in the 30-minute window around the Fed announcements and the target surprises in the same window. For the euro area, we use intraday changes in 1-month OIS as the target surprise and percentage change in USD/EUR exchange rate around the monetary event window, which covers both the press release by the ECB and the press conference by the ECB president. Sample periods for the event studies are 1994-2018 for the US and 1999-2018 for the euro area.

The estimates of basic event study regressions are given in Table 1. Surprise tightening in the US appreciates the dollar against euro, whereas surprise tightening in the euro area appreciates euro against the dollar (although the effect is not statistically significant in this sample). This is as expected. However, even when the responses are statistically significant, explanatory power of these regressions are very low. Scatter plots presented in Figures 1 and 2 explain why. In these figures, we plot monetary policy action surprises (target) and the associated percentage change in exchange rates. Green dots show the policy dates with the expected sign derived from the event study regression: surprise tightening causing an appreciation of the domestic currency. Even though most policy dates have this covariance, there are many days with the opposite sign: surprise tightening depreciating the domestic currency, which are depicted by red dots. 35 out of 83 days for the US and 61 out of 146 days for the euro area are days where the sign of the covariance is opposite of what event study regressions imply. We call these information days.

Figures 1 and 2 show the monetary policy surprises and the exchange rate reactions for the Fed and the ECB in the full sample. Our full sample, also used in the regressions, is still a subset of all policy dates, where we only consider dates where the exchange rate has changed by at least 0.2% and either the immediate policy surprise or the change in year-ahead rates (fourth eurodollar contract-implied rate for the US and one-year OIS rate for the euro area) has changed by at least two basis points. We trim the dates where either the monetary policy surprise or the exchange rate reaction was minuscule because we will count days with "normal" and "abnormal" behavior and do not want to classify dates where nothing really happened. Including these dates would not have changed our analysis but would have cluttered figures and added noise to the count of days with probable information effects.

The number of abnormal days, where the exchange rate moves in the wrong direction is what motivated Engel and Frankel (1984), and we replicate that finding with 21^{st} century data and using interest rate surprises as the monetary policy stance measure. Figures 3 and 4 display this information in a time series format, making it clear that responses of exchange rates in both directions to the same surprise were present in policy dates before 2009, when the Global Financial Crisis began and policy rates moved to the effective lower bound (ELB), and after the crisis was over as well. The abnormal behavior of exchange rates was not an artifact of the crisis and its immediate aftermath.

This is the type of evidence that leads economists to study central bank information effects. Indeed, one can easily think of a setting where, say, aggregate supply shocks are better known by the central bank and policy surprises are informative to the public about that latent variable. In that case, higher than expected policy rates may signal higher inflation and cause a depreciation of currency. While the mechanism is plausible, assessing whether it can arise in an internally consistent model requires using such a model.

4 The Model

To study the extent to which exchange rate behavior is a puzzle on some policy days and why this may be so, we will use what is now a standard model in open economy macroeconomics. The Clarida et al. (2002) model is the two country open economy variant of Clarida et al. (1999) and is a well studied, canonical framework. We first provide a very brief overview of the model in its standard full information form, emphasizing the aspects that are important for the discussion to follow. The partial information version of the same model will be discussed in this section as well.

4.1 Model Under Full Information

This is a two-country open economy New Keynesian model where, in contrast to small open economy models such as Gali and Monacelli (2005), countries' decisions have effects on global variables. We use this setting to model the EA and the US, with possible spillover effects of policy decisions.

The model, the way we employ it, has producer currency pricing and complete pass-through of exchange rates to domestic prices. Calvo pricing generates nominal price rigidities in both countries and the law of one price holds, implying purchasing power parity (PPP). On the financial side, there are complete markets (i.e., a complete set of Arrow-Debreu securities), which brings perfect international consumption risk-sharing ($C_t = C_t^*$ for all t where * indicates a foreign variable or parameter). Complete markets also make uncovered interest parity (UIP) hold. Labor, which is the sole input for intermediate goods production, is immobile across two countries.

It is useful to remember that this model is built on the closed economy New Keynesian model of Clarida et al. (1999) so insights from that well known closed economy framework continue to apply. CGG themselves used this open economy variant to study optimal discretionary monetary policy with and without international cooperation. Our interest is elsewhere and we will not be asking optimal policy questions.

The model, after the optimization problem of households and firms are solved, market clearing conditions are imposed on the first order conditions, and the resulting equations are linearized, consists of two structural equations and a monetary policy rule, per country. Of the structural equations, the IS curve is obtained from the utility maximization of households, and the Phillips curve from the profit maximization of firms.

The IS relationship is

$$\tilde{y}_t = E_t\tilde{y}_{t+1} - \frac{1}{\sigma_0}[r_t - E_t\{\pi_{t+1}\} - \bar{r}r_t] \tag{1}$$

where $\tilde{y}$ is output gap, r is the nominal interest rate, π is domestic price inflation, and $\bar{r}r$ is the natural rate of interest given by

$$\bar{rr}_t = \sigma_0 E_t\{\triangle \bar{y}_{t+1}\} + \kappa_0 E_t\{\triangle y^*_{t+1}\}, \tag{2}$$

with y^* the foreign output level and $\bar{y}$ the natural level of output of the form

$$\bar{y}_t = \frac{1}{\kappa}[(1+\phi)a_t - \kappa_0 y^*_t], \tag{3}$$

and a the aggregate productivity that follows

$$a_t = \rho_a a_{t-1} + \varepsilon^a_t. \tag{4}$$

ε^a is a white noise productivity shock with variance σ^2_a. $\sigma_0 = \sigma - \kappa_0$ where $\kappa_0 = \gamma(\sigma - 1)$, $1/\sigma$ is the intertemporal elasticity of substitution of consumption, and $\gamma \in [0, 1]$ is the country size. We assume that the countries are of equal size ($\gamma = 0.5$). Finally, ϕ is the inverse Frisch elasticity of labor supply and $\kappa = \sigma + \phi - \kappa_0$.

Note that the IS equation has a knife-edge property: σ governs the existence and direction of international spillovers and if $\sigma = 1$, international spillovers disappear from the equation (because $\kappa_0 = 0$ and $\sigma_0 = \sigma$) and we are back to the closed economy IS equation.

The New Keynesian Phillips Curve is

$$\pi_t = \beta E_t\{\pi_{t+1}\} + \lambda \tilde{y}_t + \varepsilon^\pi_t \tag{5}$$

where ε^π is a white noise inflation shock with variance σ^2_π, β is the time discount factor, $\lambda = \delta\kappa$ with $\delta = (1-\theta)(1-\beta\theta)/\theta$, and θ is the Calvo pricing parameter. Observe that when $\sigma = 1$, the slope is identical to that of the closed economy New Keynesian Phillips curve.

Note also that the exchange rate is not part of these equations. Clarida et al. (2002) show that the nominal exchange rate can be derived using the consumer price index, the goods market clearing conditions, and the purchasing power parity. Using these conditions, the nominal exchange rate is given by:[1]

$$e_t = s_t + p_{H,t} - p^*_{F,t} \tag{6}$$

where s_t is the terms of trade:

$$s_t = y_t - y^*_t \tag{7}$$

and domestic and foreign goods' price levels are given by:

$$p_{H,t} = p_{H,t-1} + \pi_t \tag{8}$$

$$p^*_{F,t} = p^*_{F,t-1} + \pi^*_t \tag{9}$$

The nominal exchange is non-stationary in this model under the interest rate rule we will estimate. To back out model implications for the nominal exchange rate, we solve the linear model for home and foreign variables. Then, using the model solution we back out the effects of structural shocks on the nominal exchange rate, employing the relationships presented above.

One option for ensuring stationarity of the nominal exchange rate is optimal monetary policy under commitment which links the domestic price inflation to the change in output gap over time. This form of stabilization also makes the domestic price level and the nominal exchange rate stationary but we estimate the policy rule under asymmetric information and cannot impose the optimal rule. Another option, which is rather trivial, is a fixed exchange rate, which would not have helped the model match the event study evidence had we assumed it. Hence, we let the model exchange rate be non-stationary.

The monetary policy rule closes the model. We will introduce partial information to the model by making various subsets of the variables on the right-hand-side of the interest rate rule unobservable. The rule is of the form

$$r_t = \rho_r r_{t-1} + (1-\rho_r)(\bar{rr}_t + \bar{\pi}_t + \phi_\pi(\pi_t - \bar{\pi}_t) + \phi_{\tilde{y}}\tilde{y}_t) + \varepsilon^r_t \tag{10}$$

[1] This equation is derived from the terms of trade: $S_t = \frac{P_{F,t}}{P_{H,t}}$ where $P_{F,t}$ is foreign goods price level in domestic currency. Using the zero trade balance condition, we have $P_{H,t}Y_t = P_tC_t$ and $P^*_{F,t}Y^*_t = P^*_tC^*_t$. Using the perfect risk sharing condition ($C_t = C^*_t$) and the PPP ($P_t = E_tP^*_t$), we have $\frac{P_{H,t}Y_t}{P^*_{F,t}Y^*_t} = E_t$ and $\frac{Y_t}{Y^*_t} = \frac{P^*_{F,t}E_t}{P_{H,t}} = \frac{P_{F,t}}{P_{H,t}} = S_t$. Using the last equality we derive the terms of trade as $S_t = \frac{Y_t}{Y^*_t}$, implying that $E_t = S_t\frac{P_{H,t}}{P^*_{F,t}}$.

where ε^r is a white noise interest rate shock with variance σ_r^2 and $\bar{\pi}_t$ is the inflation target that follows

$$\bar{\pi}_t = (1 - \rho_{\bar{\pi}})\bar{\pi} + \rho_{\bar{\pi}}\bar{\pi}_{t-1} + \varepsilon_t^{\bar{\pi}} \tag{11}$$

in which $\varepsilon^{\bar{\pi}}$ is a white noise inflation target shock with variance $\sigma_{\bar{\pi}}^2$. We set the long-run inflation target $\bar{\pi} = 0$ to avoid a further complication by trend inflation.

We have an analogous set of equations for the foreign economy whose variables and parameters are indexed by *, not shown here in the interest of space. Obviously, given the symmetry, it is irrelevant which country is home and which is foreign.

The monetary policy rule is a convenient vehicle for the discussion of policy shocks and surprises. The monetary policy shock is ε_t^r whereas the surprise is $r_t - E[r_t|\mathcal{I}_t^p]$, with $\mathcal{I}_t^p$ the information set of the public before the announcement of the policy decision. Under full information, $r_t - E[r_t|\mathcal{I}_t^p] = \varepsilon_t^r$, the monetary policy surprise and the monetary policy shock overlap and in such models surprise and shock may be used interchangeably. Under asymmetric information, the policy surprise becomes also informative about shocks and variables other than the monetary policy shock, and the surprise and policy shock become two distinct objects.

Note that the full information model described above is equivalently a model where one state variable (or equivalently a shock in case of exogenous state variable) is not currently observed by the private sector. Because the endogenous variables on the right-hand-side of the interest rate rule are functions of all state variables, it is always possible to back out a single missing state variable by inverting the interest rate rule conditional on the nominal interest rate and the observed state variables. This assumes that the information set of the central bank is at least as large as that of the private sector's and contains all relevant variables required for the unique inversion. Ellingsen and Soderstrom (2001) and Lee (2020) elaborate on this idea.

We are used to thinking of the unobserved variable as the monetary policy shock, which is "revealed" when the interest rate is observed. Under full information, this is the event study monetary policy surprise, and is also the VAR monetary policy shock. However, one can equivalently think of a world where the monetary policy shock is known (or is known to be zero at all times) but, say, the inflation shock is not observed by the public. Then, when monetary policy is announced, we will still observe a surprise in the event study sense, but the information revealed is not ε_t^r but ε_t^{π}. In the model/VAR interpretation, market participants have learned the realization of the inflation shock and asset prices will respond accordingly.

