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Does a big bazooka matter? Central bank balance-sheet policies and exchange rates

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Abstract

We estimate the effects of quantitative easing (QE) measures by the ECB and the Federal Reserve on the US dollar-euro exchange rate at frequencies and horizons relevant for policymakers. To do so, we derive a theoretically-consistent local projection regression equation from the standard asset pricing formulation of exchange rate determination. We then proxy unobserved QE shocks by future changes in the relative size of central banks' balance sheets, which we instrument with QE announcements in two-stage least squares regressions in order to account for their endogeneity. We find that QE measures have large and persistent effects on the exchange rate. For example, our estimates imply that the ECB's APP program which raised the ECB's balance sheet relative to that of the Federal Reserve by 35 percentage points between September 2014 and the end of 2016 depreciated the euro vis-à-vis the US dollar by 12%. Regarding transmission channels, we find that a relative QE shock that expands the ECB's balance sheet relative to that of the Federal Reserve depreciates the US dollar-euro exchange rate by reducing euro-dollar short-term money market rate differentials, by widening the cross-currency basis and by eliciting adjustments in currency risk premia. Changes in the expectations about the future monetary policy stance, reflecting the "signalling" channel of QE, also contribute to the exchange rate response to QE shocks.

Keywords: Quantitative easing, interest rate parity condition, CIP deviations.
JEL-Classification: E5, F3.

Non-technical summary

Since the onset of the global financial crisis in 2008, central banks around the world have engaged in a number of unprecedented and unconventional monetary policy interventions. In particular, central banks have deployed quantitative easing (QE) measures as an additional policy tool when interest rates reached their lower bound. The exchange rate has been at the center stage of the discussion about the effectiveness, transmission channels and spillovers of QE. That monetary policy actions which alter the size of the central bank's balance sheet and thereby the (relative) monetary base may affect the currency's international value is not a new topic, as it has been discussed already in the context of the monetary theory of the exchange rate and the effectiveness of exchange rate interventions. And indeed, there has been a correlation between the announcements of QE measures, the relative balance sheet of the ECB and the Federal Reserve, and the US dollar-euro exchange rate. In particular, central banks' balance sheets tended to expand and the corresponding currency to depreciate after announcements of QE measures. Against this background, a large literature that is concerned with assessing the effects of QE measures has emerged. However, the bulk of this literature has considered the high-frequency and short-term effects of QE measures, typically by means of event studies that focus on a narrow time window around their announcement. This approach is not informative regarding the persistence of the effects and the transmission channels of QE beyond the very short-term, and thereby of little help for central banks in understanding whether QE is an effective policy instrument.

In this paper we estimate the effects of QE on the exchange rate at frequencies and time horizons that are relevant for policymakers, and we explore the transmission channels through which they materialise. We focus on the exchange rate of the US dollar against the euro, as the ECB and the Federal Reserve have been carrying out the largest QE programmes after the global financial crisis, and as this is the world's most liquid currency pair. As the dollar-euro exchange rate is a relative price, in our analysis we consider the size of the ECB's balance sheet *relative* to that of the Federal Reserve as well as QE announcements by both the ECB and the Federal Reserve. Our findings suggest that QE measures have large and persistent effects on the exchange rate. For example, our estimates imply that the ECB's APP program, which raised the ECB's balance sheet relative to that of the Federal Reserve by 35 percentage points between September 2014 and the end of 2016, depreciated the euro vis-à-vis the US dollar by 12%. Regarding transmission channels, we find that a relative QE shock that expands the ECB's balance sheet relative to that of the Federal Reserve depreciates the US dollar-euro exchange rate by reducing euro-dollar short-term money market rate differentials, by widening the cross-currency basis and by eliciting adjustments in currency risk premia. A quantitatively substantial contribution to the exchange rate effects of QE stems from changes in the expectations about the future monetary policy stance, which reflects the "signalling" channel of QE.

1 Introduction

Since the onset of the global financial crisis in 2008, central banks around the world have engaged in quantitative easing (QE) measures as an additional policy tool, which resulted in dramatic expansions of their balance sheets. For instance, Figure 1 shows that the Federal Reserve was early in increasing the size of its balance sheet by purchasing large amounts of private and government securities between 2008 and 2012. The ECB initially implemented more modest asset purchase programs, but greatly expanded its provision of liquidity to the banking sector far beyond standard short-term maturities, especially after the second half of 2011. By March 2012, the nominal size of the ECB's balance sheet was similar to that of the Federal Reserve. Then, between March 2012 and the start of 2015, the asset purchases under the Federal Reserve's QE3 program again doubled the Federal Reserve's balance sheet relative to that of the ECB. Finally, in March 2015 the ECB embarked on a comprehensive program of private and public asset purchases, which returned the size of its balance sheet close to that of the Federal Reserve by the end of 2017. While at the time of writing both the ECB and the Federal Reserve are well past the peak recourse to unconventional monetary policy measures, interest in the effects of QE has not faded. Several policymakers have argued that given the secular decline in the natural interest rate, QE may remain an important component of central banks' toolkit going forward (Constancio, 2017; Yellen, 2017). Deepening our understanding of its workings is thus a central issue in monetary policy.

The exchange rate has been at the center stage of the debate about the effectiveness, transmission channels and spillovers of QE (see, for example Rajan, 2013; Bernanke, 2015; Powell, 2018). That the size of the central bank's balance sheet and thereby the (relative) supply of monetary base may affect a currency's international value is a time-honored topic in open-economy macroeconomics; it has been extensively discussed already in the context of the monetary theory of the exchange rate and the effectiveness of exchange rate interventions (Taylor and Sarno, 2001). And indeed, Figure 1 suggests that there has been a correlation between the relative balance sheet of the ECB and the Federal Reserve and the US dollar-euro exchange rate. In particular, central banks' balance sheets tended to expand and the corresponding currency to depreciate after announcements of QE measures (in the figure a fall in the exchange rate denotes a euro depreciation). These correlations are of course silent about causality, and cannot be relied on to gauge the effectiveness or transmission channels of QE measures and to calibrate structural models accordingly.

Against this background, a large literature has emerged that is concerned with assessing the effects of QE, including on the exchange rate. On the one hand, the bulk of this literature has focused on the high-frequency and short-term effects of QE measures, typically by means of event studies that consider a narrow time window around QE announcements.[1] While this approach has been successful in providing evidence on the impact effects of QE announcements on exchange rates, it is less useful for shedding light on the persistence of the effects and the

[1] This literature has become too voluminous to do equal justice to all relevant contributions. For surveys of the literature see Bhattarai and Neely (2016) and Borio and Zabai (2016). See also Woodford (2012).

transmission channels of QE beyond the very short-term. On the other hand, a second strand of the literature has investigated the spillovers from QE at longer horizons.[2] However, few of the studies in this literature have focused on the effects of QE on the exchange rate and its transmission channels — despite the prominence of the exchange rate in both academic and policy debates about the effectiveness, transmission channels and spillovers of QE. And even if the exchange rate has been among the variables considered in some of these studies, several gaps remain. Specifically, the existing evidence on the effects of QE on the exchange rate stems exclusively from structural VAR models, which rely on (usually contemporaneous) zero or sign-restrictions on balance sheet variables and some asset prices to identify QE shocks. Notably, the VAR approach does not take into account the important fact that QE measures have been announced by central banks usually prior to their implementation, and that, as documented by event studies in the literature, forward-looking asset prices such as the exchange rate have responded almost instantly to these announcements.

Our contribution fills these gaps. In particular, we estimate the effects of QE on the exchange rate at horizons that are relevant to inform policymakers and structural models, and we explore the transmission channels through which the effects materialise over time. In line with the monetary theory of the exchange rate as a relative price, we consider the size of the ECB's balance sheet *relative* to that of the Federal Reserve, as well as QE announcements by both the ECB and the Federal Reserve. Our findings suggest that QE measures have large and persistent effects on the exchange rate. Specifically, a back-of the-envelope calculation based on our estimates implies that the ECB's APP program, which raised the ECB's balance sheet relative to that of the Federal Reserve by 35 percentage points between September 2014 and the end of 2016, depreciated the euro vis-à-vis the US dollar by 12%. Regarding the transmission channels, we find that a QE shock that expands the ECB's balance sheet relative to that of the Federal Reserve persistently reduces the euro-dollar short-term money market interest rate differential. The effects of QE on short-term interest rate differentials stem in part from liquidity effects in money markets, especially when the demand for central bank reserves is not satiated, and in part from expectations of further monetary policy accommodation over the medium term — the so-called "signalling" channel of QE (see Woodford, 2012). Further supporting the existence of a "signalling" channel, we find that a QE shock which expands the ECB's balance sheet relative to that of the Federal Reserve shifts markets' expectations regarding relative "time-to-lift-off" farther into the future. While changes in short-term interest rate differentials play an important role in the transmission of QE shocks to the exchange rate, our results suggest that the largest quantitative contribution stems from persistent effects of QE on risk premia in foreign exchange markets. Finally, we document that an expansionary relative QE shock exacerbates limits to arbitrage in foreign exchange markets, as it widens CIP deviations reflected in the cross-currency basis. However, the response of CIP deviations accounts only for a negligible fraction of the overall effects of QE on the exchange rate.

We obtain our findings by adopting an empirical approach that draws on elements from several strands of the literature. In particular, borrowing from the news shocks literature (Schmitt-

[2] We review this literature in Section 2.

Grohe and Uribe, 2008), we conceive QE measures that are announced in period t as shocks which materialise in period t but which are anticipated by agents to affect central banks' balance sheets in the current and future periods $t+m$, $m = 0, 1, \ldots, M$. We then show that while these QE shocks are unobserved by the econometrician they can be proxied by future changes in central banks' balance sheets. In turn, we show that in the framework that we posit the endogeneity of the future changes in central banks' balance sheets can be accounted for by using announcements of QE measures as instruments. We consider QE *shocks* rather than *announcements* as the main variable of interest in our empirical framework because this allows us to establish a quantitative assessment of the overall effects of the ECB's and the Federal Reserve's QE programs on the exchange rate. In particular, our framework allows us to determine an elasticity that reflects the change in the exchange rate implied by a QE measure that changes the relative central bank balance sheet by a given magnitude.

More technically, we estimate the effects of QE on the dollar-euro exchange rate using local projections (Jorda, 2005). We derive a theoretically-consistent local projection regression equation from the standard asset pricing formulation of exchange rate determination, according to which the spot exchange rate is given by current and future expected fundamentals. Specifically, the local projection regression for the exchange rate at horizon h is implied by the difference between the (generalised) uncovered interest rate parity (UIP) conditions for periods $t+h$ and $t-1$.[3] In order to address the endogeneity of the central banks' relative balance sheet — which we use as proxy for the QE shocks unobserved by the econometrician — in the local projection regression equation, we exploit announcements of ECB and Federal Reserve QE measures as instruments in two-stage least squares regressions (Jorda et al., 2015; Ramey and Zubairy, 2018). Deriving the local projection regression equation from a structural equation for the exchange rate disciplines the empirical specification we bring to the data, for example by pointing to the possible sources of endogeneity, guiding the inference, the choice of control variables and their timing. We also pay great attention to model specification tests, including on instrument validity and power. An appealing feature of our empirical framework is that it allows us to take into account changes in central banks' balance sheets that occur both contemporaneously and up until relatively long horizons in the future in order to proxy QE shocks; in contrast, the existing literature typically conceives QE shocks as contemporaneous changes in the central bank balance sheet. Given that the exchange rate is a forward-looking variable that is affected by expected changes in future fundamentals, we believe that our framework is especially well-suited to assess the dynamic effects of QE on exchange rates. Finally, we explore several robustness checks related to variations of the identification of QE shocks (e.g. by exploiting stock price changes on the day of the announcements), various aspects of the regression specification and data frequency (e.g. we show that the results are broadly unchanged when we use weekly rather than monthly data).

The paper is organised as follows. Section 2 reviews the extant literature on the dynamic effects of QE on exchange rates. In Section 3 we review standard exchange rate determination according to asset pricing theory, and we derive the local projection equation for the exchange rate. Then, in Section 4 we describe the empirical specification of the local projection regression, followed

[3] This generalised UIP allows for currency risk-premia and deviations from CIP.

by the presentation of our results in Section 5. Section 6 presents robustness checks, and Section 7 concludes.