This concludes the description of the model. Two important notes are in order. The first concerns the nominal exchange rate. It is worth repeating that the exchange rate is non-stationary in this setting. It therefore does not enter the system of equations to be solved but can be backed out using the consumer price index, the goods market clearing conditions, and the purchasing power parity. Other models will have different implications about exchange rates, in particular breaking the tight link between nominal exchange rates and consumption, but that will not change the main point we are making.

The second has to do with the yield curve. We can, and do, also back out longer-term interest rates and a full yield curve assuming expectations hypothesis. We will be interested in changes in yield curves in response to shocks hence need to assume only a weak form of the expectations hypothesis, allowing maturity-specific term premia but will assume away time-varying prices of risk. In general, we will not be studying dynamics in risk pricing, for exchange rates, yields, or other asset prices.

Next, we move to the description of the model under asymmetric information.

4.2 The Model Under Asymmetric Information

The model under full information is the proper starting point to think of a particular case of information asymmetry. As discussed above, if only one variable is not observed by the public but is known to the central bank, monetary policy will reveal that variable exactly. Hence, the *asset price* response on the day of policy announcement will be the response to that variable. If only the monetary policy shock were unknown, the response will be to monetary policy. But if there is no genuine monetary policy shock, the only driver of the policy surprise can be the latent (from the public's perspective) variable, which will enter the public information set by the realization of the policy rate. Thus, studying the contemporaneous responses of the short rate and exchange rate to shocks to *other* variables provides guidance on which variable's unobservability to the public may create the puzzling covariances we find in the event studies.

Before moving further with the analysis, we have to properly define what "unobservability" in the asymmetric information context means. Here we assume that the central banks in both countries have full information about the state, where the information set at time t is given by $\mathcal{I}_t^f$. However the public will solve a signal extraction problem since it has partial information about the state of the economy. We denote private sector's information set at time t as $\mathcal{I}_t^p$, which is a subset of $\mathcal{I}_t^f$. In this setup monetary policy actions reveal information to the public about the state of the economy. Private sector forms expectations conditional on their information set, $E_t^p[.] = E[.|\mathcal{I}_t^p]$, whereas the central bank forms expectations conditional on full information, $E_t^f[.] = E[.|\mathcal{I}_t^f]$. We assume that private sectors in both countries have identical information sets. Note that if $\mathcal{I}_t^p = \mathcal{I}_t^f$ we are in the full information world.

Solving DSGE models with asymmetric information is a nontrivial task. To solve the model under partial information, we use the solution method of Pearlman et al. (1986). The method adopts the Kalman filter to model expectations formation under partial information. As Svensson and Woodford (2003, 2004) note, the signal extraction problem in a forward-looking model like ours is complicated by the circularity where current forward-looking variables depend on their future expectations, which in turn depend on the estimates of unobservables. But the estimates are dependent on the current forward-looking variables whether they are observed or not. For a linear(ized) model, it is possible to overcome this issue and obtain a unique stable solution. Because we use a Taylor rule to model monetary policy, Pearlman et al.'s method is readily applicable to our setting where the central bank has a larger information set than the private sector. Lee (2020) provides details.

The solution method requires that the private sector information set is introduced to the model through a measurement/observation equation of the form

$$Z_t = DX_t + \nu_t \tag{12}$$

where Z_t is the vector of observable variables such as inflation and interest rates, D is a loading matrix, X_t is the vector of state variables, and ν_t is the vector of measurement errors. To make this point clearly, let us consider a setting where the private sector has the following information set:

$$\mathcal{I}_t^p = \{r_s, r_s^*, \pi_s, \pi_s^*, D, V, \tilde{\Theta} | s \leq t\}. \tag{13}$$

with the observation equation:

$$\begin{bmatrix} r_t \\ r_t^* \\ \pi_t \\ \pi_t^* \end{bmatrix} = D \begin{bmatrix} r_t \\ r_t^* \\ \pi_t \\ \pi_t^* \\ \tilde{z}_t \\ \tilde{x}_t \end{bmatrix} + \nu_t \tag{14}$$

where V is the variance-covariance matrix of measurement errors ν_t (equal to zero for the models we study in the paper), $\tilde{\Theta}$ is the vector of model parameters, $\tilde{z}_t$ is the vector of unobservable exogenous variables, and $\tilde{x}_t$ is the vector of unobservable endogenous variables. D is the selection matrix that consists of 0's and 1's with the following form:

$$D = \begin{bmatrix} 1 & 0 & 0 & 0 & 0_{\tilde{z}} & 0_{\tilde{x}} \\ 0 & 1 & 0 & 0 & 0_{\tilde{z}} & 0_{\tilde{x}} \\ 0 & 0 & 1 & 0 & 0_{\tilde{z}} & 0_{\tilde{x}} \\ 0 & 0 & 0 & 1 & 0_{\tilde{z}} & 0_{\tilde{x}} \end{bmatrix} \tag{15}$$

with $0_{\tilde{z}}$ and $0_{\tilde{x}}$ zero vectors corresponding to the sizes of $\tilde{z}$ and $\tilde{x}$, respectively. All partial information models that we consider in this paper can be cast in the form shown above.

It is important to underline that although the model has many variables, its internal consistency limits the combinations of possible unobservable variables. If the histories and current values of all eight (four in each country) shocks in the model are observable, other model variables will necessarily be known as these can be expressed as functions of the shocks. And if all model variables are observable, these imply the realizations of the shocks. In the final analysis, it is various combinations of these shocks that may need to be inferred, which require shocks and some variables to be unobservable.

5 Discussion

5.1 Full Information

To parameterize the model under full and partial information, we estimate 26 parameters using 27 moments of quarterly EA and US real GDP, short-term interest rate, and CPI from 1998 to 2008 using GMM. All moments we use for estimation can be computed analytically for the perfect (full) information model as well as the partial (asymmetric) information models.

Table 2 shows the moments in the data and the estimated moments, as well as the parameter estimates for the full information model. Note the difference between the estimates of the elasticity of substitution between the US and the euro area. We will see that these being on either side of unity is a result of the full information assumption we impose on the model and that the best fitting model, with partial information, will have elasticities of substitution that are closer and impulse responses more similarly behaved.

With these parameters in hand, Figure 5 shows the standard set of impulse-response functions to monetary policy surprises (recall that policy surprise and policy shock are the same under full information) by the ECB and the Fed. These are all as expected, importantly with the exchange rate appreciating in response to a positive policy rate shock.

To complement these, we provide yield curve responses on impact (with the horizontal axis being maturity rather than response horizon) and the impulse-response function for the nominal exchange rate under different one standard deviation shocks, shown in Figure 6. The yield curves are obtained via expectations hypothesis. The first figure is for the EA shocks and the second for the US ones. We observe asymmetries in the yield curve responses to monetary policy shocks: whereas a positive monetary policy shock in the EA raises yield curves in both the EA and the US, a positive shock in the US raises only the US yield curve and shifts down the EA yield curve (the third rows). This is also the case for inflation shock (the first rows). These results are driven by the estimates of the inverse elasticities of intertemporal substitution which determine the coefficients of the structural equations presented above ($\sigma = 3.29$ for the US and $\sigma^* = 0.15$ for the EA).

Armed with the parameter estimates for the full information model, we continue by studying the responses of interest rates in the US and euro area, as well as the exchange rate to model defined shocks. If one of these has the desired contemporaneous covariance, consistent with an information effect, we may then ask which information structure in the model may give rise to inference about that shock as a result of monetary policy announcements. The responses of interest rates and the exchange rate to various shocks were shown in Figure 6, hence we turn there again.

Our quest to find model defined shocks that, when realized, produce the abnormal covariances we are after, produces good and bad news. The good news is that the effort is successful, we find in the model contemporaneous correlations that would be abnormal had they taken place on monetary policy days. The bad news is that the answer is not unique, there are several variables that produce this result. We will also find below that the non-uniqueness comes in other flavors as well.

This observation is salient. We find that inflation and inflation target shocks are both candidates to match the abnormal behavior of exchange rates in their own right. The contemporaneous covariance produces one moment condition and matching that in a reasonably rich model is possible with a variety of mechanisms. This is an issue for a large part of the literature on central bank information effects, most of which is concerned with a particular contemporaneous covariance, based on event studies.

We will not dwell on the longer horizons in the IRFs, our focus will be on the contemporaneous relationships. Under full information, the event study captures the moment the shock is realized and we observe the contemporaneous covariances of variables that react immediately. Those jump variables are the asset prices, in this model the exchange rate and interest rates at various maturities, including the short (policy) rate. This makes it clear why some exchange rate-policy surprise correlations are puzzling from the lens of the model, where the covariance should always have the same sign, a tightening policy shock should always lead to an exchange rate appreciation. In the data, we have seen many policy days where the covariance has the opposite sign. This is where we ask whether changing the information structure in the model helps pin down the mechanism that generates the data we observed.

5.2 Asymmetric Information

Estimated parameters of a model with asymmetric information are not the same as the parameters estimated assuming full information and then changing the information partition. Hence, we re-estimate the model under different assumptions about the information structure. This exercise is interesting when multiple variables are unobserved so that there is an inference problem to be solved by the public. We estimate the same parameters, using the same moment conditions as the full information case.

Table 3 gives the fit of various partial information models relative to the perfect information benchmark. We classify the models by which model defined variables are observable, with the other variables and the eight shocks unobservable. Moments and estimated parameter values for the best fitting model and some of the close competitors are presented in Tables 4 and 5. We find that the best-fitting partial information model (where only r, π, and $\bar{\pi}$ are observed) fits better than the best-fitting perfect information model.

Using this model, we first ask whether the monetary policy shock alone delivers the abnormal correlation between the nominal interest rate and the nominal exchange rate that we take to be an indication of information effect. It does not, as Figure 7 shows. That is, even in the best fitting partial information model, the monetary policy surprise is informative primarily of the monetary policy shock, not of other latent model variables.

We can still ask whether there is any shock that delivers the puzzling exchange rate behavior. The answer is affirmative. The Figures 8 and 9 show that the inflation shock does indeed produce that behavior, as well as the inflation target shock. The finding about the inflation target has a counterpart in Schmitt-Grohe and Uribe (2018) who find that a permanent interest rate shock generates similar behavior. Their permanent interest rate shock is a credible change in the inflation target. Hence, if the monetary policy shock were informative about either inflation or its target, we would have seen the abnormal exchange rate behavior generated by the model. One is then tempted to conclude that days of monetary policy announcements where the exchange rate moved in the "wrong" direction must have led the market participants to update their beliefs about something related to inflation, either inflation itself or its target. That conclusion would be premature.

Market participants need not be inferring information about a single shock or variable. Figure 10 shows that joint interest rate and productivity shocks also do the trick. As long as shocks have differential effects on the short rate and the exchange rate, regardless of the direction, there exist combinations of shocks that generate any covariance of the short rate and exchange rate, including the abnormal behavior we are studying. Hence, within the best-fitting model with asymmetric information, there is a wide set of belief updating by the public that can generate the same exchange rate behavior in response to policy surprises.

Two notes are in order. First is that this model, based on estimated parameters, suggests that market participants are *not* updating their beliefs about unobservables in response to monetary policy realizations to an extent that the abnormal behavior arises. If it did generate that behavior, the other (currently "normal") dates would turn into puzzles. The model has one covariance structure and the data has at least two.

Second, even if one allows for different signals to be inferred from the same policy surprise over time (perhaps because of time varying parameters, which is a case of continuous regime changes), lack of identification on what that information is about runs deeper than the discussion above suggests. We have shown that different shocks and shock combinations deliver the same sign of exchange rate response within the best fitting model. That is lack of identification within the model.

There is also lack of identification across models. Models with different information structures also imply similar contemporaneous covariances between the short rate and the exchange rate. Figure 11 shows this for a set of models. Models that are similar to the best fitting one but having different informational asymmetries also produce the abnormal effects we observe in the data, in response to some model-defined shocks.