2 Existing literature

Some previous work has explored the dynamic effects of QE in VAR models. A first set of studies has focused on US QE shocks. Bhattarai et al. (2018) estimate a random-coefficients panel VAR model in which QE is reflected by the size of the Federal Reserve's balance sheet, and identify QE shocks with non-recursive short-run restrictions. Bhattarai et al. (2018) find that emerging market economies' currencies appreciated following US QE. Similarly, Anaya et al. (2017) estimate a global VAR model including the Federal Reserve's balance sheet, and, using sign restrictions, they find that US QE shocks significantly appreciated emerging market economies' currencies. Conversely, using a global VAR model with recursive (Choleski) identification and conceiving QE shocks as VAR innovations to US term or corporate bond spreads Chen et al. (2016) find only minor effects of US QE shocks on foreign exchange pressure indices. Finally, Punzi and Chantapacdepong (2017) set up a panel VAR model with a recursive identification, finding that US QE shocks as reflected in VAR innovations to a shadow short rate appreciated Asian currencies.

A second set of studies has focused on QE in the euro area. Bluwstein and Canova (2016) estimate two-country mixed-frequency VAR models in which QE is represented by ECB asset purchases and identification is based on contemporaneous zero (exclusion) restrictions. Bluwstein and Canova (2016) find that the euro broadly depreciated against European currencies in response to QE shocks. Similarly, Garcia Pascual and Wieladek (2016) estimate a VAR with ECB asset purchases and a mix of zero and sign restrictions, and find that the euro broadly depreciated against European currencies in response to QE shocks. Babecka Kucharcukova et al. (2016) consider two-country VAR models where ECB QE shocks are identified with contemporaneous zero-restrictions on innovations to a monetary conditions index, and find effects on European economies' exchange rates. Moder (2017) explores the spillovers from QE to South Eastern European economies using bilateral VAR models conceiving QE shocks as VAR innovations to the ECB's balance sheet identified by zero and sign restrictions, finding mostly insignificant exchange rate responses. Finally, Feldkircher et al. (2017) estimate a global VAR model with sign and zero restrictions imposed on innovations to the euro term spread, and find that exchange rates of Eastern European economies appreciated in response to an ECB QE shock.

The existing literature differs from our paper in several respects. First, the existing evidence on the exchange rate effects of QE essentially stems from VAR models which consider either Federal Reserve or ECB QE shocks, but never both sets of shocks together. However, given that the exchange rate is a relative (asset) price, one should consider ECB and Federal Reserve QE measures jointly in order to reduce omitted variable bias and to improve efficiency of estimation. Second, the existing literature relies on identification approaches very different from ours, mostly not taking into account information from central bank QE announcements — which event studies have shown affect exchange rates on impact. Finally, none of the existing work zooms in on the effects of QE on the exchange rate, exploring in detail the transmission channels.

3 A framework for the estimation of the effects of QE on the exchange rate

In this section we motivate the local projection regression equation for the exchange rate that we will use in order to estimate the effects of QE measures. To do so, we first draw on textbook asset pricing theory and review exchange rate determination in the presence of frictions that may give rise to deviations from CIP. The associated UIP condition implies that the value of the spot exchange rate in period t is equal to the un-discounted sum of current and future expected fundamentals, i.e. interest rate differentials, CIP deviations and currency risk premia up to horizon T, as well as the expected exchange rate at horizon T. Finally, we show that we can estimate the effects of QE shocks on the exchange rate at horizon h based on a theoretically-consistent local projection regression equation derived as the difference between the UIP conditions for periods $t+h$ and $t-1$.

3.1 Exchange rate determination and CIP deviations

Consider an investor whose relevant nominal discount factor is expressed in US dollars ("American" investor), $\mathcal{D}_t^{\$}$.[4] Under standard conditions, the relation between $\mathcal{D}_t^{\$}$ and the one-period nominally risk-free US dollar nominal interest rate $R_t^{\$}$ is then given by:

$$1 = E_t\left(\mathcal{D}_{t+1}^{\$}\right) R_t^{\$}. \tag{1}$$

Equation (1) implies that one dollar today has to be equal to the certain dollar amount $R_t^{\$}$ in period $t+1$, appropriately discounted by the expected marginal value of wealth across the two periods. Similarly, denoting by $R_t^{€}$ the one-period risk-free euro nominal rate, by $F_{t,t+1}$ the forward dollar price of one euro, and by S_t the spot exchange rate expressed in the amount of dollars per euro, the investor would price the nominally safe investment of one dollar today into $1/S_t$ euro yielding the safe dollar payoff $F_{t,t+1}R_t^{€}$ in period $t+1$ as:

$$1 = E_t\left(\mathcal{D}_{t+1}^{\$}\right) \frac{F_{t,t+1}R_t^{€}}{S_t}. \tag{2}$$

More generally, if the investor is potentially borrowing constrained, the two Euler equations

[4] Under general conditions, the stochastic discount factor is equal to the ratio of Lagrange multipliers on the agent's future and current budget constraint, i.e., her marginal value of wealth (see Lucas, 1978). The nominal discount factor is not necessarily a function of consumption growth only. For instance, with Epstein-Zin-Weil preferences, it is a nontrivial function of wealth growth itself.

above read as follows:

$$1 \geq 1 - \lambda_t^{\$} = E_t\left(\mathcal{D}_{t+1}^{\$}\right) R_t^{\$}, \tag{3}$$

and

$$1 \geq 1 - \lambda_t^{€} = E_t\left(\mathcal{D}_{t+1}^{\$}\right) \frac{F_{t,t+1} R_t^{€}}{S_t}. \tag{4}$$

When $\lambda_t^{\$} = 0$, Equation (3) holds with equality and the investor is not facing a binding borrowing constraint at the desired level of investment in the dollar cash market. Even in the presence of borrowing constraints, this is the case when the desired investment is positive, i.e. when the investor is saving. When $\lambda_t^{\$} > 0$, one dollar in period t is worth more than (the appropriately discounted value of) $R_t^{\$}$ in $t+1$. In the absence of borrowing constraints, the investor would borrow against future income until the value of one dollar in periods t and $t+1$ is equalised. Thus, $\lambda_t^{\$} \geq 0$ can be interpreted as the shadow value of borrowing one additional dollar.[5] The rationale for $\lambda_t^{€}$ is analogous, but refers to borrowing and saving in the synthetic risk-free dollar market at the rate $\frac{F_{t,t+1} R_t^{€}}{S_t}$.

Combining Equations (3) and (4) implies the CIP condition:

$$R_t^{\$} = \frac{F_{t,t+1} R_t^{€}}{S_t} \cdot (1 - \lambda_t), \tag{5}$$

where $\lambda_t \equiv 1 - \frac{1-\lambda_t^{\$}}{1-\lambda_t^{€}}$ represents CIP deviations.[6,7] In particular, in case $\lambda_t > 0$, meaning that $\lambda_t^{\$} > \lambda_t^{€} \geq 0$, we have that borrowing is more expensive in the synthetic dollar market at the rate $\frac{F_{t,t+1} R_t^{€}}{S_t}$ than in the cash market at the rate $R_t^{\$}$; this implies that dollar cash market borrowing constraints are tighter. Taking logs of Equation (5) yields:

$$r_t^{\$} \simeq r_t^{€} + f_{t,t+1} - s_t - \lambda_t, \tag{6}$$

where we have assumed that CIP deviations λ_t are small.[8] Notice that our definition of the CIP

[5] We can also interpret λ_t^i as transaction costs. In this case, allocating one dollar to either strategy only translates into an effective investment of $1 - \lambda_t^i$ dollars. A key difference is that $\lambda_t^i > 0$ even when the investor is long.

[6] It can be shown that CIP deviations cannot arise because of counterparty risk in the forward market.

[7] The CIP condition could also be derived from the perspective of a euro area investor whose relevant nominal discount factor is $\mathcal{D}_t^{€}$ based on:

$$1 \geq 1 - \lambda_t^{€} = E_t\left(\mathcal{D}_{t+1}^{€}\right) R_t^{€},$$
$$1 \geq 1 - \lambda_t^{\$} = E_t\left(\mathcal{D}_{t+1}^{€}\right) \frac{S_t R_t^{\$}}{F_{t,t+1}}.$$

[8] Deviations from CIP could in principle also arise if the dollar or euro cash rates were not safe, say because of default risk, and if this risk was different across rates. In this case, the conditions under which the CIP condition was derived above would fail. Instead, one would have:

$$1 = E_t\left(\mathcal{D}_{t+1}^{\$} R_t^{€}\right) \frac{F_{t,t+1}}{S_t} = E_t\left(\mathcal{D}_{t+1}^{\$} R_t^{\$}\right).$$

In this case, arbitrage does not ensure anymore that the forward-spot discount is equal to the interest rate differential. However, several contributions have shown that interest rate default risk has not been a key source of CIP deviations recently (see, for example, Du et al., 2018).

deviation implied by Equation (6), namely

$$\lambda_t \equiv r_t^{€} - \left(r_t^{\$} - f_{t,t+1} + s_t \right), \tag{7}$$

coincides with the market definition of the cross-currency basis, except for having the *opposite* sign (see, for example, Du et al., 2018).

As regards the pricing of the forward rate, arbitrage forces ensure that the one-period risk-adjusted expected return of investing in the dollar-euro forward market or in the dollar-euro spot market are the same, namely:

$$\frac{E_t\left(\mathcal{D}_{t+1}^{\$}\right)F_{t,t+1}}{S_t}R_t^{€} = \frac{E_t\left(\mathcal{D}_{t+1}^{\$}S_{t+1}\right)}{S_t}R_t^{€}. \tag{8}$$

Hence, we have the following relation between the forward and the expected spot exchange rate:

$$F_{t,t+1} = E_t\left(S_{t+1}\right) + \frac{Cov_t\left(\mathcal{D}_{t+1}^{\$}, S_{t+1}\right)}{E_t\left(\mathcal{D}_{t+1}^{\$}\right)}. \tag{9}$$

Assuming log-normality and taking logs yields:

$$\begin{aligned} f_{t,t+1} &= E_t s_{t+1} + Cov_t\left(d_{t+1}^{\$}, s_{t+1}\right) + \frac{1}{2}Var_t\left(s_{t+1}\right) \\ &= E_t s_{t+1} + \pi_t. \end{aligned} \tag{10}$$

Taking into account Jensen's inequality (the term $\frac{1}{2}Var_t\left(s_{t+1}\right)$), the forward rate exceeds (falls short of) the expected spot rate when the investor is willing to pay a positive (negative) premium. The latter is the case when the spot rate is expected to co-vary positively (negatively) with the investor's discount factor.[9]

By substituting the forward rate in Equation (10) in the CIP condition in Equation (6), we obtain the UIP condition:

$$s_t = E_t s_{t+1} + dr_t - \lambda_t + \pi_t, \tag{11}$$

where $dr_t \equiv r_t^{€} - r_t^{\$}$. Iterating forward Equation (11) for T periods and applying the law of iterated expectations yields:

$$s_t = E_t s_{t+T} + \sum_{j=0}^{T-1} E_t dr_{t+j} - \sum_{j=0}^{T-1} E_t \lambda_{t+j} + \sum_{j=0}^{T-1} E_t \pi_{t+j}, \tag{12}$$

which shows that the spot exchange rate in period t is determined by current and expected future fundamentals — i.e. short-term interest rate differentials, risk premia, CIP deviations, and the expected value of the exchange rate at horizon T. Equation (12) implies that QE measures

[9] Specifically, premium π_t is positive if a dollar depreciation against the euro (a higher S_{t+1}) is expected to go hand in hand with a higher marginal value of wealth (higher $\mathcal{D}_{t+1}^{\$}$). This means that the dollar currency risk of a nominally safe euro investment provides a hedge to the investor, who then requires compensation to hold the forward. Conversely, the premium π_t negative when dollar depreciation is expected to be associated with a lower discount factor of the investor.

can impact the current value of the exchange rate only to the extent that they affect current and expected future fundamentals. For instance, the classic monetary approach to exchange rate determination provides a possible channel through which QE can affect the exchange rate to the extent that changes in the relative supply of high-powered money have liquidity effects on current and expected money-market rates (Dornbusch, 1976) or on CIP deviations in the presence of frictions as those discussed above. Likewise, QE can impact the exchange rate to the extent that it affects the expectations component of long-term rates (i.e. the sum of expected short-term interest rates) and/or if term premia are correlated with currency risk premia. The effect of QE on the exchange rate through the expectations component of long-term interest rates is usually referred to as the "signalling" channel (Woodford, 2012). Specifically, under the signalling channel QE measures convey information about future monetary policy rates. If effective, it is clear from Equation (12) that the signalling channel of QE is in general also reflected by changes in the expectation of the exchange rate at some longer horizon T.

3.2 Deriving a local projection equation for the exchange rate

Consider the UIP condition in Equation (12) and subtract from both sides the corresponding equation lagged by one period:

$$\begin{aligned} s_t - s_{t-1} = & - dr_{t-1} + \lambda_{t-1} - \pi_{t-1} \\ & + E_t s_{t+T} - E_{t-1} s_{t+T} + \sum_{j=0}^{T-1} \left(E_t dr_{t+j} - E_{t-1} dr_{t+j} \right) \\ & - \sum_{j=0}^{T-1} \left(E_t \lambda_{t+j} - E_{t-1} \lambda_{t+j} \right) + \sum_{j=0}^{T-1} \left(E_t \pi_{t+j} - E_{t-1} \pi_{t+j} \right). \end{aligned} \tag{13}$$

The terms in the second and third row involve differences between the same variables, but in terms of expectations formed in period t and $t-1$, respectively. Under rational expectations, these terms are functions of the structural shocks in period t, i.e. the vector of mutually uncorrelated white noise variables $\boldsymbol{\varepsilon}_t$ with $E_{t-1}(\boldsymbol{\varepsilon}_t) = 0$, which is also orthogonal to all lagged terms in Equation (13). Assuming linearity, we can replace the changes in expectations by the impact of structural shocks and write Equation (13) as:

$$s_t - s_{t-1} = \omega_{t-1,0} + \boldsymbol{\alpha}_0' \boldsymbol{\varepsilon}_t, \tag{14}$$

where

$$\omega_{t-1,0} \equiv - dr_{t-1} + \lambda_{t-1} - \pi_{t-1}, \tag{15}$$

$$\begin{aligned} \boldsymbol{\alpha}_0' \boldsymbol{\varepsilon}_t \equiv & E_t s_{t+T} - E_{t-1} s_{t+T} + \sum_{j=0}^{T-1} \left(E_t dr_{t+j} - E_{t-1} dr_{t+j} \right) \\ & - \sum_{j=0}^{T-1} \left(E_t \lambda_{t+j} - E_{t-1} \lambda_{t+j} \right) + \sum_{j=0}^{T-1} \left(E_t \pi_{t+j} - E_{t-1} \pi_{t+j} \right). \end{aligned} \tag{16}$$

Analogously to the difference between periods t and $t-1$ in Equation (13), for the difference between the exchange rate in periods $t+h$ and $t-1$ we have

$$s_{t+h} - s_{t-1} = \omega_{t-1,h} + \boldsymbol{\alpha}_0' \boldsymbol{\varepsilon}_{t+h} + \boldsymbol{\alpha}_1' \boldsymbol{\varepsilon}_{t+h-1} + \ldots + \boldsymbol{\alpha}_h' \boldsymbol{\varepsilon}_t, \tag{17}$$

where

$$\begin{aligned}\omega_{t-1,h} \equiv & - dr_{t-1} + \lambda_{t-1} - \pi_{t-1} \\ & - \sum_{j=1}^{h-1} E_{t-1} dr_{t+j-1} + \sum_{j=1}^{h-1} E_{t-1} \lambda_{t+j-1} - \sum_{j=0}^{h-1} E_{t-1} \pi_{t+j-1}.\end{aligned} \tag{18}$$

Taking expectations of Equation (17) as of period t yields

$$E_t s_{t+h} - s_{t-1} = \omega_{t-1,h} + \boldsymbol{\alpha}_h' \boldsymbol{\varepsilon}_t, \tag{19}$$

which shows that the coefficients $\boldsymbol{\alpha}_h$ represent the impulse response of the exchange rate at horizon h to the structural shocks $\boldsymbol{\varepsilon}_t$ occurring in period t. As the structural shocks are white noise satisfying $Cov(\nu_{t,h}, \boldsymbol{\varepsilon}_t) = Cov(\nu_{t,h}, \omega_{t-1,h}) = 0$, we can in principle estimate the coefficients $\boldsymbol{\alpha}_h$ by ordinary least squares (OLS) from the local projection regression

$$s_{t+h} - s_{t-1} = \omega_{t-1,h} + \boldsymbol{\alpha}_h' \boldsymbol{\varepsilon}_t + \nu_{t,h}, \tag{20}$$

where

$$\nu_{t,h} \equiv \sum_{j=0}^{h-1} \boldsymbol{\alpha}_h' \boldsymbol{\varepsilon}_{t+h-j}. \tag{21}$$

Before we introduce QE shocks in Equation (20), it is worthwhile to highlight three issues. First, departures from rational expectations may imply that the forecast errors $\boldsymbol{\epsilon}_t$ in Equation (14) are forecastable (see Bordalo et al., 2018; Iovino and Sergeyev, 2018, for an application to QE). In this case, we would not be able to interpret $\boldsymbol{\epsilon}_t$ as structural shocks. However, in this case one could project the forecast errors on lagged variables in order to obtain the structural shocks. Hence, in the context of our paper one would have to include additional lagged variables on the left-hand side of Equation (16) in order to isolate the structural shocks. And as we explain in more detail in Section 4 below, in the empirical specification of our regressions we do include lags of a number of variables, even though this would not be strictly necessary under rational expectations. Second, some evidence in the empirical literature on exchange rates suggests that "UIP does not hold" (Fama, 1984). However, notice that what the "failure of UIP" refers to in this literature is that OLS estimation of Equation (11) produces a coefficient estimate on the interest rate differential different from unity (see Engel, 1996, 2014, for a survey), rather than UIP not holding as a no-arbitrage relation.[10] Most importantly, this notion of "failure of UIP"

[10] The counterintuitive finding of a coefficient estimate different from unity arises because structural shocks affect at the same time the interest rate differential and risk premia, and because risk premia are unobserved, hence included in the regression residual and ultimately giving rise to omitted variable bias. Therefore, this notion of "failure of UIP" does not refer to Equation (12) not holding true as a no-arbitrage relationship given unobserved risk premia and CIP deviations.

does not affect the derivation of Equation (14). Third, notice that Equation (14) is consistent with the exchange rate being very difficult to predict, especially if the volatility of shocks is large, and close to a random walk (Meese and Rogoff, 1983).

3.3 Introducing QE shocks

In order to see how the local projection in Equation (20) can be used to estimate the effects of QE on the exchange rate we first conceptualise the notion of QE shocks in our context. Specifically, we first partition the vector of structural shocks into $\boldsymbol{\varepsilon}_t = (\varepsilon_t^{qe}, \boldsymbol{e}_t')'$, such that ε_t^{qe} is a QE shock, and $\boldsymbol{e}_t$ includes non-QE structural shocks such as conventional monetary policy shocks or money demand shocks. Then, borrowing from the news shock literature (see, for example, Schmitt-Grohe and Uribe, 2008) and again assuming linearity, we posit a QE shock ε_t^{qe} such that

$$\varepsilon_t^{qe} = \sum_{m=0}^{M} \eta_{t+m|t}, \tag{22}$$

where $\eta_{t+m|t}$ represents a QE shock that materialises in period t but that is anticipated by agents to affect the central bank balance sheet through asset purchases only in period $t+m$. Accordingly, we assume that the central bank balance sheet evolves as

$$\Delta BS_t = \delta_0 + \sum_{m=0}^{M} \eta_{t|t-m} + \boldsymbol{\delta}'\boldsymbol{e}_t. \tag{23}$$

As we are interested in the effects of QE on the exchange rate and as the exchange rate is a relative price, we interpret ε_t^{qe} as a *relative* QE shock. Specifically, ε_t^{qe} is positive when a QE shock occurs in the euro area in the absence of an analogous shock in the US; conversely, ε_t^{qe} is negative when a QE shock occurs in the US in the absence of an analogous shock in the euro area. Against this background, Equation (23) specifies the evolution of the *relative* central bank balance sheet, that is the balance sheet of the ECB relative to that of the Federal Reserve.

Partitioning the vector of impulse response coefficients accordingly as $\boldsymbol{\alpha}_h = (\alpha_h^{qe}, \boldsymbol{a}_h')'$ we can then write the local projection for the exchange rate in Equation (20) as

$$s_{t+h} - s_{t-1} = \alpha_h^{qe} \left(\sum_{m=0}^{M} \eta_{t+m|t} \right) + \omega_{t-1,h} + \boldsymbol{a}_h'\boldsymbol{e}_t + \nu_{t,h}. \tag{24}$$

The intuition underlying Equation (24) is that because the exchange rate is a forward-looking asset price it will respond to a relative QE shock that materialises in period t, even if it involves asset purchases that will be — and are anticipated by agents to be — carried out in the future.

Notice that the analytical framework represented by Equation (24) does not take a stance on the channels through which QE shocks affect the exchange rate, and, as $\{\alpha_h^{qe}\}_{h=0,1,\ldots}$ may be zero, even not on whether QE shocks impact exchange rates at all. Notice also that the analytical framework for the exchange rate we consider in this paper differs from the approaches in the existing time-series literature on the effects of QE discussed in the Section 2, which do not take into account the component of QE shocks that is reflected in future changes in central banks' balance sheets, that is $\eta_{t+m|t}$ with $m > 0$.[11] We therefore believe that our framework is better suited to assess the exchange rate effects of QE relative to the typical VAR framework used in the existing literature.

3.4 Proxying QE shocks by central bank balance sheet changes

Estimating the effects of QE shocks on the exchange rate in Equation (24) is of course complicated by the fact that the former are not observed by the econometrician. However, given Equation (23) we can proxy the unobserved relative QE shocks by changes in the relative central bank balance sheet. In particular, we can substitute the QE shocks in the local projection of the exchange rate in Equation (24) using Equation (23) and

$$\eta_{t+m|t} = \Delta BS_{t+m} - \left(\delta_0 + \sum_{\substack{k=0 \\ k\neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{\delta}' \boldsymbol{e}_{t+m} \right),$$

to obtain

$$s_{t+h} - s_{t-1} = \alpha_h^{qe} \left(\sum_{m=0}^{M} \Delta BS_{t+m} \right) + \omega_{t-1,h} + (M+1)\delta_0 + \zeta_{t,h}, \quad (25)$$

where

$$\zeta_{t,h} \equiv -\alpha_h^{qe} \boldsymbol{\delta}' \sum_{m=0}^{M} \boldsymbol{e}_{t+m} - \alpha_h^{qe} \sum_{m=0}^{M} \sum_{\substack{k=0 \\ k\neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{a}_h' \boldsymbol{e}_t + \nu_{t,h}. \quad (26)$$

Notice that the term $\sum_{m=0}^{M} \sum_{k=0,\, k\neq m}^{M} \eta_{t+m|t+m-k}$ in Equation (26) only contains future and lagged but no contemporaneous QE shocks, i.e. we have that $x \neq t$ for $x \equiv t + m - k$. It is worthwhile to stress that we are positing that future changes in the relative balance sheet may affect future exchange rates; in this sense our theoretical framework is again consistent with the literature on the difficulty of forecasting exchange rates in real time and out-of-sample (Meese and Rogoff, 1983).

3.5 Two-stage least squares regression framework

Of course, as can be seen from Equation (23) the variable of interest, $\sum_{m=0}^{M} \Delta BS_{t+m}$, is endogenous in Equation (25) due to its correlation with $\zeta_{t,h}$.[12] Intuitively, central banks' balance sheets

[11] Exceptions are Boeckx et al. (2017) as well as Gambacorta et al. (2014), who impose sign restrictions on impact and one month after the impact period. Only Weale and Wieladek (2016) consider the expected amount of asset purchases expected over the full horizon of the relevant QE programs. However, none of these studies explores the exchange rate effects of QE.