We therefore conclude that (a) no model in this family generates the information effect in response to the monetary policy surprise but perhaps they should not anyway as these are the average effects and the standard monetary policy shock may well dominate on average, and (b) neither within nor across models is there identification of the information structure or the shocks that may be generating the abnormal behavior.

The former point has to do with having models with a single regime. Monetary policy cannot sometimes generate one effect and sometimes another in these. But estimating a regime switching model across regimes that are not smoothly transitioning is likely unfeasible. Thus, we may have to be satisfied with asking whether there is any shock in an asymmetric information model that may be generating the abnormal behavior. In that case we are faced with lack of identification. One moment (one stylized fact) is too easy for these models to match and several models, as well as several (combinations of) shocks within models, indeed do so.

We therefore ask whether we can bring in further moments to discipline the model.

6 Event studies: A Deeper Look

This time, rather than only studying the covariance of the policy rate surprise with the exchange rate, we pay attention to covariances of other asset price reactions as well. In particular, we study the behavior of longer-term interest rates. It is, of course, conceivable to study other asset prices, such as multiple exchange rates, indexed-bonds, stock prices, options, etc. But these do not have ready model counterparts. Note that the model implies a pricing kernel and a law of motion of model variables. Thus, all other asset prices are implied by the model (the model prices a complete set of Arrow-Debreu securities on all dates) but explicitly introducing these into the model and solving and estimating a model with those features has not yet been done. That would be a most welcome exercise.

In the monetary policy event study, along with the exchange rate, we now focus on the behavior of the policy setting surprise (target) and the forward guidance (path) surprise, measured by orthogonalizing the change in one-year rate with target and taking the residual. We also have data and model implications on five-year and ten-year interest rates but the mapping between the data and the model here should be taken with a handful of salt, as the model prices longer-term securities with expectations hypothesis and at those maturities term premia variance is not negligible.[2]

The exercise we are now doing is in the spirit of Cieslak and Schrimpf (2019), who in a paper written for the International Seminar on Macroeconomics, classify policy surprises by the behavior of short rates, long rates, and stock prices. That is a rare paper using multiple asset prices. The multi-asset structure is similar but here we focus on a different set of assets, bringing in the exchange rate and, importantly, try to reconcile the event study with structural

[2]This is not a major issue for shorter-term interest rates as both the average size and the variance of term premia decrease as maturity decreases. The way Federal Funds Futures are used in calculating the policy surprise implicitly assumes that the term premium for the spot one-month contract does not change at all around the policy announcements.

model implications.

The variety of monetary policy responses may be due to intrinsic multi-dimensionality in monetary policy announcements. We therefore use the target-path decomposition and condition on both types of policy surprises. Table 6 and Figures 12 and 13 show the result and make it clear that the path surprise is responsible for most of the policy-related signals in this sample, as well as driving the exchange rate responses. The binding ELB and associated forward guidance is one reason, but even before that policy makers had become skilled at signaling the forthcoming policy action and genuine target surprises were few and far between. Path surprises were always prevalent in this period, as shown by Figures 14 and 15.

An important finding is that most of the abnormal exchange rate responses flagged based on the target surprise are no longer abnormal for the US when conditioning on the path surprise. The number of abnormal exchange rate reaction dates decline by a half and the remaining ones are days of smaller asset price movements. In the euro area, the number of abnormal reaction dates also decline but not as much as in the US.

The difference between the US and EA is likely due to at least two reasons. First, as Goldberg and Klein (2011) show, market perceptions of the ECB's reaction to inflation in the early part of our sample were changing as market participants slowly learned the relative weight of inflation in the ECB's reaction function. ECB, with no history, had more scope to signal its preferences. Second reason is the "saving the euro effect". Policy instances when the ECB signaled easier than expected monetary conditions going forward (negative path surprises) which were interpreted as commitments to hold the euro area together during the crisis, led to appreciations of the euro. There is no counterpart of the "saving the euro" phenomenon in the US and it is natural to find more abnormal dates, even after conditioning on path surprises, in the euro area. A proper analysis of these possible channels, including whether these should be thought of as information effects is work that we leave for future.

An interesting observation is the presence of days when neither the target nor the path surprise correlate in the expected sign with the exchange rate reaction, both in the US and in the euro area. Whatever information effects there may be, they do not manifest themselves completely in the perceived forward guidance. This is consistent with Cieslak and Schrimpf (2019), who found a separate role for stock prices after controlling for the short and long-ends of the yield curve.

We will look more carefully into a few selected dates to give a sense of the policy communication and financial press interpretation, but before doing so should highlight an important point. From an information asymmetry perspective, path surprises themselves are possibly results of central bank information revelation (Delphic surprises) and finding exchange rate correlations with these that accord with standard full information models do not constitute evidence against asymmetric information. That finding perhaps puts more discipline on the nature of the information structure and the source of shocks. We will return to this issue below.

6.1 Selected days of abnormal exchange rate behavior

Some of the dates with abnormal exchange rate reactions stand out in the figures we have displayed so far. We look at a few of those closely and relay the market commentary associated with the observed exchange rate reactions. We choose days that have the "wrong" covariance of the surprise and exchange rate response when the surprise is measured by the target factor and discuss dates when the path factor "explains" the exchange rate (although path itself may be an artifact of information revelation) and dates when the exchange rate movement is abnormal regardless of which measure of policy surprise is used. Note again that such dates are very rare in the US.

6.1.1 Discussion of Selected US Information Days

- June 30, 1999 (Target: -3 bps, Path: -9.5 bps, dollar appreciates 0.3%)

  The exchange rate response on this date is inconsistent with both the target and the path surprises. The FOMC raised interest rates by 25 basis points, which was largely expected by the market participants (small target surprise). "But the central bank indicated its tiny quarter point increase may be all that is needed to keep inflation under control... The Fed said in a statement that it felt the need to be 'especially alert to the emergence, or potential emergence, of inflationary forces that could undermine economic growth.' But at the same time, the Fed indicated that it was moving its policy directive, which signals the future course of interest rates, back to neutral... 'The message from the Fed is that they are not in any big hurry nor particularly worried that quick action is necessary on inflation front. The markets are relieved because the central bank could have been a lot tougher.'" (Fed. Reserve Raises Interest Rates, Bloomberg, June 30, 1999).

  Fed's statement about neutral rates implied a negative path surprise since the investors were expecting higher interest rates in the future due to inflationary forces. According to the commentary "[Fed] removed its tilt, or bias, toward higher rates. That bias change was a surprise to most investors and gives the market room to rally." (U.S. Bonds Surge as Fed Hints at Limited Rate Rises (Update1), Bloomberg, June 30, 1999).

Appreciation of the dollar is unexpected, given the jointly negative target and path surprises.

- March 20, 2001 (Target: 7 bps, Path: -11 bps, dollar depreciates 0.8%)

  The Fed cuts policy rates by 50 basis points and signals another rate cut could come in an intermeeting move. In the statement, "policy makers cited falling stocks, a slump in manufacturing and 'weakness in global economic conditions' as the reasons for their decisions to lower rates by 50 basis points." Fed adds in its statement that "In these circumstances, when the economic situation could be evolving rapidly, the Federal Reserve will need to monitor developments closely." The last comment made analysts forecast another cut in the next meeting, or even before then, if need be. "This reads like they are more scared than they have been willing to admit, and that they are ready to cut rates further – maybe soon." (U.S. Bonds Rise After Fed Cuts Rates a Half-Point to 5 Percent, Bloomberg, March 20, 2001).

  This is a good example of an exchange rate reaction, although unexpected when judged by the positive target surprise, being consistent with the path surprise; but the path surprise itself likely stemming from Delphic forward guidance. It is likely that the same signal about outlook or preferences moved both path and the exchange value of the dollar.

- January 27, 2010 (Target: -0.5 bps, Path: 7.4 bps, dollar appreciates 0.3%)

  This is a policy date with a negligible target surprise, but a large path surprise. The FOMC did not change the policy rate, with one member of the committee dissenting on the decision. The statement read "With substantial resource slack continuing to restrain cost pressures with long-term inflation expectations stable, inflation is likely to be subdued for some time." Kansas City Fed President Hoenig "believed that economic and financial conditions had changed sufficiently that the expectation of exceptionally low levels of the federal funds rate for an extended period was no longer warranted." The dissent was of particular interest to the market participants. "The dissent from Hoenig was a big boost for dollar. There is a good chance there are other officials who are less dovish as well." (Dollar Climbs to Six-Month High Against Euro on Fed Dissent, Bloomberg, January 27, 2010).

  It is important to note that dovishness/hawkishness pertains to policymaker preferences more than anything else. Again, the same signal is moving the path factor and the exchange rate.

6.1.2 Discussion of Selected Euro Area Information Days

- October 7, 1999 (Target: -17 bps, Path: 5 bps, euro appreciates 0.2%)

  The ECB kept the policy rate unchanged, however Euro appreciated on speculation the ECB might raise its benchmark lending rate soon. ECB president said at the news conference that with the economic outlook improving "we have to adopt and to have a monetary policy stance which is conducive to sustainable, non-inflationary growth." "People are more optimistic on European growth prospects going into 2000. Eventually the ECB is going to push to start raising rates. The euro has found and held support." (Euro Gains on Speculation ECB May Raise Rates in Months Ahead, Bloomberg, October 7, 1999).

  Despite the negative and large target surprise, the euro appreciates, consistent with the positive path surprise.

- April 11, 2001 (Target= 17 bps, Path= 5.3 bps, euro depreciates 0.9%)

  This is an example of a policy date where the exchange rate movements cannot be reconciled either with the target surprise or the path surprise. This was a day of no policy rate change.

  "Even though the ECB was projecting itself for a no change, some people were positioning themselves for a cut and when it didn't go through, the euro had a pretty sharp reaction. I think the market is pretty bearish in the short term as every one wanted ECB to cut, which would have helped (the euro)" (Euro Falls Then Recovers, Bloomberg, April 11, 2001). "For them to not even cut rates amid this global slowdown is seen as disappointing." "The ECB once again disappointed the markets, so the euro went down. Right now, the market favors those currencies whose central banks have shown a willingness to cut rates and spur growth." (Euro Falls vs Dollar, Yen After ECB Leaves Key Rate Unchanged, Bloomberg, April 11, 2001).

- December 6, 2001 (Target: -1.3 bps, Path: 6.2 bps, euro appreciates 0.2%)

  The ECB left its benchmark interest rate unchanged, which was largely expected by the market (small target surprise). "The central bank has been trying to bring inflation below its 2 percent ceiling, and the failure to cut may be taken by some investors as evidence the ECB isn't doing enough to bolster the region's economy. 'The euro may come off as the ECB will be perceived as being anti-growth,' 'The press conference did not give the impression a new rate cut is just around the corner.'" (Euro Little Changed After ECB Leaves Benchmark Rate Unchanged, Bloomberg, December 6, 2001).

  Again, the path surprise "justifies" the exchange rate reaction but whether one should attribute the path surprise itself to Odyssean ("rate cut is [not] around the corner") or Delphic in the preference sense ("ECB will be perceived as being anti-growth") is not clear.

  This is a clear example of some information effect in play, but whether this has to do with the fundamental soundness of the euro area, the growth prospects, or ECB preferences is not obvious.

- June 5, 2008 (Target: -0.1 bps, Path: 20 bps, euro appreciates 0.9%)

  The ECB left interest rates unchanged, but Trichet said an "interest rate increase in the next meeting is 'possible'" and said policy makers are in a state of "hightened alertness" over inflation. "'Trichet's comments were interpreted as more hawkish than expected. We don't expect the Fed to hike anytime soon, so there's still a substantial interest-rate advantage for the euro.' The ECB has cited accelerating inflation as a reason for not cutting rates as the US economic slowdown spread to Europe." (Euro Rises After Trichet Says July Rate Increase is 'Possible', Bloomberg, June 5, 2008).