[12] As we do not have information on the signs of $\boldsymbol{\delta}$ and $\boldsymbol{a}_h$ we cannot predict whether the endogeneity bias affecting the estimate of α_h^{qe} is positive or negative.

change not only in response to QE shocks, but also in response to non-QE shocks $\boldsymbol{e}_t$, such as money demand and conventional monetary policy shocks. In order to address this endogeneity, as in Jorda et al. (2015) and Ramey and Zubairy (2018), we adopt a local projection two-stage least squares approach using QE announcements as instruments for $\sum_{m=0}^{M} \Delta BS_{t+m}$ in Equation (25).[13] In particular, we assume that ECB and Federal Reserve QE announcements a_t^{ECB} and a_t^{Fed} are related to anticipated relative QE shocks according to

$$\eta_{t+m|t} = \sigma_m + \mu_m^{\text{ECB}} a_t^{\text{ECB}} + \mu_m^{\text{Fed}} a_t^{\text{Fed}} + u_{t,m}, \quad m = 0, 1, \ldots, M. \tag{27}$$

The intuition for Equation (27) is that a QE announcement in period t is generally followed by changes in the relative central bank balance sheet m periods in the future. Summing Equation (27) over horizons $m = 0, 1, \ldots, M$ yields

$$\begin{aligned} \sum_{m=0}^{M} \eta_{t+m|t} &= \left(\sum_{m=0}^{M} \sigma_m\right) + \left(\sum_{m=0}^{M} \mu_m\right) a_t^{\text{ECB}} + \left(\sum_{m=0}^{M} \mu_m\right) a_t^{\text{Fed}} + \left(\sum_{m=0}^{M} u_{t,m}\right) \\ &= \overline{\sigma} + \overline{\mu}^{\text{ECB}} a_t^{\text{ECB}} + \overline{\mu}^{\text{Fed}} a_t^{\text{Fed}} + \overline{u}_t. \end{aligned} \tag{28}$$

In turn, summing the relative balance sheet in Equation (23) over horizons $m = 0, 1, \ldots, M$ yields

$$\begin{aligned} \sum_{m=0}^{M} \Delta BS_{t+m} &= (M+1)\delta_0 + \sum_{m=0}^{M} \sum_{k=1}^{M} \eta_{t+m|t+m-k} + \boldsymbol{\delta}' \sum_{m=0}^{M} \boldsymbol{e}_{t+m} \\ &= (M+1)\delta_0 + \sum_{m=0}^{M} \eta_{t+m|t} + \sum_{m=0}^{M} \sum_{\substack{k=1 \\ k \neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{\delta}' \sum_{m=0}^{M} \boldsymbol{e}_{t+m}, \end{aligned} \tag{29}$$

which shows that our variable of interest in Equation (25) that is affected by endogeneity, $\sum_{m=0}^{M} \Delta BS_{t+m}$, is correlated with the sum of future anticipated QE shocks $\sum_{m=0}^{M} \eta_{t+m|t}$, which can be forecasted by QE announcements in Equation (28).

Against the background of Equations (25), (28) and (29), we thus consider a two-stage least squares regression approach in which the second-stage regression is given by Equation (25) and the first-stage regression by

$$\sum_{m=0}^{M} \Delta BS_{t+m} = \varpi + \theta^{\text{ECB}} a_t^{\text{ECB}} + \theta^{\text{Fed}} a_t^{\text{Fed}} + \omega_{t-1,h} + \xi_t. \tag{30}$$

Our identifying assumptions are that the instruments for the relative balance sheet variable $\sum_{m=0}^{M} \Delta BS_{t+m}$ in Equation (25) given by the QE announcements a_t^{ECB} and a_t^{Fed} in period t:

(i) are uncorrelated with the error term in the second-stage regression $\zeta_{t,h}$ defined in Equa-

[13] The use of external instruments was originally introduced in the VAR context by Stock (2008), subsequently used by Stock and Watson (2012) as well as Mertens and Ravn (2013), and has recently gained prominence through Gertler and Karadi (2015) as well as Caldara and Kamps (2017). See Stock and Watson (2018) for a survey and discussion.

tion (26), i.e. with contemporaneous and future non-QE structural shocks, $\boldsymbol{e}_{t+m}$, $m = 0, 1, \ldots, M$, future and past QE shocks $\eta_{t+m|t+m-k}$, $k, m = 0, 1, \ldots, M$, $k \neq m$, as well as future structural shocks in $\nu_{t,h}$ defined in Equation (21) (instrument validity)

(ii) predict changes in the relative balance sheet between periods t and $t+m$ in the future, i.e. $\theta^{\text{ECB}} \neq 0$ and/or $\theta^{\text{Fed}} \neq 0$ in Equation (30) (instrument relevance)

Notice that (ii) is satisfied already when $\mu_m^{\text{ECB}} \neq 0$ and/or $\mu_m^{\text{Fed}} \neq 0$ in Equation (27) for *some* horizon m. This contrasts with the approaches in the existing literature, which typically require the stronger assumption $\mu_0^j \neq 0$ for identification.

In our estimations, we formally test the validity of these assumptions by means of the Hansen J-test of over-identification (a test for the exogeneity/validity of the instruments) and the Kleibergen and Paap (2006) test of under-identification (a test for instrument relevance). We also report tests for weak instruments by Montiel Olea and Pflueger (2013) based on the effective F-statistic as implemented in Stata by Pflueger and Wang (2015).[14] We discuss and explore some possible concerns with these assumptions in the robustness checks in Section 6.

Finally, one may wonder why we do not just use Equation (27) to substitute the QE shocks with QE announcements in the local projection for the exchange rate in Equation (24) instead of adopting the more complicated two-stage least squares framework in which changes in the relative central bank balance sheet proxy unobserved QE shocks. In particular, the former approach would spare us from endogeneity problems and thereby at first glance substantially facilitate the analysis. However, doing so would entail an important limitation regarding the interpretation of our estimates. Specifically, in our two-stage least squares framework the impulse response of the exchange rate represents the impact of a QE shock that raises the relative central bank balance sheet by one percentage point over M months. In contrast, if we replaced the unobserved QE shocks by the QE announcements in the local projection for the exchange rate in Equation (24) using Equation (27), we would not be able to "scale" the impulse response. Thus, in this case we would not be able to establish a quantitative assessment of the effects of QE shocks on the exchange rate.

[14] Stock and Watson (2018) discuss an additional "lead/lag exogeneity" requirement for consistent estimation with local projections with external instruments. In particular, in general instruments need to be uncorrelated with future and past structural shocks, at least after including control variables. Here this requires that QE announcements must be uncorrelated with past structural — such as demand and risk — shocks. To the extent that QE measures are a systematic response of central banks to adverse shocks, this requirement is unlikely to be satisfied. Although the derivation of our local projection regression equation from a structural equation for the exchange rate shows that in the particular context of this paper our estimation only requires that QE announcements are uncorrelated with contemporaneous and future structural shocks, we nevertheless address the issue of "lead/lag exogeneity" by including variables that reflect the shocks to which the QE announcements might be responses to as controls in the second-stage regression (Jorda et al., 2015; Stock and Watson, 2018). The lags we include in order to control for $\omega_{t-1,h}$ should also be good proxies for such past shocks. See Section 4 for details.

4 Empirical specification

4.1 Sample period

Since we are interested in the effects of QE measures introduced in the wake of the global financial crisis and its aftermath, our sample spans the time period from January 2009 to December 2017. Our analysis is carried out using data sampled at the monthly frequency; we consider weekly data in robustness checks in Section 6. We transform the data for financial variables available at higher frequencies to monthly observations by calculating averages over daily or weekly data.

4.2 Central banks' balance sheets and controls

We specify BS_t as the logarithm of the ratio of the ECB's and the Federal Reserve's nominal balance sheet in their respective currencies. The variable $\sum_{m=0}^{M} \Delta BS_{t+m}$ then boils down to the percentage point change of the relative balance sheet between periods $t+M$ and $t-1$, i.e. $BS_{t+M} - BS_{t-1}$. Notice that $BS_{t+M} - BS_{t-1}$ also represents the percentage-points difference between the nominal growth rates of the ECB's and the Federal Reserve's balance sheets between periods $t+M$ and $t-1$. We choose $M = 9$, which appears to be a reasonable choice given that the QE measures announced by the ECB and the Federal Reserve that we consider in this paper and that we discuss below involved continued asset purchases over at least several months. We report results for alternative choices of M below as well. The data on the size of the ECB's and the Federal Reserve's balance sheets are obtained from Haver.

We proxy the variables in the vector $\omega_{t-1,h}$ that includes period-$t-1$ values and period-$t-1$ expectations of future values of the UIP fundamentals by lags of the policy rate, three-month money-market and two-year sovereign rate differentials, CIP deviations, the CitiGroup Macroeconomic Surprise indices, the VIX; moreover, as suggested by Stock and Watson (2018), we also include in the vector $\omega_{t-1,h}$ the lags of our instruments given by the ECB and Federal Reserve QE announcements. For the respective policy rates we use the Federal Funds target rate as well as the ECB deposit facility rate (DFR).[15] The data for these variables are obtained from Haver; the only exception is the data for the CIP deviation, for which we use the three-month cross-currency basis from Bloomberg multiplied by minus one in order to align the definition of the basis with that of the CIP deviation in this paper (see Section 3.1). We consider three-month rather than one-month money market rates for consistency, as Bloomberg does not provide data for the one-month cross-currency basis.

In order to more cleanly identify QE shocks and to distinguish them from conventional monetary policy shocks, we include the contemporaneous policy rate differential as a control in the second and first-stage regressions. This element of our identification strategy corresponds to the assumption of a Choleski ordering in a VAR in which the relative balance sheet would be ordered

[15] The results are almost identical when we consider the ECB's main refinancing operations (MRO) rate rather than the DFR.

after those variables whose contemporaneous values appear in the first-stage regression. Intuitively, our identification assumption here is that QE shocks do not contemporaneously affect the policy rate differential. Notice that this is almost trivially true, because (i) both the policy rate and the balance sheet are under the control of the central bank and (ii) the technicalities of monetary policy implementation: On the one hand, conventional monetary policy shocks on the policy rate may involve a contemporaneous change in the central bank balance sheet, as this is the rate that is charged on banks for borrowing reserves from the central bank; on the other hand, QE shocks in the form of central bank asset purchases can be implemented without contemporaneous changes in policy rates.

4.3 QE announcements

We specify the QE announcements a_t^{ECB} and a_t^{Fed} as indicator variables which equal unity if the Federal Reserve or the ECB reveal some information about future asset purchases or credit easing programs. Tables 1 and 2 report the ECB and Federal Reserve QE announcements we consider.[16] The dates in question are assigned to their respective calendar month t.[17] We only consider announcements of QE measures that had a tangible impact on central banks' balance sheets. For example, we do not include the announcements of the ECB's intention to do "whatever it takes" to preserve the euro in July 2012 and of the "Outright Monetary Transactions" programme in September 2012, because these announcements did not result in asset purchases by the time of writing. Furthermore, we do not include the ECB announcement of the Securities Market Programme in May 2010, because the associated asset purchases were sterilised and did therefore not increase the ECB's balance sheet. Following the same logic, we do not consider the Federal Reserve's announcements of its maturity extension programme "Operation Twist", which resulted in an increase in the weighted average maturity of its asset holdings but did not expand its balance sheet. As can be seen from Equation (23), including these QE announcements in our analysis would reduce the power of our instruments for the change in the relative central banks' balance sheets in the first-stage regression. It should be noted, however, that our focus on announcements of QE measures that had a tangible impact on central banks' balance sheets does *not* reflect an assumption that measures such as "Outright Monetary Transactions" or "Operation Twist" did not impact the exchange rate. Rather, we just do not explore their effects because our analytical framework is not well-suited to account for them. In that sense, such other QE shocks are part of the vector $\boldsymbol{e}_t$, and, if these measures did have an effect, our findings reflect a lower bound on the exchange rate impact of QE.

Tables 1 and 2 also report information on the change in the Eurostoxx and S&P500 stock price indices on the day of the ECB and Federal Reserve QE announcements. In most cases, stock price movements on the announcement days were notable, i.e. greater than 0.5%, suggesting that the QE announcements we consider had at least some unexpected, surprise component. We

[16]The announcement dates of the QE measures of the Federal Reserve are taken from Rogers et al. (2014). Those for the ECB are taken from the ECB's website.

[17]The dummies also equal unity when there is more than one announcement in a given month, but this occurs only once in our dataset in the case of Federal Reserve announcements in October 2010.

discuss the relevance of the instances in which the stock price responses were negative in the robustness checks in Section 6.

An extension to the use of the QE announcement dummies that would improve the power of our instruments in the first-stage regression in Equation (30) would be to consider announcement dummies weighted by the announced amounts of purchases under the respective QE measures (see Weale and Wieladek, 2016, for QE in the UK and the US). However, the size of the QE measures in question was not known on the date of the announcement in several cases. For example, in the case of various exceptional liquidity operations conducted by the ECB, the overall size of the measures depended on take-up by banks, rather than being determined by the ECB. Also, some of the QE measures such as the ECB's APP were open ended, so that the total amount of purchases could not possibly have been announced.

5 Estimation results

5.1 First-stage regression: Predictive content of QE announcements

The first column in Table 3 reports the results for the first-stage regression of Equation (30). The estimates indicate that ECB and Federal Reserve QE announcements in period t predict future changes in the relative balance sheet. Specifically, following an ECB QE announcement, its balance sheet expanded statistically significantly relative to that of the Federal Reserve by 13.4 percentage points over the next nine months, i.e. around 1.5 percentage points per month. To put this number in perspective, notice that on average over our sample period a 1.5 percentage-point expansion of the ECB's balance sheet relative to that of the Federal Reserve amounted to an expansion by roughly 45 bil. euros.[18] Notice that the latter figure is about two thirds of the initial size of monthly asset purchases of 60 bil. euros under the ECB's APP program launched in early 2015. Moreover, notice that from its start and until the end of 2016 the APP program expanded the ECB balance sheet by 35 percentage points relative to that of the Federal Reserve. Analogously, following a Federal Reserve QE announcement, the Federal Reserve's balance sheet expanded statistically significantly by 17.1 percentage points relative to that of the ECB. Finally, the results reported in Table 3 also document that the null of instrument validity cannot be rejected by the Hansen J-test, and that the null of under-identification is rejected by the Kleibergen and Paap (2006) test. Moreover, the first-stage regression results are associated with an effective F-statistic that is larger than the relevant 5% critical value, suggesting that the QE announcements are unlikely to be weak instruments.[19]

[18] On average over our sample period the ECB's balance sheet stood at 2.587 tn. euros, and that of the Federal Reserve at 3.319 tn. USD. The average relative balance sheet was thus $(2.587\,tn.\,\text{euro})/(3.319\,tn.\,\text{USD}) = 0.7795$. The implied balance sheet of the ECB in case of an expansion of the relative balance sheet by 1.5 percentage points is given by $3.319\,tn. \times (0.7795 + 0.015)$.

[19] As suggested by Montiel Olea and Pflueger (2013) and as in Ramey and Zubairy (2018) we consider critical values at the 5% and 10% significance level for the null hypothesis that the bias of the two-stage least squares estimator is greater than 10% of the "worst-case" benchmark.

5.2 Second-stage regression: Dynamic effects of QE shocks

We now turn to the dynamic responses of the bilateral US dollar-euro exchange rate and the UIP fundamentals in Equation (12). In the following figures, all impulse response estimates are reported with 90% confidence bands. Notice that the structure of the error term in the second-stage regression in Equation (26) implies serial correlation of order $max(M, h-1)$. For this reason, the confidence bands we report are based on the fixed-b heteroskedasticity-autocorrelation (HAC) robust standard errors introduced by Kiefer and Vogelsang (2005).[20]

5.2.1 US dollar-euro exchange rate response

The left-hand side panel of Figure 2 presents the impulse response of the nominal US dollar-euro exchange rate to a QE shock that expands the ECB's balance sheet relative to that of the Federal Reserve by one percentage point over the following nine months. The depreciation of the euro triggered by the QE shock bottoms at around 0.35% below baseline after nine months; the depreciation is quite persistent, at the 5% (one-sided) significance level at least up to 16 months (recall that with local projections responses are estimated separately at each horizon). Treating the launch of the APP program as a series of QE shocks, our results imply that the APP program, which expanded the ECB's balance sheet by 35 percentage points relative to that of the Federal Reserve between September 2014 when the APP was announced for the first time and the end of 2016, depreciated the euro vis-à-vis the US dollar by about 12% ($= 35pp \times 0.35\%/pp$). This is a substantial effect when compared to the overall depreciation of the euro vis-à-vis the US dollar by about 20% over the same time period. The right-hand side panel of Figure 2 presents the impulse response of the real US dollar-euro exchange rate. The results suggest that the response of the real exchange rate is very similar to that of the nominal exchange rate, except that it is less persistent and returns to baseline after roughly 12 months.

In the baseline we choose $M = 9$ primarily based on the presumption that ECB and Federal Reserve QE programs were seen by markets to have relatively long horizons. Columns (2) and (3) in Table 3 report the results from the first-stage regressions for the cases in which we choose $M = 6$ and $M = 12$, and Figure 3 presents the corresponding estimates of the responses of the nominal bilateral exchange rate. The results are very similar to those from the baseline in Figure 2. Quantitatively, for $M = 6$ point estimates are somewhat larger, and for $M = 12$ they are smaller. Moreover, for $M = 12$ the effective F-statistics suggest that the corresponding estimates might be subject to weak instrument problems.

[20] Under fixed-b HAC robust standard errors the bandwidth of the covariance matrix estimator is modeled as a fixed proportion of the sample size. This contrasts with the traditional Newey-West HAC standard errors, where the bandwidth increases slower than the sample size and where the asymptotic distributions of HAC robust tests do not depend on the bandwidth or kernel. Kiefer and Vogelsang (2005) document in finite sample simulations that standard errors based on fixed-b asymptotics are more accurate than those based on the traditional asymptotics. In our estimations it turns out that confidence bands based on traditional Newey-West HAC standard errors are somewhat tighter, especially at longer horizons h.

5.2.2 Decomposition of the exchange rate response

As discussed in Section 3.1, in order to decompose the response of the exchange rate to QE shocks, we also estimate the dynamic responses of the policy rate differential, the euro-dollar short-term money market rate differential as well as the CIP deviation. For response variables other than the exchange rate, the impulse responses are obtained from two-stage least squares estimations analogous to that for the exchange rate, but in which the dependent variable in the second stage is the relevant response variable.

Interest rate differential The left-hand side panel in the top row of Figure 4 depicts the impulse response of the three-month euro-dollar money market rate differential to the relative QE shock. The estimates suggest that euro area money market rates decline statistically significantly relative to those in the US in response to a relative QE shock. The short-term money market rate differential falls statistically significantly after five months, and bottoms at around two basis points after 13 months. The decline is very persistent, and statistically significant up to 18 months. The right-hand side panel in the top row of Figure 4 shows the dynamic response of the policy rate differential to the relative QE shock. While the impact response is by assumption restricted to be zero, also the point estimates of the response for up to at least six months after the QE shock are essentially zero.[21] The estimated drop in the policy rate differential becomes statistically significant only around 15 months after the QE shock occurred, when it falls by about one basis point. The lack of a statistically significant drop in the policy rate differential for several months suggests that we are not confounding the effects of a QE shock with those of a conventional monetary policy shock that occurs in the wake of QE announcements. This is an important finding, as the ECB lowered its policy rates several times during the sample period we consider; for example, the ECB's DFR (MRO rate) was lowered from 2% (2.5%) to -0.4% (0%) between January 2009 and March 2016, including four instances in which ECB QE measures were announced alongside policy rate changes.

Our findings for the responses of the policy and the three-month interest rate differentials provide some indications regarding the transmission channels through which QE impacts the exchange rate. In particular, notice that according to standard asset pricing theory, at every point in time the three-month rate differential should closely reflect expectations of the policy rate differential over the subsequent three months. Hence, the estimated persistent decline of the three-month and policy rate differentials at horizons beyond twelve months is consistent with QE shocks conveying signals about a future accommodative relative monetary policy stance, at least under the assumption that risk and liquidity premia are not affected by QE shocks at these horizons. The hypothesis of the signalling channel of QE in the case of the exchange rate is also supported by the finding that there remains a statistically significant residual expected depreciation of

[21] We impose that the policy rate differential does not react to QE shocks on impact by including on the right-hand side in the local projection regression of Equation (25) the contemporaneous policy rate differential as control. As a consequence, for $h = 0$ the fit of the local projection regression is perfect, with a coefficient estimate of unity on the contemporaneous policy rate differential, and a coefficient estimate of zero on the instrumented relative balance sheet change.

the euro vis-à-vis the US dollar well after 12 months. In particular, this finding implies that QE asset purchases have credibly signalled to market participants central banks' intentions to keep policy rates low in the medium term, possibly even after other central banks start to raise rates.[22]

To further investigate the relevance of the signalling channel, we examine two additional pieces of evidence. First, the left-hand side panel of Figure 5 reports the response of the two-year sovereign yield differential to the QE shock, and the right-hand side panel reports the corresponding expectations component.[23] The two-year differential essentially declines on impact in response to the relative QE shock, mostly driven by the response of the expectations component, which reflects expected future short-term and hence policy rates. Second, rather than looking at interest rates we consider as dependent variables in the local projections markets' expectations about the time until central banks will normalise monetary policy rates. To do so, we consider data on "time-to-lift-off" for the ECB and the Federal Reserve, defined as the number of months until the policy rate is expected to be raised by ten basis points, conditional on being at the effective lower bound.[24,25] The estimates presented in Figure 6 suggest that ECB QE shocks shifted markets' expectations regarding monetary policy normalisation farther into the future, with a one percentage-point increase in the relative central bank balance sheet persistently raising lift-off expectations by around half a month. Specifically, the results suggest that a doubling of the ECB's balance sheet — which is roughly what the ECB's APP achieved beteen 2015 and 2016 — relative to that of the Federal Reserve caused by QE shifted markets' expectations for monetary policy normalisation in the euro area by around four years into the future (100pp $\times 0.5$ months/pp $=50$ months). In contrast to the ECB, for the Federal Reserve the effects of QE shocks on "time-to-lift-off" are overall not statistically significant. Interestingly, these findings are consistent with differences in the communication of monetary policy between the ECB and the Federal Reserve. In particular, ECB communication emphasised that policy rates would remain unchanged well past the end of purchases under the APP, thereby directly linking lift-off expectations to the horizon of asset purchases. In contrast, the Federal Reserve placed more emphasis on the dependence of the path of monetary policy on the evolution of macroeconomic data. Overall, we interpret this evidence as suggesting that especially ECB QE shocks impacted

[22]One may wonder how policy rates could fall in response to QE shocks in the medium term, given that the ECB and the Federal Reserve were at their effective lower bounds for a considerable part of the time period we consider. However, notice that our estimates are average effects over the sample period, and that neither the ECB nor the Federal Reserve were at their effective lower bounds over the entire sample period. Partly reflecting the latter fact, an important caveat to the interpretation of this evidence in support of the signalling channel is that the point estimates of the policy rate differential are — except briefly after 15 months — not statistically significant at the 90% significance level.

[23]The two-year rate expectations components are obtained from the term-structure models of Joslin et al. (2011) for the euro area and Adrian et al. (2013) for the US.

[24]The data for "time-to-lift-off" are constructed using the EONIA forward and the Federal Funds futures curves. We assume that the effective lower bound is at -0.4% for the ECB and at 0% for the Federal Reserve. At every point in time t, the "time-to-lift-off" is determined as the distance to the future date at which the forward curve reaches -0.3% for the ECB and 0.1% for the Federal Reserve.

[25]We set to zero the value of "time-to-lift-off" for the time periods in which the ECB or the Federal Reserve were not at their effective lower bounds. Ideally, we would estimate the regression only for the time period in which the ECB and the Federal Reserve were at their respective effective lower bounds. However, the resulting sample especially in case of the ECB is too short to obtain meaningful estimates. A caveat is thus that these zeros potentially introduce bias in our least squares estimates (Wooldridge, 2010).

the exchange rate at least in part by "signalling" an accommodative monetary policy stance in the future.

Finally, while our estimates for the responses of the three-month interest and policy rate differentials are consistent in the sense that the former at every point in time reflects expectations of the latter over the subsequent three months, this is not the case at shorter horizons. In particular, at least in the first few months after the shock the point estimates of the response of the three-month differential fall by more than what would be implied by the point estimates of the response of the policy rate. A plausible explanation for the fall in the money-market rate differential, at least in the short term, is the impact of QE on frictions in money markets (Garcia-de-Andoain et al., 2016). In particular, the increased liquidity offered by the ECB or the Federal Reserve, when the demand for central bank reserves is not fully satiated, can compress liquidity premia of money-market rates, for example by reducing the balance sheet costs of banks (see Martin et al., 2013). A related possible explanation for the decline in money-market rate differentials in the absence of a corresponding decline in (future) policy rate differentials relates to the "flow effects" of QE, under which asset purchases under QE reduce interest rates in particular during periods of market stress when they are actually carried out (see D'Amico and King, 2013).