  This episode once again raises the good question of whether hawkishness is a function of central bank preferences or forecast. Market participants have received information that led them to update their beliefs about the policy path, and the exchange rate along with that, but the nature of information is again unclear.

This in depth look at some of the events, the central bank statements, and associated financial press write ups shows that there are many shades of possible information effects. It is particularly difficult to distinguish between Delphic and Odyssean forward guidance by reading the central bank statements, and the financial press mostly focuses on rationalizing the asset price reactions. Nonetheless, it is clear that, when it comes to asset price movements that are puzzling with respect to the target surprise, a significant share of these are "explained" by the path surprise, which suggests the same information revelation by the central bank affects different markets similarly. But path by itself is still not sufficient to capture all the different ways exchange rates move in response to monetary policy surprises, especially in the euro area.

7 Reflections on the Model

An important observation to make on the data and discussion presented in section 5, relevant for monetary policy in open economies, is that the inference market participants make change from event to event. No model with a single regime will match that. This, of course, is an issue for all models of central bank information: financial market responses are indicative of information effects only on some dates. But this becomes even more of an issue when multiple asset prices and covariances are studied.

Focusing only on dates where the target surprise and the exchange rate covary in the "wrong" direction, the following two points become pertinent. The first point of note, very importantly, is that for most dates in the US and many dates in the EA (the difference likely being due to the saving the euro effect or the market participants learning about the ECB) the path surprise has the "correct" covariance with the exchange rate. But this, in itself, is a problem for the model. For any shock, the model always implies the same yield curve response. That is, in the IRF year-ahead rates contain the same information as instantaneous rates. There are no separate target and path surprises.[3]

This brings to mind Odyssean forward guidance, which will trivially make target and path surprises differ. In that case the fact that these are Odyssean not Delphic surprises imply that information-based stories will have to be put aside. It may be possible to relate Odyssean forward guidance to central banker preferences, which would be a fruitful avenue of research.

There is a further complication when target and path surprises differ in sign. It is not obvious which should dominate in determining the exchange rate response. This will depend on their relative sizes and the persistence of the forward guidance shock, also discussed by Gali (2020).

The effort in estimating these models with rich information structures is not in vain, however. As Figure 16 shows, although the monetary policy surprise does not generate the responses seen in the event studies, different shocks in that model do generate various aspects of the responses. For example, a combination of a positive inflation shock and a (smaller) negative monetary policy shock depreciates the dollar and inverts the yield curve (in changes) at the same time. This suggests that joint inference about these shocks may help explain some of the event study findings, including path surprises which may have opposite signs of target surprises. The literature has not focused on inference about multiple shocks at all. Doing so

[3]Private central bank information that would make the policymaker signal tighter policy in the future would also make her tighten policy now and the relationship does not change. Hence, target and path are not two distinct elements, except at the ZLB –not studied here– which necessarily changes the covariance structure.

increases the degrees of freedom in the model and obviously helps fit the moments better but also worsens the identification problem.

The second point of note is that there remain the dates where neither the target nor the path surprise explain the exchange rate reaction. That dynamic requires a separate study. Those dates are difficult to make sense of even when the discipline of the model is not imposed on the yield curve and one only looks for some policy signal that is consistent with the exchange rate behavior.

Hence, although the central bank information literature is built on our theoretical understanding of how asset prices should respond to monetary policy and other shocks, the family of models we employed neither uniquely nor completely fit the event studies we have looked at. In making this assessment, it is important to remember that a particularly pertinent type of information asymmetry is not present here, that of central bank preferences. The only preference that can be unobserved by the public and would have repercussions on asset prices in the model is the inflation target. This is an artifact of the solution algorithm that uses local approximations at the steady state, which makes the policy smoothing parameter and relative weights of inflation versus output gap stabilization vanish. Bringing those in for open economy models is clearly a fruitful avenue of further research.

We do not see our findings as negative results. No one will be surprised that we are having difficulty understanding exchange rate movements,[4] in any window, conditional on any event. We also know that the world is more complicated than any one model can and should be. But the model we employed, a canonical open economy model, helped us put exchange rate responses to monetary policy in perspective and see which lines of argument are internally consistent, which are identified, and where we are falling short.

8 Conclusion

We find that asset price anomalies, from the perspective of standard models, that arise in event studies and motivate the literature on central bank information effects are present in exchange rates as well. These exchange rate abnormalities are common. They are also easy to explain with asymmetric information models, where the public infers the realization of some variables from the central bank's policy decision. In fact, fitting that one moment, the "wrong"

[4] The model prices the exchange rate using UIP, which does not find much favor in the data. But it is worth noting that UIP does not prevent the model from fitting remarkably well to the macro data. Non-UIP-based exchange rate mechanisms are good candidates for future research, but will not by themselves address the information-related difficulties in generating target and path surprises with opposite signs.

covariance of exchange rate changes and monetary policy surprises, turns out to be too easy, with many information structures producing the same effect.

Bringing in more moments from event studies, we find that target and path surprises and exchange rate responses to these surprises are heterogeneous, and no model with a single regime can match the data. More importantly, there is no information structure that makes any of the candidate models fit the constellation of moments multiple assets produce, even if one only focuses on the dates that have the problematic response judged by the target and exchange rate covariance. An interesting finding here is the path surprise resolving the puzzling exchange rate reaction in almost all cases in the US and many cases in the euro area. However, path surprises themselves may be due to information effects. Focusing on these is clearly a viable avenue of study.

The literature on central bank information effects offer information-based explanations with reference to standard models, often without specifying those models, seldom asking whether the information story being presented is the only one that is consistent with the data even within a particular model, and even more seldom asking what the implications for other asset prices may be. Macroeconomic models are helpful when they are properly specified and confronted with ample moments in the data. The literature has moved in that direction for the purpose of analyzing real macroeconomic variables, with the CGG model analyzed here a pioneering example of that. It is time that we do the same for financial variables.

The best fitting model to the macro data is an asymmetric information model. But the model implied asset price responses to monetary policy surprises in the open economy are not those that are observed in the event studies. Estimating a two country open economy model with information asymmetries that helps analyze exchange rates and yield curves is a major undertaking. Having done this, we find that with a single moment from the event study to match, the model is under-identified and with multiple moments finding a model that fits all moments simultaneously is not easy. We do have a way to go in reconciling event study data for monetary policy with model-based mechanisms of asset pricing based on macroeconomic dynamics.

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Tables and Figures

	USD/EUR	USD/EUR
Target Surp. (US)	-0.02^{***}	
	(0.007)	
Target Surp. (EA)		0.01
		(0.01)
R^2	0.1	0.01
N	83	146

Table 1: Event study regressions for the US and the euro area. Robust standard errors are in parentheses. Sample for the US is 1994-2018 and for the euro area 1999-2018.

Moments	Data Moments	Model Moments	Parameters	Explanations	Values
SD of Interest Rate (EA)	0.009	0.003	β	Discount Factor (US)	0.999
SD of Interest Rate (US)	0.018	0.001	σ	Inv. Elast. of Sub. (US)	3.291
SD of RGDP (EA)	0.009	0.009	ϕ	Inv. Frisch Elast. (US)	5.000
SD of RGDP (US)	0.009	0.011	θ	Calvo Pricing Fric. (US)	0.698
SD of Inflation (EA)	0.004	0.004	ρ_a	Pers. of TFP (US)	0.999
SD of Inflation (US)	0.008	0.009	ρ_r	Coef. on Lagged Int. (US)	0.841
Corr of EA and US Interest Rate	0.519	0.136	ϕ_π	Coef. on Inf. (US)	2.500
Corr of EU Interest Rate and RGDP	0.764	-0.073	$\phi_{\tilde{y}}$	Coef. on OG (US)	0.788
Corr of EA Interest Rate and US RGDP	0.140	0.096	$\rho_{\bar{\pi}}$	Pers. of Inf. Targ. (US)	0.602
Corr of EA Interest Rate and Inflation	0.347	0.355	β^*	Discount Factor (EA)	0.988
Corr of EA Interest Rate and US Inflation	0.173	0.170	σ^*	Inv. Elast. of Sub. (EA)	0.150
Corr of US Interest Rate and EU RGDP	0.439	-0.054	ϕ^*	Inv. Frisch Elast. (EA)	1.272
Corr of US Interest Rate and RGDP	0.681	0.075	θ^*	Calvo Pricing Fric. (EA)	0.479
Corr of US Interest Rate and EU Inflation	-0.198	-0.182	ρ_{a*}	Pers. of TFP (EA)	0.999
Corr of US Interest Rate and Inflation	0.223	0.281	ρ_{r*}	Coef. on Lagged Int. (EA)	0.136
Corr of EA and US RGDP	0.391	0.146	$\phi_{\pi*}$	Coef. on Inf. (EA)	2.266
Corr of EA RGDP and Inflation	0.176	0.190	$\phi_{\tilde{y}*}$	Coef. on OG (EA)	1.493
Corr of EA RGDP and US Inflation	0.087	0.112	$\rho_{\bar{\pi}*}$	Pers. of Inf. Targ. (EA)	0.908
Corr of US RGDP and EA Inflation	-0.104	-0.045	σ_π	SD of PC Shock (US)	1.138×10^{-6}
Corr of US RGDP and Inflation	0.365	0.396	σ_a	SD of TFP Shock (US)	6.590×10^{-4}
Corr of EA and US Inflation	0.612	-0.001	σ_r	SD of Int. Shock (US)	1.854×10^{-3}
First Order Autocorr of EA Interest Rate	0.944	0.693	$\sigma_{\bar{\pi}}$	SD of Inf. Targ. Shock (US)	0.013
First Order Autocorr of US Interest Rate	0.952	0.527	$\sigma_{\pi*}$	SD of PC Shock (EA)	2.188×10^{-4}
First Order Autocorr of EA RGDP	0.884	0.931	σ_{a*}	SD of TFP Shock (EA)	1.624×10^{-4}
First Order Autocorr of US RGDP	0.825	0.920	σ_{r*}	SD of Int. Shock (EA)	9.679×10^{-3}
First Order Autocorr of EA Inflation	0.669	0.541	$\sigma_{\bar{\pi}*}$	SD of Inf. Targ. Shock (EA)	1.585×10^{-3}
First Order Autocorr of US Inflation	0.485	0.553	γ	Relative Country Size	0.5
			$\bar{\pi}$	Long-run Inf. Target (US)	0
			$\bar{\pi}^*$	Long-run Inf. Target (EA)	0

Table 2: Data moments and perfect information model moments and parameters. The last three parameters are fixed.

Observable	r	r, π	r, π, $\bar{\pi}$	r, π, $\bar{rr}$	r, π, $\bar{\pi}$, $\bar{rr}$	r, π, $\bar{rr}$, $\tilde{y}$	Perfect Info
Ratio	1.18	0.98	0.88	0.96	1.06	1.03	1

Table 3: Fit of the model to the data (relative to the perfect information model). The variables in the columns of the first row (from the second to the last one) apply to both the euro area and the US. For instance, the second column is an information structure where policy rates in both countries are observed by the private sectors in both economies.