CIP deviation Recall the definition of the CIP deviation in Equation (6)

$$\lambda_t = r_t^{€} - \left(r_t^{\$} - f_{t,t+1} + s_t \right), \tag{31}$$

which coincides with that of the cross-currency basis, except for having the opposite sign (Du et al., 2018). Intuitively, according to our definition a positive value of the CIP deviation amounts to a euro cash rate that is larger than the synthetic euro rate (or a synthetic dollar rate that is larger than its cash counterpart); alternatively, for a given interest rate differential, one can think of a positive value of the CIP deviation as one euro having a lower dollar price in the forward market relative to the spot foreign exchange market than what CIP would imply. The panel in the bottom row of Figure 7 presents the estimated response of the CIP deviation to the relative ECB QE shock. CIP deviations rise by up to around half of a basis point for over six months in response to the relative QE shock, though this response is not always statistically significant at the 10% level. Our results thus imply that relative ECB QE shocks have contributed to the widening of the cross-currency basis over the sample period we consider, which is consistent with the findings of Sushko et al. (2016) as well as Du et al. (2018). In terms of the definition of CIP deviations as reflecting differential tightness of borrowing constraints in cash and synthetic dollar markets discussed in Section 3, the estimated increase in the CIP deviation implies that from a US investor's perspective a relative ECB QE shock further eases borrowing constraints in the synthetic dollar market relative to those in the cash market: The spot dollar relative to the forward dollar rate appreciates by slightly more than what is implied by the fall in the euro-dollar interest rate differential. The rationale for relative ECB QE shocks increasing the CIP deviation — or rendering more negative the cross-currency basis — typically alluded to in this context relates to an asymmetry between the demand and supply for foreign exchange swap contracts for high and low-yielding currencies. In particular, lower funding costs in the euro area caused by ECB QE shocks attract foreign borrowers, who desire to hedge their euro exposure and thereby increase the demand for swap contracts. Against the background of borrowing constraints or other frictions limiting the supply of such contracts and arbitrage opportunities, foreign borrowers accept a lower price for one euro in terms of US dollars in the forward market — i.e. a lower value of $f_{t,t+1}$ for a given s_t — than what CIP would imply.

Contributions of individual fundamentals to the overall exchange rate response Finally, we decompose the response of the exchange rate to QE shocks as outlined in Equation (12) into the contributions accounted for by the response of the euro-dollar short-term money market rate differential as well as the CIP deviation. Because we are using three-month interest rates and CIP deviations due to data availability restrictions, we need to consider a modified version of Equation (12), obtained by iterating forward the following generalised UIP condition

$$s_t = dr_{t,3} - \lambda_{t,3} + \pi_{t,3} + E_t s_{t+3}, \tag{32}$$

where $dr_{t,3}$ is the three-month interest rate differential, $\lambda_{t,3}$ is three-month CIP deviations and $\pi_{t,3}$ is the corresponding currency risk premium.[26] The contribution of currency risk premia is obtained as a residual, taking as given the estimates of the responses of the interest rate differential, the CIP deviation and the expected exchange rate at the terminal horizon T.[27]

The left-hand side panel in Figure 8 presents the decomposition based on point estimates, and the right-hand side panel presents the decomposition based only on those estimates that are statistically significant at the 90% significance level. While CIP deviations do not contribute much to effects of QE on the exchange rate, falling current and expected future interest rate differentials underpin the depreciation of the euro vis-à-vis the US dollar in response to the relative QE shock. Residual currency risk premia play a large role, in particular when we set to zero the impulse response estimates which are not statistically significant — most importantly, exchange rate responses at the terminal horizon. This large role of risk premia in the dynamics of exchange rates echoes the evidence from the classic studies of Engel and West (2010) as well as Engel (2016), who find that a large share of the variation in the dollar exchange rate is attributable to a residual risk premium component.

6 Robustness

In this section we present results of a battery of robustness checks. Specifically, we explore whether our findings change when we (i) weigh QE announcements with high-frequency surprises in asset markets; (ii) use data at weekly rather than monthly frequency; (iii) include more

[26]The terminal date T of expectations of $E_t s_{t+T}$ is different for horizons $T = 0, 3, 6, \ldots, 18$, horizons $T = 1, 4, 7, \ldots, 17$; and horizons $T = 2, 5, 8, \ldots, 16$.

[27]Notice that in contrast to the derivation of the local projection equation for the exchange rate, the decomposition of its impulse response does require that Equation (12) holds.

controls; (iv) generalise the definitions of QE shocks and (v) the relative balance sheet; (vi) consider only either ECB or Federal Reserve QE announcements. The results of the corresponding first-stage regressions are reported in Table 4, and the impulse responses of the euro-dollar exchange rate are depicted in Figure 9. In order to save space the corresponding responses of CIP deviations and the three-month money-market rate differential are relegated to an appendix available upon request.

6.1 Heterogeneity of QE measures and separating monetary policy from information shocks

There are several possible concerns with our choice of QE announcements and the use of announcement dummies. First, it could be that the QE measures underlying the announcements we consider are all different in magnitude; this issue relates to the notion that one would ideally use announcement dummies weighted by the announced amounts of asset purchases, as discussed already in Section 4.3. Not doing so in general implies a reduction of the power of the QE announcements we consider as instruments. Second, it could be that some of the QE measures we consider were expected by markets. In this case, even if the QE measures were announced in period t, one should conceive them as QE shocks in earlier periods $\eta_{t+m|t-s}$, $s > 0$. From an econometric point of view, this concern implies a violation of the assumption that $Cov(\eta_{t+m|t-s}, a_t^j) = 0$ for $s > 0$, which is required for instrument validity (see Equations (25) and (26)). And finally, it could also be that rather than being perceived as expansionary monetary policy shocks, some QE measures might have been perceived by market participants as a revelation of private information about adverse demand or financial shocks that central banks were aware of but markets were not (see Campbell et al., 2017; Miranda-Agrippino and Ricco, 2017; Nakamura and Steinsson, 2018). In this case, even if the QE measures were unexpected in period t, one should conceive them as central bank information shocks, i.e. non-QE structural shocks $\boldsymbol{e}_t$. This concern undermines the assumption that $Cov(\boldsymbol{e}_t, a_t^j) = 0$, which is also required for instrument validity (see Equations (25) and (26)).

Addressing these concerns requires to identify those QE announcements which were unexpected, not a revelation of private information of the central bank about adverse shocks, and to weight the QE announcements according to the size of the underlying purchase programs. In order to do so, we borrow from the literature on high-frequency identification of monetary policy shocks (see, for example, Rogers et al., 2014; Jarocinski and Karadi, 2018). Specifically, rather than Equation (27) we assume the following relation between unobserved QE shocks and announcements

$$\eta_{t+m|t} = \sigma_m + \mu_m^{\text{ECB}} \cdot \left[a_t^{\text{ECB}} \times \Delta e_t^{€} \times I(\Delta e_t^{€} > 0)\right] + \mu_m^{\text{Fed}} \cdot \left[a_t^{\text{Fed}} \times \Delta e_t^{\$} \times I(\Delta e_t^{\$} > 0)\right] + u_{t,m}, \quad (33)$$

where $\Delta e_t^{€}$ and $\Delta e_t^{\$}$ represent the changes in euro area and US equity prices on the day of QE announcements, and $I(\Delta e_t^{€} > 0)$ and $I(\Delta e_t^{\$} > 0)$ are indicator variables which equal unity when the equity price changes are positive and zero otherwise. First, considering only those QE announcements which were followed by a positive equity price response ensures that we distinguish expansionary QE shocks from negative central bank information shocks (Jarocinski and Karadi, 2018). Second, weighting by the size of the — positive — equity price response ensures that QE announcements which surprised the market have a greater impact on our estimates than announcements that were largely expected. Finally, to the extent that larger QE programs induce larger equity price movements, other things equal, weighting by the size of the equity price response also ensures that QE announcements on programs that were larger in size have a greater impact on our estimates. The third column in Tables 1 and 2 indicates that there are ten announcements for the ECB and six for the Federal Reserve that satisfy this restriction.

The results for the first-stage regression of this specification are reported in column (2) of Table 4, and the impulse responses of the exchange rate in the top left-hand side panel of Figure 9. The first-stage results are very similar to those from our baseline, even though the effective F-statistic drops below the 5% critical value, pointing to a slight loss in instrument power. Notably, the estimated coefficient of the ECB announcements implies that an announcement which was associated with a 1% increase in euro area equity prices on the day of the announcement raised the balance sheet of the ECB by 7.8 percentage points relative to that of the Federal Reserve over the following nine months. Analogously, the coefficient estimate for the Federal Reserve implies an increase in the relative balance sheet by 12.3 percentage points over the following nine months. The response of the nominal exchange rate to an ECB QE shock which raises the relative balance sheet by one percentage point is also very similar to the baseline, if anything showing a more persistent depreciation in the euro-dollar exchange rate.

6.2 Weekly data

Recall that in our baseline specification data frequency is monthly. We do not use weekly data in our baseline even if this would allow us to more accurately assign QE announcements to the respective time periods because weekly data are considerably more noisy. Column (3) in Table 4 reports the first-stage regression results for the specification with weekly data, and the top right-hand side panel of Figure 9 presents the corresponding estimated response of the exchange rate to the QE shock. In line with the baseline specification, in the first-stage regression the dependent variable is the growth rate of the relative balance sheet over 36 weeks. The results for both the first and second-stage regressions are again very similar to those of our baseline. As expected, the R-squared of the first-stage regression is lower. The response of the exchange rate is as large and as persistent as in the baseline.

6.3 Including additional macro variables or leads of the instruments as controls

Stock and Watson (2018) discuss a “lead/lag exogeneity” requirement for consistent estimation with local projections with external instruments. In particular, in general instruments need to be uncorrelated with future and past structural shocks, at least after including control variables. Applied to this paper this requires that QE announcements must be uncorrelated with past structural — such as demand and risk — shocks. To the extent that QE measures are a systematic response of central banks to adverse shocks, this requirement is unlikely to be satisfied. Although the derivation of our local projection regression equation from a structural equation for the exchange rate shows that in the particular context of this paper our estimation only requires that QE announcements are uncorrelated with contemporaneous and future structural shocks, we explore the robustness of our findings to the inclusion of variables as controls that proxy lagged structural shocks to which the QE announcements might respond to (Jorda et al., 2015; Stock and Watson, 2018). In particular, we include as additional controls the lags of the differential between euro area and US industrial production growth and consumer-price inflation.

Furthermore, Stock and Watson (2018) suggest that in order to improve efficiency one can include future values of the instruments as controls in the local projection regression. The underlying intuition is that the error term $\zeta_{t,h}$ defined in Equation (26) of the second-stage regression in Equation (25) includes future QE shocks. Given our identifying assumption reflected in Equation (30), these future QE shocks should be correlated with future QE announcements a_t^j. Hence, including future QE announcements as controls should reduce the variance of the error term in Equation (26), and therefore improve efficiency of estimation. Of course this is not necessarily to be expected to materialise in finite samples, such as the one we work with in this paper.

Column (4) of Table 4 reports the results for the first-stage regression of the specification with additional lagged macro variables as controls. As the first-stage results (at least for $h = 0$) are identical to those of the baseline specification when leads of QE announcements are added as controls, we do not report them in Table 4; for higher h, when h leads of the instruments are included as controls, the first-stage regression and test results are similar to the baseline. The corresponding impulse responses of the exchange rate are reported in the left-hand and right-hand side panels of the second row of Figure 9. The first-stage regression results are very similar to those of the baseline in the sense that we cannot reject the validity of the instruments and that there is no indication of weak instrument problems. The estimated responses of the nominal exchange rate to a relative QE shock are also very similar to the baseline.

6.4 Generalising the definition of the QE shock

Recall that in our baseline in Equation (22) we assumed that a QE shock is defined as

$$\varepsilon_t^{qe} = \sum_{m=0}^{M} \eta_{t+m|t}. \tag{34}$$

We can generalise this and assume

$$\varepsilon_t^{qe} = \sum_{m=0}^{M} \phi_m \eta_{t+m|t} \tag{35}$$

The intuition for this generalisation is that it may be plausible to assume that markets discounted expected future asset purchases. This could have been because given the unprecedented scope of

QE measures markets were not fully convinced whether the ECB and the Federal Reserve would indeed carry out the measures in the way they were announced. In this case, we would have $\phi_m > \phi_{m+1}$. In order to address this possibility while precluding proliferation of parameters, we assume geometric discounting, i.e. $\phi_m = \phi^m$. Under this assumption, the second-stage regression is given by

$$s_{t+h} - s_{t-1} = \alpha_h^{qe} \left(\sum_{m=0}^{M} \phi^m \Delta BS_{t+m} \right) + \omega_{t-1,h} + (M+1)\delta_0 + \zeta_{t,h}. \tag{36}$$

While it is not possible to separately estimate ϕ and α_h^{qe}, we can explore whether our results are sensitive to plausible values of ϕ. The results for the first-stage regression of this specification are reported in column (5) of Table 4 for $\phi = 0.8$, and the left-hand side panel in the third row of Figure 9 presents the corresponding response of the exchange rate to the QE shock. The results are very similar to those from the baseline.[28]

6.5 Generalising the law of motion of the relative central bank balance sheet

Recall that in our baseline specification we assume that the relative central bank balance sheet is a random walk process, which implies that shocks have permanent effects. In fact, it seems this is not too implausible an assumption practically, as with a value of .994 the estimate of the autoregressive coefficient in our data is virtually indistinguishable from unity. Nevertheless, instead of Equation (23) one could specify

$$BS_t = \delta_0 + \rho BS_{t-1} + \sum_{m=0}^{M} \eta_{t|t-m} + \boldsymbol{\delta}' \boldsymbol{e}_t. \tag{37}$$

We can then substitute the anticipated QE shock $\eta_{t+m|t}$ in the local projection of the exchange rate by

$$\eta_{t+m|t} = BS_{t+m} - \rho BS_{t+m-1} - \left(\delta_0 + \sum_{\substack{k=0 \\ k \neq m}}^{M} \eta_{t+m|t+m-k} + \boldsymbol{\delta}' \boldsymbol{e}_{t+m} \right),$$

to obtain

$$s_{t+h} - s_{t-1} = \alpha_h^{qe} \left(\sum_{m=0}^{M} BS_{t+m} - \rho BS_{t+m-1} \right) + \omega_{t-1,h} + (M+1)\delta_0 + \zeta_{t,h}. \tag{38}$$

In turn, the first-stage regression is then be given by

$$\sum_{m=0}^{M} BS_{t+m} - \rho BS_{t+m-1} = \varpi + \theta^{\text{ECB}} a_t^{\text{ECB}} + \theta^{\text{Fed}} a_t^{\text{Fed}} + \omega_{t-1,h} + \xi_t. \tag{39}$$

[28] Notice that because the variable of interest in the second-stage regression is $\sum_{m=0}^{M} \phi^m \Delta BS_{t+m}$ rather than $BS_{t+M} - BS_{t-1}$ as in our baseline, the impulse response cannot be interpreted anymore as the effect of a QE shock that increases the relative balance sheet by one percentage point.

While it is again not possible to separately estimate ρ and α_h^{qe}, we can explore whether our results are sensitive to plausible values of ρ. The results for the first-stage regression are reported in column (6) of Table 4 for $\rho = 0.95$, and the right-hand side panel in the third row of Figure 9 presents the corresponding responses of the exchange rate to the QE shock. The results are very similar to those of the baseline.[29]

6.6 Using only ECB or Federal Reserve QE announcements

In the baseline specification we implicitly assume that a change in the relative central bank balance sheet has the same effect on the exchange rate regardless of whether it is elicited by ECB or Federal Reserve QE shocks. Given the many differences in the QE policies carried out by the two central banks, it is not obvious that we should expect this to be the case. Columns (7) and (8) in Table 4 report the first-stage regression results for specifications in which we use either ECB or Federal Reserve QE announcements as instruments. Analogously, the last row in Figure 9 presents the estimates of the responses of the exchange rate to a QE shock that raises the ECB's balance sheet relative to that of the Federal Reserve, instrumented by either the ECB or the Federal Reserve announcement dummies. The estimates of the impulse responses are similar, suggesting that a change in the relative balance sheet impacts the exchange rate in a similar way regardless of whether it is elicited by an ECB or a Federal Reserve QE shock. If anything, the response of the exchange rate is somewhat greater when the relative balance sheet changes due to ECB QE shocks. However, as the effective F-statistics are below the relevant critical values, using only the announcements from one of the central banks might be associated with weak instrument problems. This again suggests that some of the evidence in the existing literature analysing the effects of ECB or Federal Reserve QE shocks *separately* might have to be taken with caution.

7 Concluding remarks

The exchange rate has been at the center stage of the discussion about the effectiveness, transmission channels and the spillovers from QE. Surprisingly, however, little research exists which is concerned with the estimation of the effects of QE on the exchange rate at frequencies and horizons that are relevant for policymakers and the calibration of structural models. This paper addresses this gap in the literature. In particular, we estimate the effects of QE measures by the ECB and the Federal Reserve on the US dollar-euro exchange rate at frequencies and horizons relevant for policymakers and structural models. We do so using two-stage least squares regressions of theoretically consistent local projections for the exchange rate, in which QE announcements serve as instruments for changes in the relative central bank balance sheet. Deriving the local projection regression equation from a structural equation for the exchange rate disciplines

[29]Notice again that because the variable of interest in the second-stage regression is $\sum_{m=0}^{M} BS_{t+m} - \rho BS_{t+m-1}$ rather than $BS_{t+M} - BS_{t-1}$ as in our baseline, the impulse response cannot be interpreted as the effect of a QE shock that increases the relative balance sheet by one percentage point.

the empirical specification we bring to the data, for example by pointing to possible sources of endogeneity, guiding the inference, the choice of control variables and their timing. We also pay great attention to model specification tests, including on instrument validity and power. We find that QE measures have large and persistent effects on the exchange rate, and that they materialise through a change in interest rate differentials, partly reflecting expectations of the future monetary policy stance. Nevertheless, our results suggest that the largest quantitative contribution stems from persistent effects of QE on risk premia in foreign exchange markets.

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A Tables

Table 1: ECB announcements of QE measures

Date	Event	Stock market response
07/05/2009	12-month SLTROs and other measures	-0.99%
04/08/2011	SLTROs and other measures	0.39%
06/10/2011	12/13-month SLTROs	2.74%
08/12/2011	36-month VLTROs and other measures	-2.09%
05/06/2014	Targeted longer term refinancing operations (TLTROs)	0.62%
04/09/2014	Announcement of ABSPP and CBPP3	0.73%
22/01/2015	Expanded Asset purchase programme (APP)	1.44%
05/03/2015	Implementation details of APP	0.65%
03/09/2015	Increase of PSPP's issue share limit	1.40%
10/03/2016	CSPP announcement	-0.98%
21/04/2016	CSPP starting date announcement and details	-0.30%
02/06/2016	CSPP Implementation details	0.07%
08/12/2016	Extension of APP	0.78%
26/10/2017	Extension of APP	0.75%

Note: The stock market response is the one-day change of the Eurostoxx 300 on the day of the announcements.

Table 2: Fed announcements of QE measures

Date	Event	Stock market response
28/01/2009	Fed stands ready to expand QE and buy Treasuries	1.62%
18/03/2009	LSAPs expanded	0.08%
27/08/2010	Bernanke suggest role for additional QE	1.04%
12/10/2010	FOMC members 'sense' 'additional accommodation appropriate'	-1.07%
15/10/2010	Bernanke reiterates Fed stands ready to further ease policy	-0.54%
03/11/2010	QE2 announced: Fed will purchase $600 bn in Treasuries	0.00%
22/08/2012	FOMC members 'judge additional accommodation likely warranted'	-0.60%
13/09/2012	QE3 announced: Fed will purchase $40 bn of MBS per month	0.67%
12/12/2012	QE3 expanded	0.42%

Note: The stock market response is the one-day change of the S&P 500 on the day of the announcements.

Table 3: First-stage regression results

	(1)	(2)	(3)
	$BS_{t+9} - BS_{t-1}$	$BS_{t+6} - BS_{t-1}$	$BS_{t+12} - BS_{t-1}$
ECB QE announcement	0.134***	0.117***	0.101*
	(3.46)	(5.18)	(1.79)
Fed QE announcement	-0.171***	-0.117***	-0.150**
	(-3.20)	(-3.26)	(-2.16)
Observations	98	101	95
Hansen-J (p-value)	1.00	0.74	0.97
Kleibergen-Paap-Test (p-value)	0.00	0.00	0.04
F-Stat (1st-stage)	11.98	23.03	4.05
Effective F-statistic	12.17	19.98	4.11
5% crit. value	5.62	8.28	6.13
10% crit. value	4.51	6.81	4.94
R-squared	0.70	0.69	0.71

t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 4: First-stage regression results for robustness checks

	(1) Baseline	(2) Weighted	(3) Macro	(4) $\phi = .8$	(5) $\rho = .95$	(6) Weekly	(7) ECB	(8) Fed
ECB QE announcement	0.134***	0.078***	0.099**	0.065***	0.067**	0.129***	0.162***	
	(3.46)	(2.74)	(2.37)	(4.32)	(2.51)	(4.68)	(4.21)	
Fed QE announcement	-0.171***	-0.123***	-0.169***	-0.051**	-0.140***	-0.195***		-0.197***
	(-3.20)	(-3.24)	(-3.17)	(-2.38)	(-3.35)	(-4.28)		(-3.80)
Observations	98	98	98	98	98	483	98	98
Hansen-J (p-value)	1.00	0.93	0.86	0.55	0.57	0.59	.	.
Kleibergen-Paap-Test (p-value)	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.02
F-Stat (1st-stage)	11.98	10.38	8.37	14.34	9.64	21.16	17.68	14.43
Effective F-statistic	12.17	9.81	8.50	13.00	9.92	19.96	17.68	14.43
5% crit. value	5.62	11.14	5.35	6.47	6.25	8.47	23.11	23.11
10% crit. value	4.51	9.40	4.27	5.23	5.01	6.97	19.75	19.75
R-squared	0.70	0.64	0.73	0.73	0.80	0.43	0.64	0.65