Param	Explanation	Perfect	r	r, π	$r, \pi, \bar{\pi}$	$r, \pi, \bar{rr}$	$r, \pi, \bar{\pi}, \bar{rr}$	$r, \pi, \bar{rr}, \tilde{y}$
β	Discount Factor (US)	0.999	0.980	0.980	0.980	0.999	0.980	0.999
σ	Inv. Elast. of Sub. (US)	3.291	2.136	3.273	0.747	0.200	3.321	2.496
ϕ	Inv. Frisch Elast. (US)	5.000	5.000	5.000	5.000	0.200	5.000	5.000
θ	Calvo Pricing Fric. (US)	0.698	0.159	0.650	0.858	0.380	0.662	0.686
ρ_a	Pers. of TFP (US)	0.999	0.955	0.999	0.999	0.999	0.999	0.999
ρ_r	Coef. on Lagged Int. (US)	0.841	0.846	0.873	0.996	0.984	0.906	0.938
ϕ_π	Coef. on Inf. (US)	2.500	1.091	2.500	1.554	1.876	2.500	2.400
$\phi_{\tilde{y}}$	Coef. on OG (US)	0.788	1.063	0.015	1.500	8.956×10^{-3}	1.492	0.676
$\rho_{\bar{\pi}}$	Pers. of Inf. Targ. (US)	0.602	0.978	0.781	0.869	0.902	0.813	0.817
β^*	Discount Factor (EA)	0.988	0.999	0.981	0.988	0.980	0.991	0.999
σ^*	Inv. Elast. of Sub. (EA)	0.150	1.056	0.150	0.183	0.357	0.153	0.154
ϕ^*	Inv. Frisch Elast. (EA)	1.272	5.000	0.746	2.450	4.989	0.871	1.026
θ^*	Calvo Pricing Fric. (EA)	0.479	0.773	0.483	0.565	0.493	0.481	0.536
ρ_{a^*}	Pers. of TFP (EA)	0.999	0.998	0.998	0.977	0.975	0.993	0.992
ρ_{r^*}	Coef. on Lagged Int. (EA)	0.136	0.813	0.192	0.687	0.941	0.014	0.614
ϕ_{π^*}	Coef. on Inf. (EA)	2.266	2.500	2.496	1.000	1.054	2.320	1.530
$\phi_{\tilde{y}^*}$	Coef. on OG (EA)	1.493	0.091	1.499	0.667	0.992	0.099	1.500
$\rho_{\bar{\pi}^*}$	Pers. of Inf. Targ. (EA)	0.908	0.794	0.968	0.999	0.963	0.848	0.949
σ_π	SD of PC Shock (US)	1.138×10^{-6}	2.166×10^{-4}	4.854×10^{-5}	5.958×10^{-3}	1.466×10^{-5}	5.031×10^{-9}	7.887×10^{-8}
σ_a	SD of TFP Shock (US)	6.590×10^{-4}	2.606×10^{-3}	9.805×10^{-5}	2.766×10^{-4}	1.046×10^{-4}	4.169×10^{-7}	3.030×10^{-4}
σ_r	SD of Int. Shock (US)	1.854×10^{-3}	9.043×10^{-4}	2.194×10^{-3}	5.139×10^{-5}	4.332×10^{-5}	2.784×10^{-3}	1.021×10^{-3}
$\sigma_{\bar{\pi}}$	SD of Inf. Targ. Shock (US)	0.013	5.223×10^{-3}	6.001×10^{-3}	0.012	2.642×10^{-3}	5.737×10^{-3}	5.441×10^{-3}
$\sigma_{\pi*}$	SD of PC Shock (EA)	2.188×10^{-4}	3.204×10^{-3}	6.203×10^{-4}	1.069×10^{-3}	8.430×10^{-5}	2.593×10^{-8}	8.559×10^{-6}
σ_{a*}	SD of TFP Shock (EA)	1.624×10^{-4}	6.991×10^{-4}	3.729×10^{-4}	1.414×10^{-3}	1.392×10^{-3}	7.670×10^{-4}	1.003×10^{-3}
σ_{r*}	SD of Int. Shock (EA)	9.679×10^{-3}	6.500×10^{-4}	9.588×10^{-3}	1.799×10^{-3}	1.996×10^{-5}	7.140×10^{-3}	3.903×10^{-3}
$\sigma_{\bar{\pi}*}$	SD of Inf. Targ. Shock (EA)	1.585×10^{-3}	3.061×10^{-3}	9.723×10^{-4}	1.246×10^{-3}	3.610×10^{-3}	2.070×10^{-3}	1.825×10^{-3}
γ	Relative Country Size	0.5	0.5	0.5	0.5	0.5	0.5	0.5
$\bar{\pi}$	Long-run Inf. Target (US)	0	0	0	0	0	0	0
$\bar{\pi}^*$	Long-run Inf. Target (EA)	0	0	0	0	0	0	0

Table 4: Estimated parameters. The top row indicates observables corresponding to different models. The last three parameters are fixed.

Moment	Data	Perfect	r	r,π	$r,\pi,\bar{\pi}$	$r,\pi,\bar{rr}$	$r,\pi,\bar{\pi},\bar{rr}$	$r,\pi,\bar{rr},\tilde{y}$
SD of Interest Rate (EA)	0.009	0.003	0.001	0.003	0.002	7.099×10^{-4}	0.003	0.002
SD of Interest Rate (US)	0.018	0.001	0.001	0.002	3.392×10^{-4}	4.923×10^{-4}	0.003	0.001
SD of RGDP (EA)	0.009	0.009	0.012	0.009	0.008	0.007	0.009	0.011
SD of RGDP (US)	0.009	0.011	0.008	0.010	0.013	0.012	0.010	0.010
SD of Inflation (EA)	0.004	0.004	0.004	0.004	0.004	0.003	0.004	0.004
SD of Inflation (US)	0.008	0.009	0.006	0.010	0.007	0.008	0.009	0.009
Corr of EA and US Interest Rate	0.519	0.136	0.004	0.072	0.048	0.065	0.024	0.020
Corr of EA Interest Rate and RGDP	0.764	-0.073	-0.046	-0.082	-0.073	0.089	-0.096	-0.058
Corr of EA Interest Rate and US RGDP	0.140	0.096	0.086	0.088	0.170	0.144	0.085	0.089
Corr of EA Interest Rate and Inflation	0.347	0.355	0.386	0.359	0.417	0.410	0.371	0.376
Corr of EA Interest Rate and US Inflation	0.173	0.170	0.175	0.169	0.120	0.171	0.143	0.190
Corr of US Interest Rate and EA RGDP	0.439	-0.054	0.217	-0.037	0.343	0.261	-0.020	0.001
Corr of US Interest Rate and RGDP	0.681	0.075	0.328	0.070	0.331	0.205	0.020	0.074
Corr of US Interest Rate and EA Inflation	-0.198	-0.182	-0.158	-1.161	-0.071	-0.115	-0.071	-0.118
Corr of US Interest Rate and Inflation	0.223	0.281	0.260	0.271	0.324	0.294	0.264	0.277
Corr of EA and US RGDP	0.391	0.146	-0.166	0.181	0.280	0.394	0.176	0.145
Corr of EA RGDP and Inflation	0.176	0.190	0.254	0.213	0.179	0.142	0.219	0.236
Corr of EA RGDP and US Inflation	0.087	0.112	0.092	0.110	0.085	0.092	0.104	0.112
Corr of US RGDP and EA Inflation	-0.104	-0.045	-0.013	-0.055	-0.106	-0.074	-0.057	-0.056
Corr of US RGDP and Inflation	0.365	0.396	0.202	0.335	0.473	0.556	0.331	0.399
Corr of EA and US Inflation	0.612	-0.001	0.161	0.001	-0.093	-0.237	-0.006	-0.011
First Order Autocorr of EA Interest Rate	0.944	0.693	0.513	0.734	0.929	0.957	0.586	0.835
First Order Autocorr of US Interest Rate	0.952	0.527	0.916	0.651	0.967	0.899	0.757	0.712
First Order Autocorr of EA RGDP	0.884	0.931	0.924	0.919	0.908	0.955	0.910	0.926
First Order Autocorr of US RGDP	0.825	0.920	0.954	0.931	0.759	0.788	0.930	0.917
First Order Autocorr of EA Inflation	0.669	0.541	0.534	0.591	0.528	0.341	0.575	0.569
First Order Autocorr of US Inflation	0.485	0.553	0.291	0.523	0.265	0.360	0.547	0.540

Table 5: Moments. The top row indicates observables corresponding to different models.

	USD/EUR	USD/EUR
Target Surp. (US)	-0.02^{***}	
	(0.004)	
Target Surp. (EA)		0.01
		(0.008)
Path Surp. (US)	-0.05^{***}	
	(0.005)	
Path Surp. (EA)		0.06^{***}
		(0.009)
R^2	0.43	0.19
N	83	146

Table 6: Event study regressions with target and path surprises for the US and euro area. Robust standard errors are in parentheses. Sample for the US is 1994-2018 and for the euro area 1999-2018. Construction of path surprises are described in text.

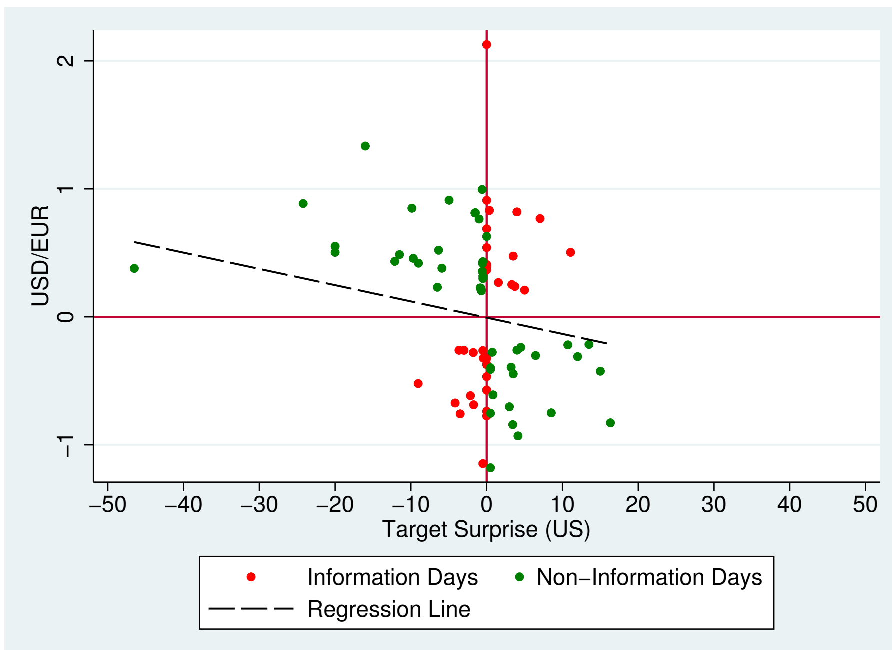

Figure 1: Scatter plot of target surprises and associated changes in USD/EUR exchange rate for the US. The dashed line is the regression line fitted to the data presented in the scatter plot. Sample is 1994-2018.

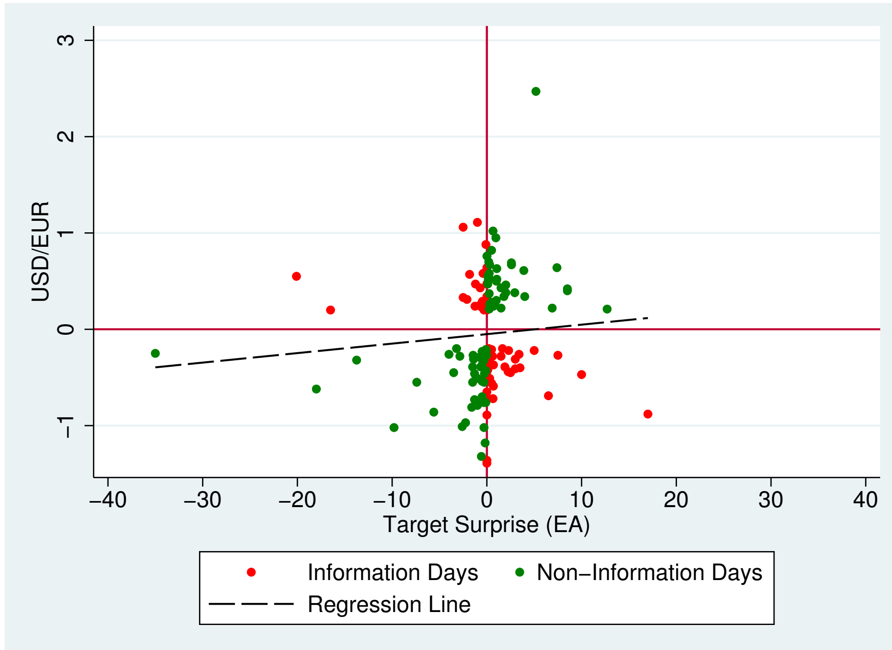

Figure 2: Scatter plot of target surprises and associated changes in USD/EUR exchange rate for the euro area. The dashed line is the regression line fitted to the data presented in the scatter plot. Sample is 1999-2018.

Figure 3: Bar plot for target surprises and associated changes in USD/EUR exchange rate for the US. Upper panel is for the sample 1994-2007 and lower panel is for the sample 2008-2018.

Figure 4: Bar plot for target surprises and associated changes in USD/EUR exchange rate for the euro area. Upper panel is for the sample 1999-2007 and lower panel is for the sample 2008-2018.

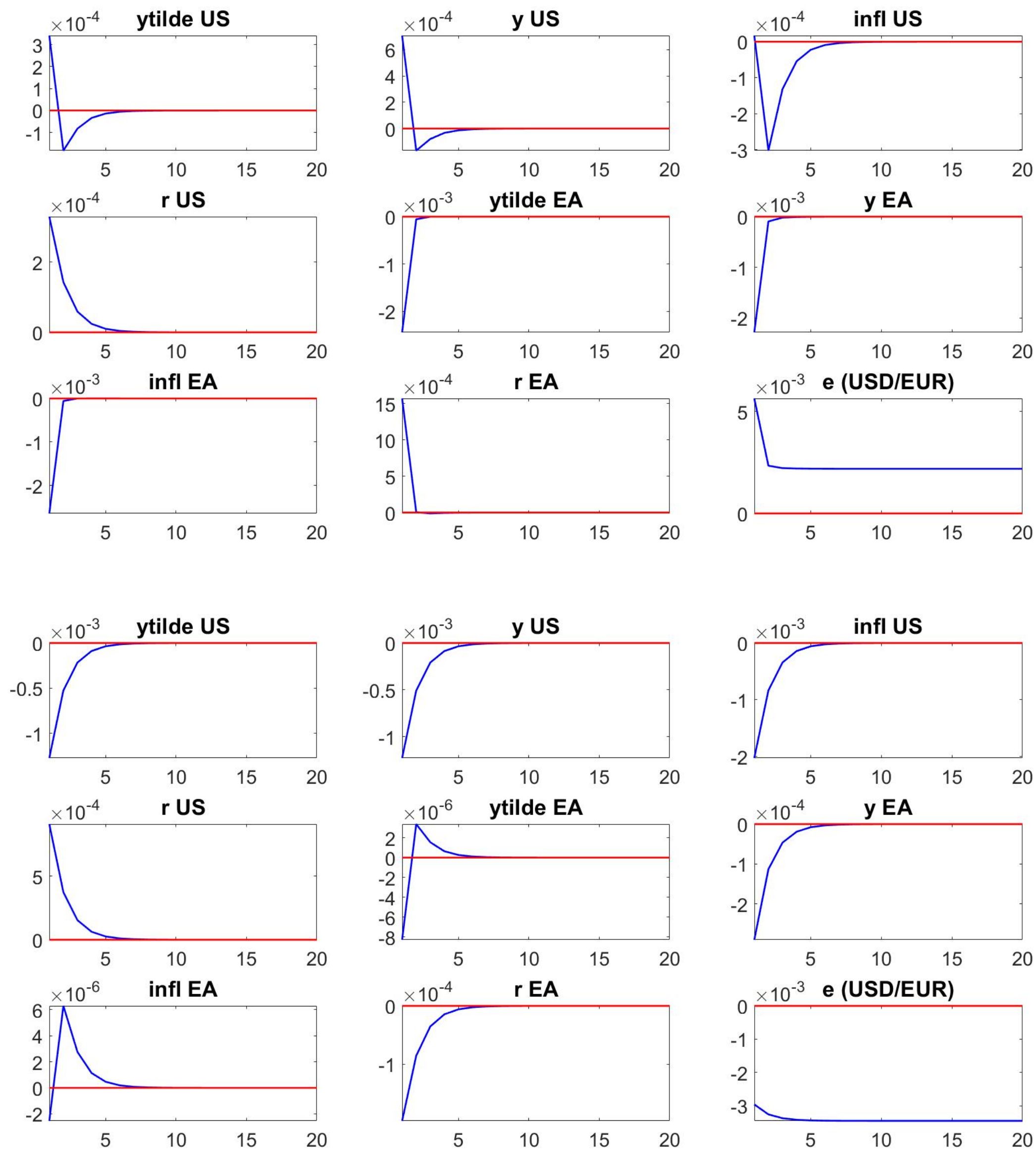

Figure 5: IRFs for one standard deviation monetary policy shock in the EA (upper) and the US (lower).

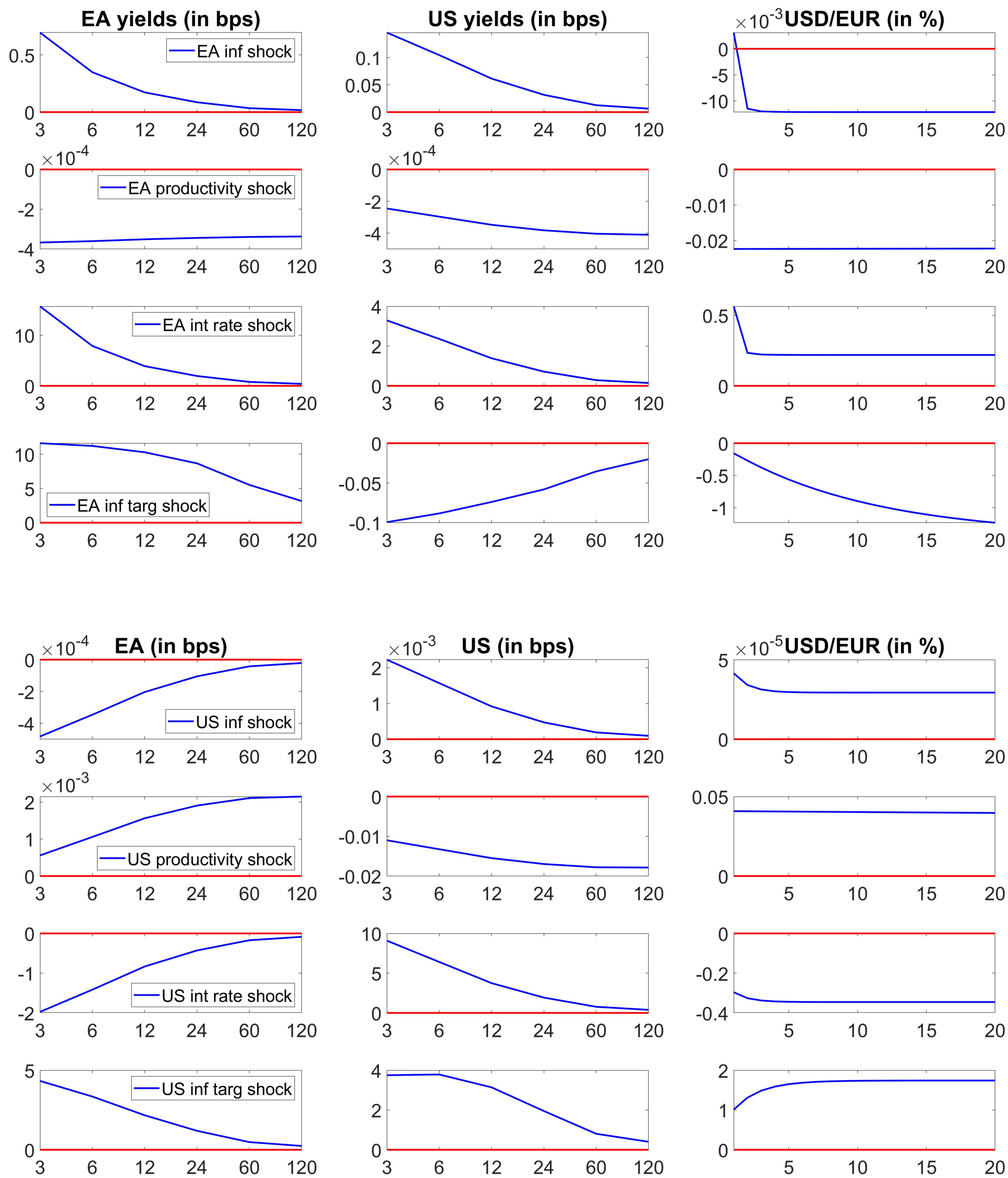

Figure 6: Yield curve responses on impact and IRFs for nominal exchange rate.The shocks are as follows: Upper: first row - EA inflation; second row - EA productivity; third row - EA interest rate; fourth row - EA inflation target. Lower: first row - US inflation; second row - US productivity; third row - US interest rate; fourth row - US inflation target. The horizontal axis for the first two columns gives bond maturities in months. The horizontal axis for the third column is horizons in quarters.

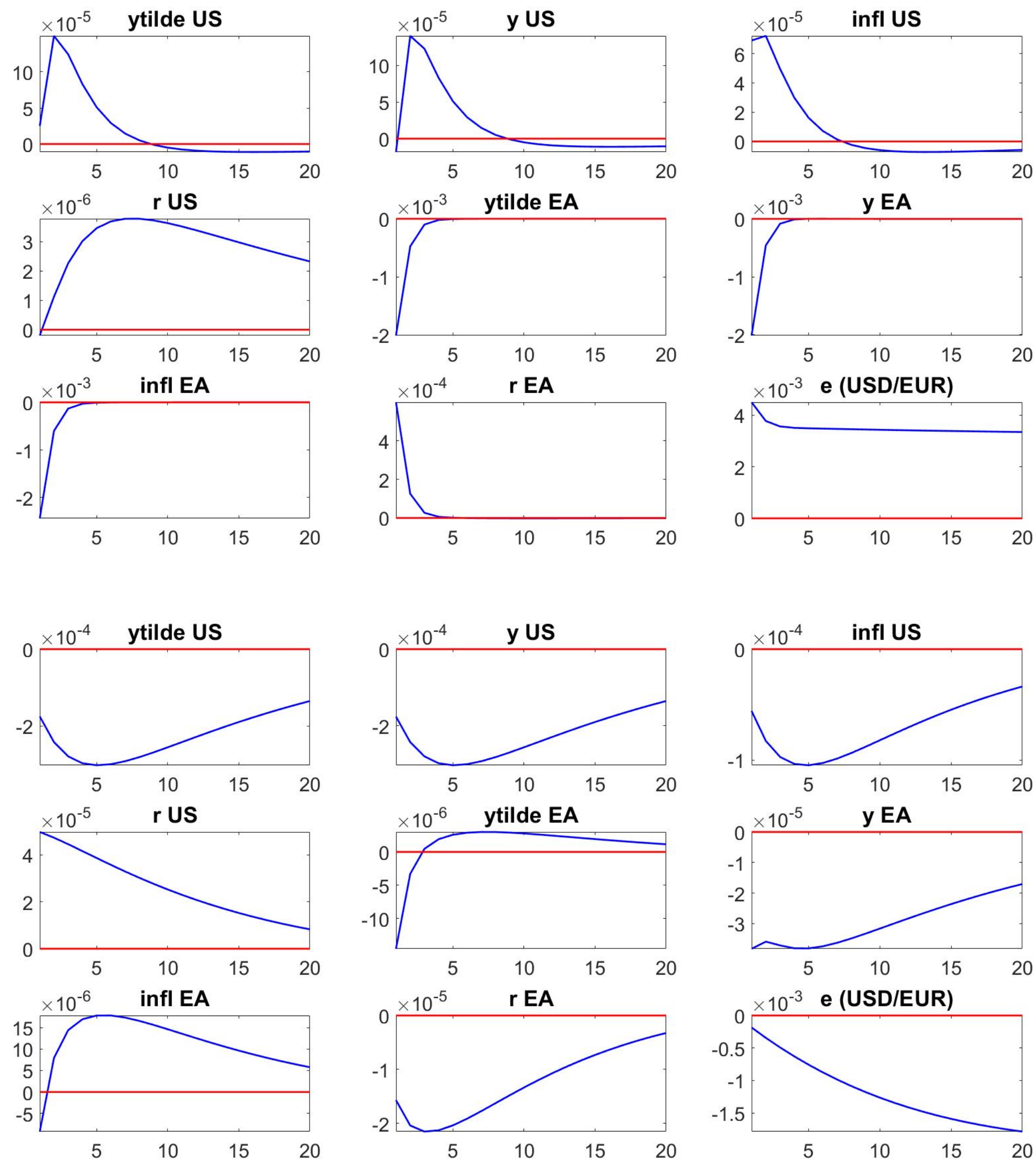

Figure 7: IRFs for one standard deviation monetary policy shock in the EA (upper) and in the US (lower)

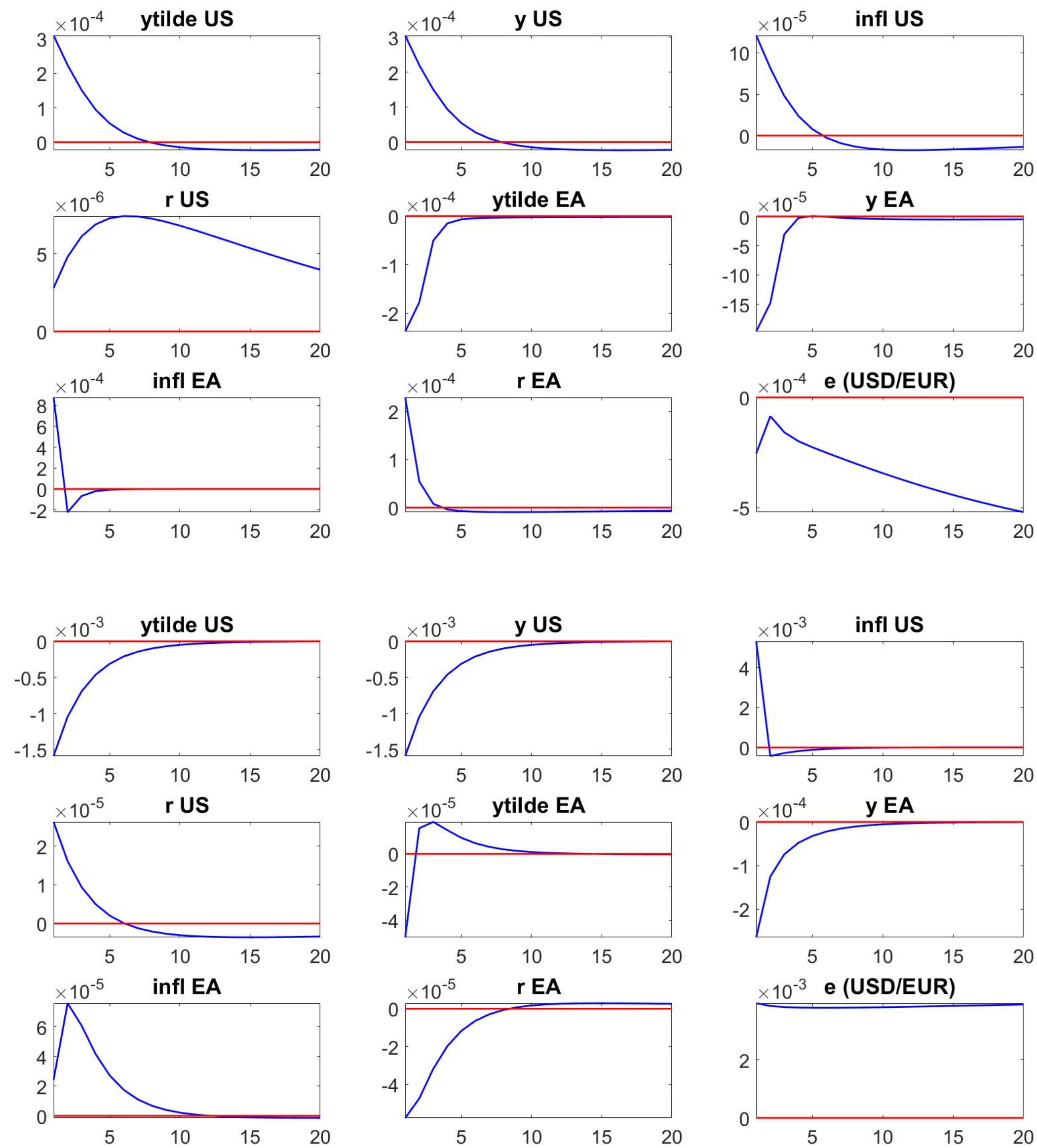

Figure 8: IRFs for one standard deviation inflation shock in the EA (upper) and in the US (lower).

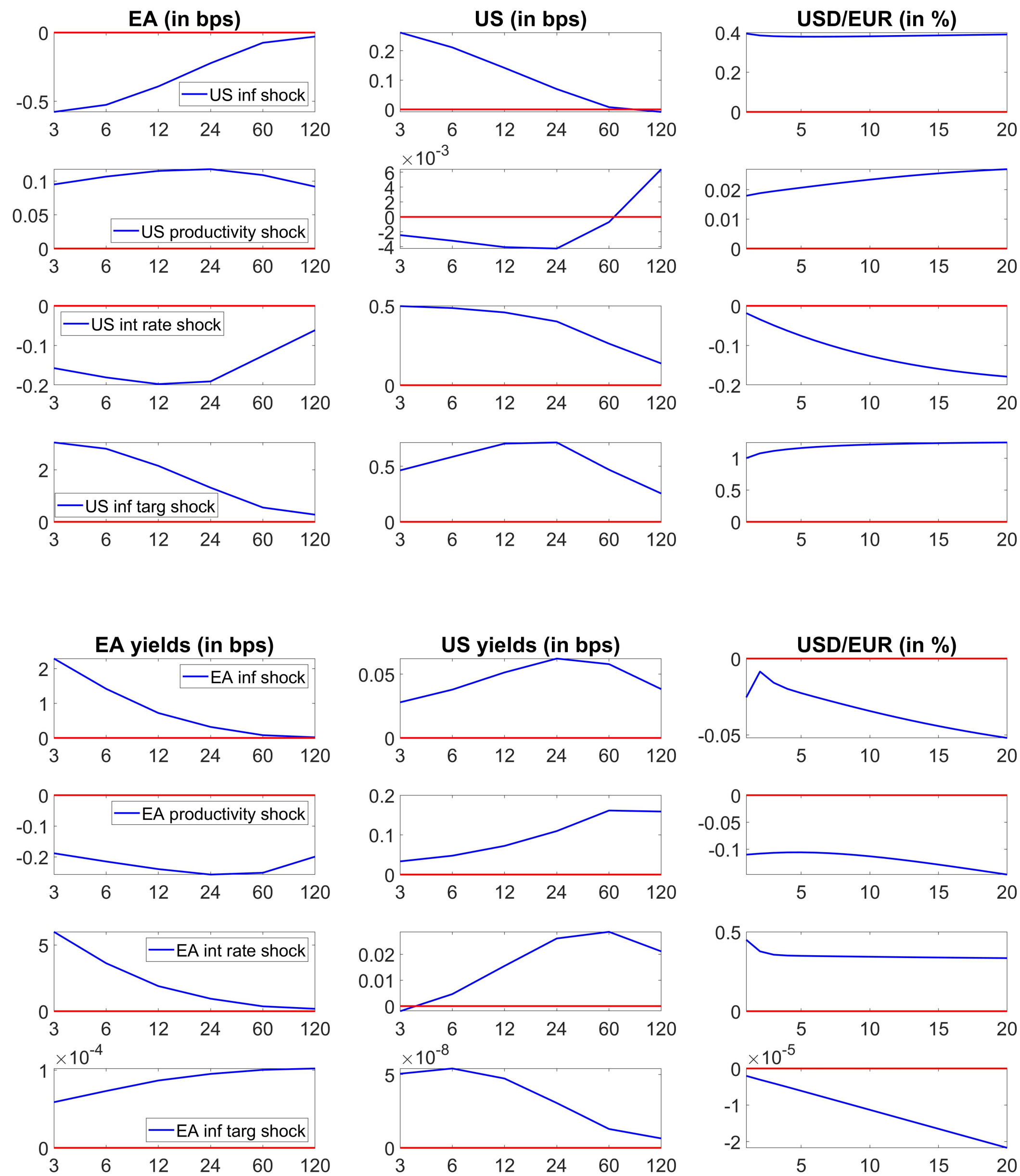

Figure 9: Yield curve responses on impact and IRFs for nominal exchange rate. Upper: first row - EA inflation; second row - EA productivity; third row - EA interest rate; fourth row - EA inflation target. Lower: first row - US inflation; second row - US productivity; third row - US interest rate; fourth row - US inflation target. The horizontal axis for the first two columns gives bond maturities in months. The horizontal axis for the third column is horizons in quarters.

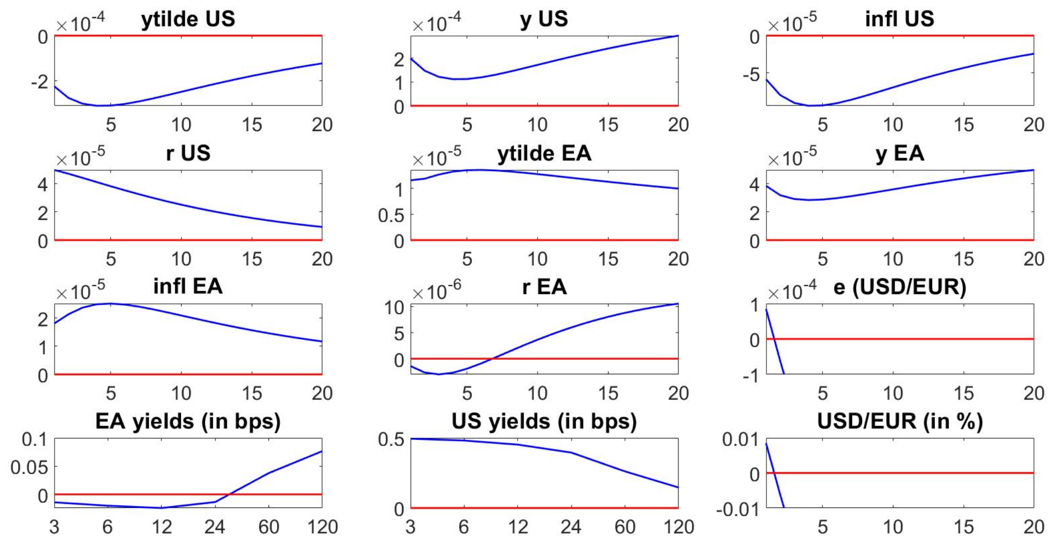

Figure 10: Positive productivity and monetary policy shocks in the US. First three rows: IRFs for positive productivity and interest rate shocks. Last row: Yield curve responses on impact and IRF for nominal exchange rate. The sub-figures for the nominal exchange rate are magnified.

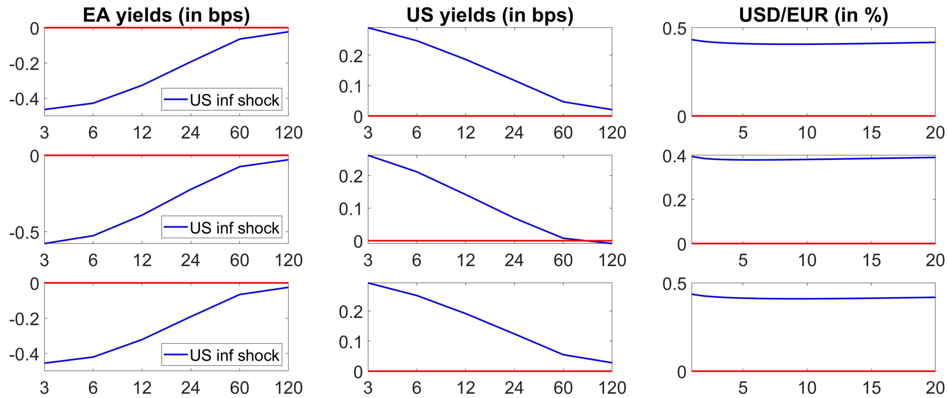

Figure 11: Yield curve responses on impact and IRF for nominal exchange rate. Shock: US inflation. Models: first row - r and π observable; second row - r, π, and $\bar{\pi}$ observable; third row - $\bar{rr}$, r, and π observable. The horizontal axis for the first two columns is bond maturities in months. The horizontal axis for the third column is horizons in quarters. To preserve comparability, the models are evaluated at the parameter values of the best-fitting partial information model (the second row), but the implications are the same if we use the best-fitting parameter values for the respective models.

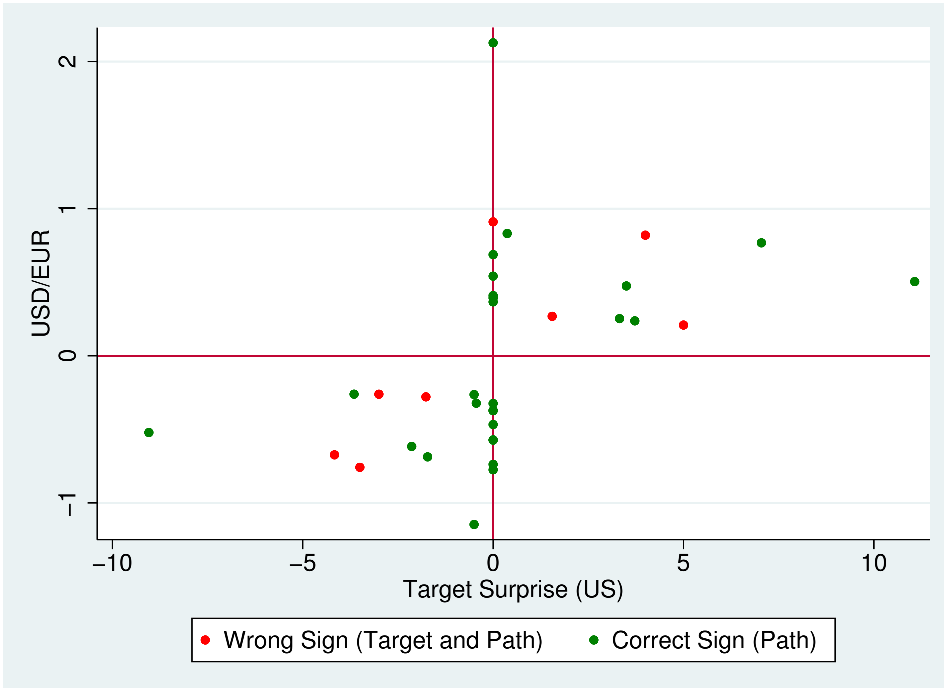

Figure 12: Scatter plot of information days conditional on the target surprise for the US. Green dots are the policy dates where the exchange rate movements can be explained by the path surprise. Red dots are the policy dates where the exchange rate movements cannot be explained either by the target surprise or by the path surprise. The sample is 1994-2018.

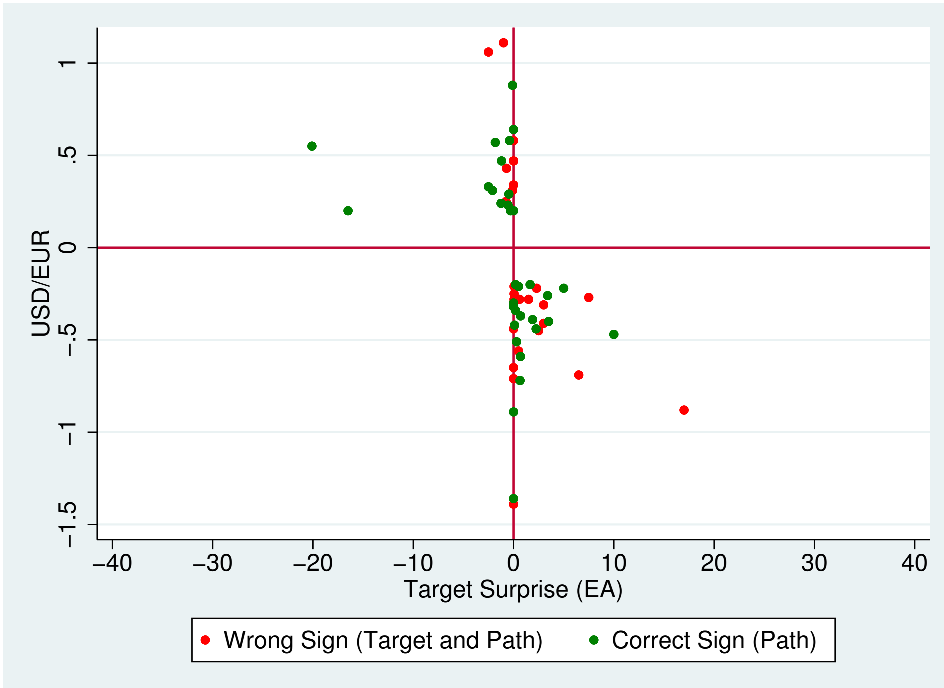

Figure 13: Scatter plot of information days conditional on the target surprise for the euro area. Green dots are the policy dates where the exchange rate movements can be explained by the path surprise. Red dots are the policy dates where the exchange rate movements cannot be explained either by the target surprise or by the path surprise. The sample is 1999-2018.

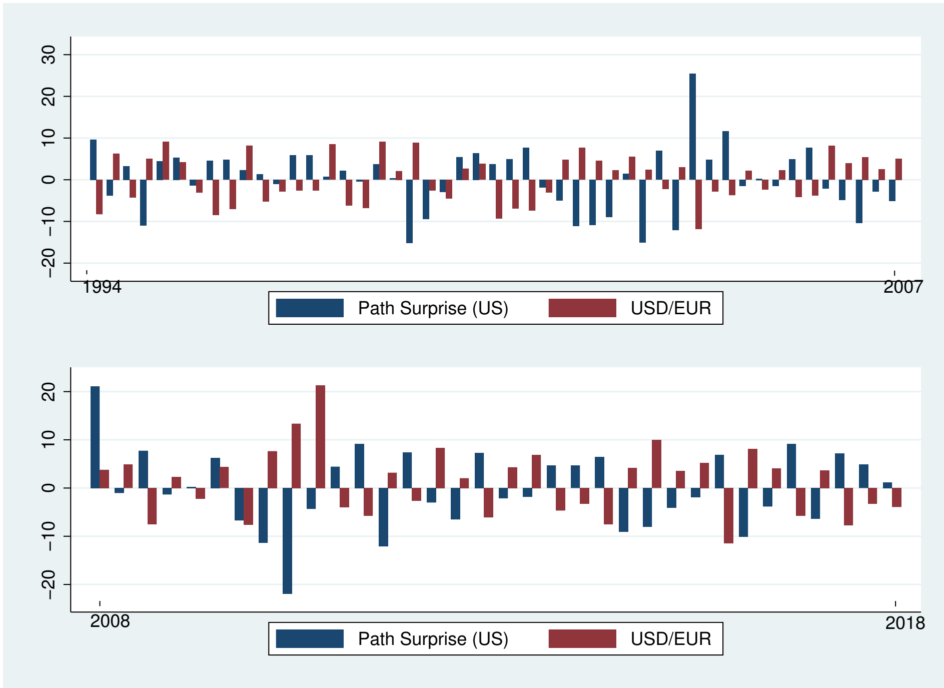

Figure 14: Bar plot for path surprises and associated changes in USD/EUR exchange rate for the US. Upper panel is for the sample 1994-2007 and lower panel is for the sample 2008-2018.

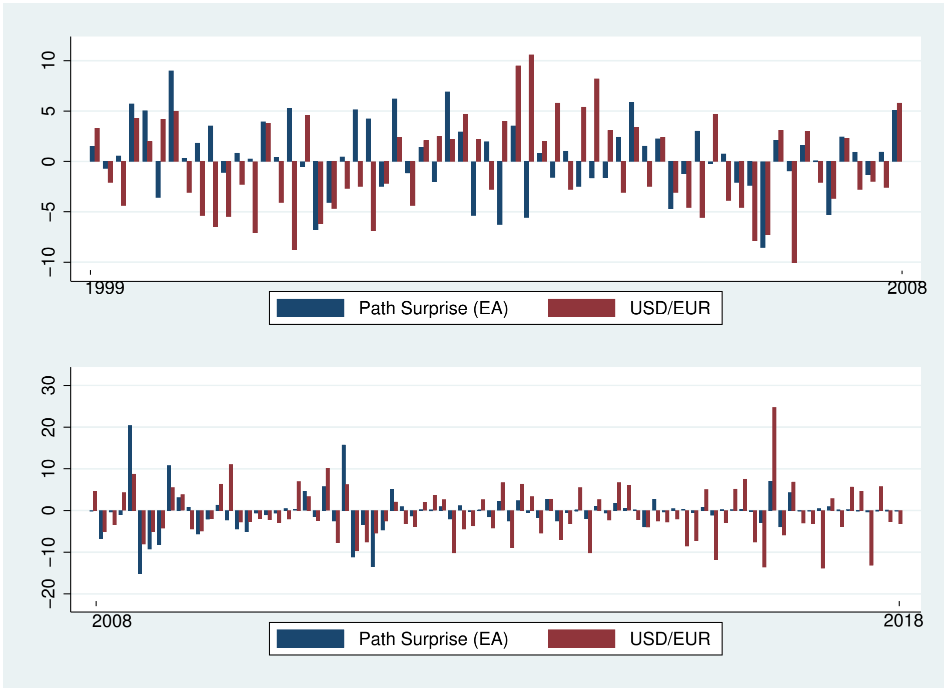

Figure 15: Bar plot for path surprises and associated changes in USD/EUR exchange rate for the euro area. Upper panel is for the sample 1999-2007 and lower panel is for the sample 2008-2018.

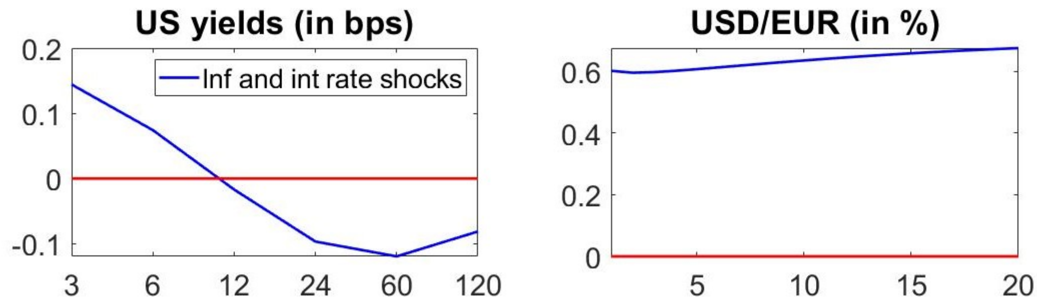

Figure 16: Response to positive inflation shock and negative monetary policy shock in the US based on the best fitting model. Yield curve responses on impact in the US and impulse response graph for nominal exchange rate.