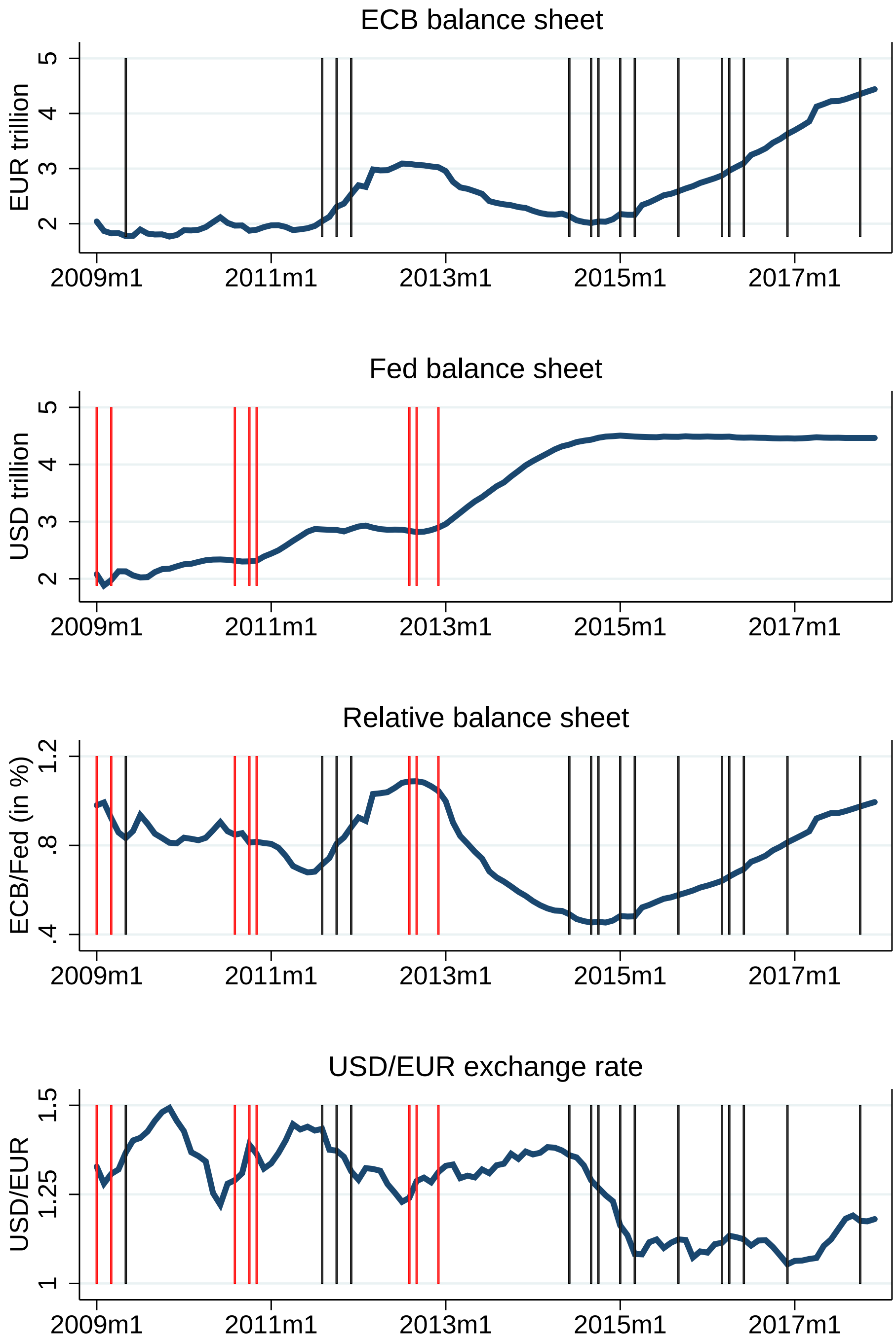
t statistics in parentheses

Standard errors robust to heteroskedasticity and serial correlation

$^{+}$ $p < 0.20$, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

B Figures

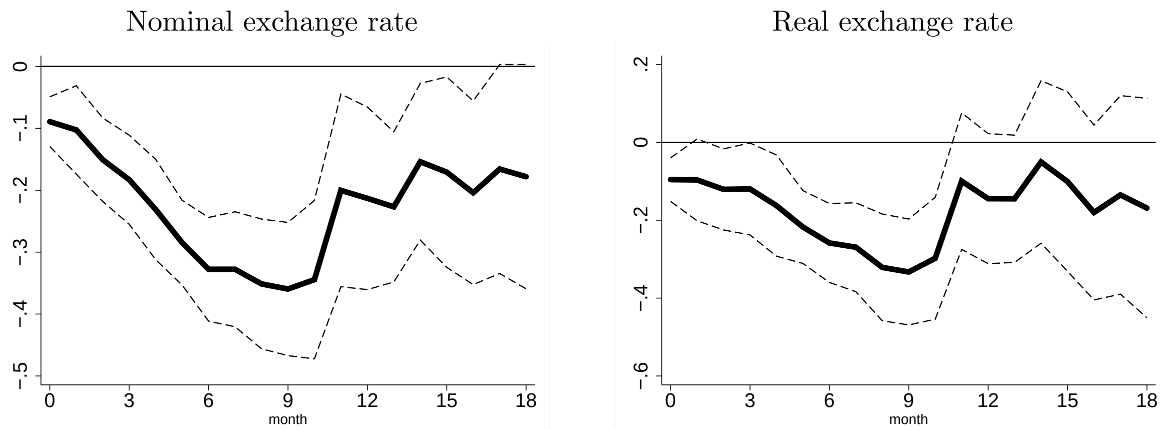
Figure 1: Balance sheet movements and QE announcements



Notes: The upper two panels of the figure show the evolution of the ECB's (top panel) and the Federal Reserve's (second from top panel) balance sheets. The second from the bottom panel shows the relative balance sheet (ECB/Fed). The bottom panel plots the USD/EUR exchange rate. Across all charts, the black (red) vertical lines indicate the dates of QE announcements by the ECB (Federal Reserve).

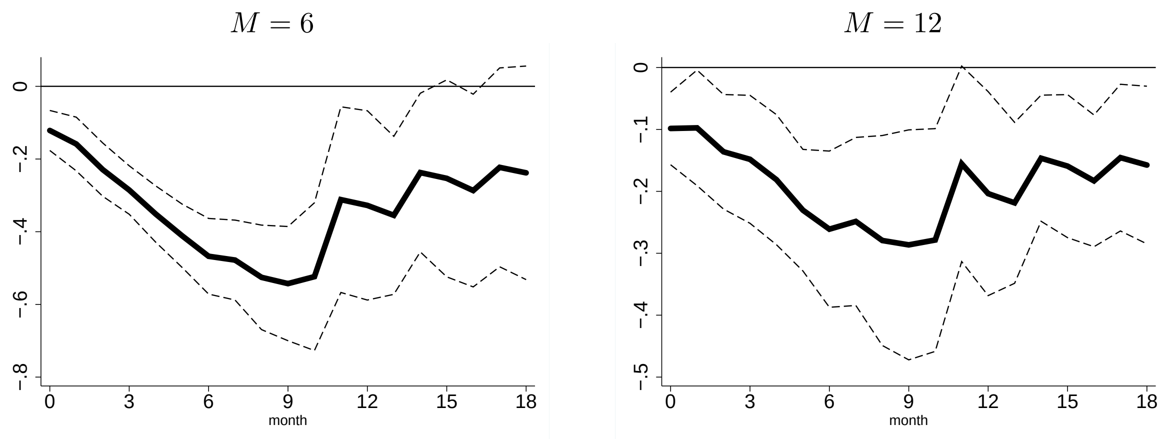
Figure 2: Exchange rate response to a relative QE shock

US dollar-euro exchange rate
(US dollar per euro, deviation from baseline in %)



Note: The figure presents the estimates of the response of the US dollar-euro nominal bilateral exchange rate to the relative QE shock that expands the ECB balance sheet relative to that of the Federal Reserve. The estimates are obtained from the two-stage least squares local projection regression in Equations (25) and (30). The dashed lines represent 90% confidence bands based on the fixed-b heteroskedasticity-autocorrelation (HAC) robust standard errors introduced by Kiefer and Vogelsang (2005).

Figure 3: Impulse responses of the exchange rate to a relative QE shock for $M = 6$ and $M = 12$

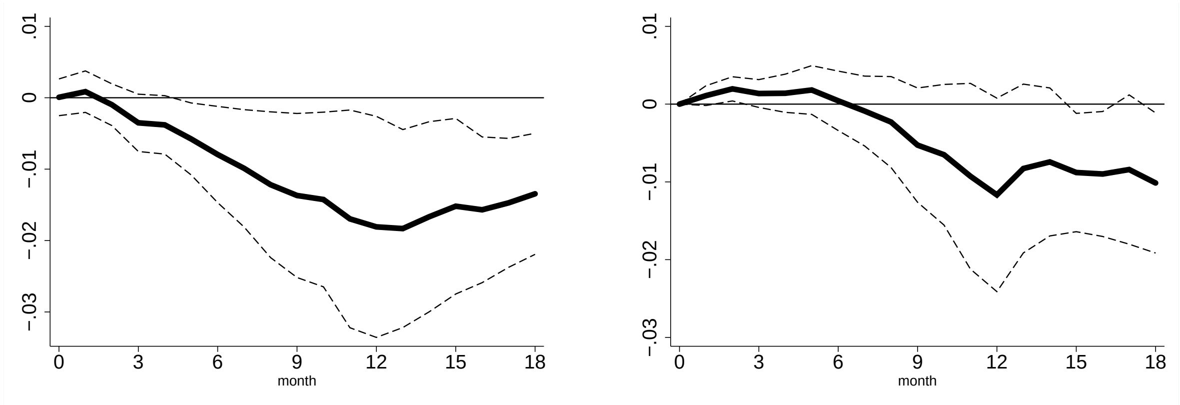


Note: See the note to Figure 2.

Figure 4: Impulse responses of the three-month money-market and the policy rate differential to a relative QE shock

Three-month money market rate differential $(r^{€,3m} - r^{\$,3m})$ (deviation from baseline in %-age points)

DFR - Fed Funds rate $(r^{€,dfr} - r^{\$,ffr})$ (deviation from baseline in %-age points)

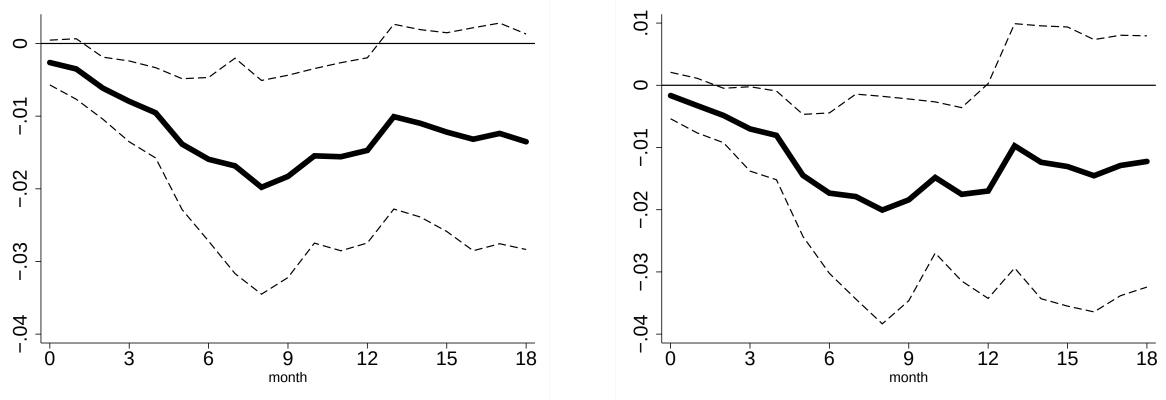


Note: See the note to Figure 2.

Figure 5: Impulse responses of the two-year sovereign yield differential to a relative QE shock

Two-year sovereign yield differential (deviation from baseline in %-age points)

Two-year expectations component differential (deviation from baseline in %-age points)

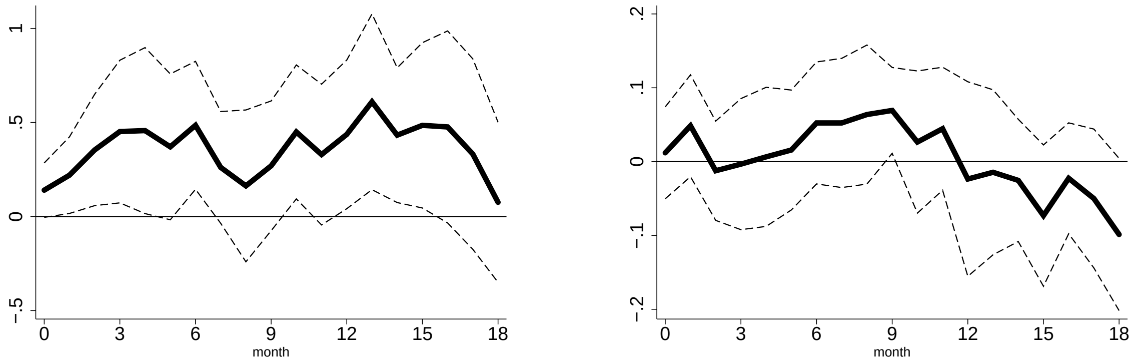


Note: See the note to Figure 2.

Figure 6: Time-to-lift-off responses to the QE shock

ECB "time-to-lift-off"
(expected months to reach -30bps)

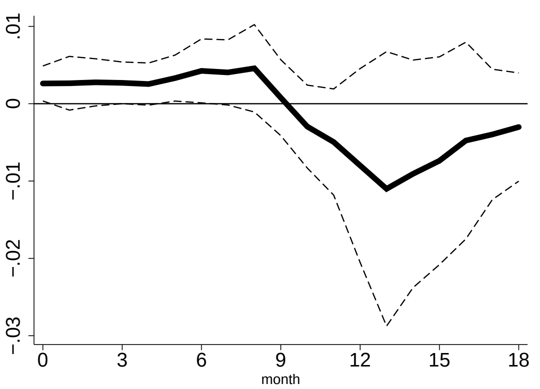
Federal Reserve "expected-time-to-zero"
(expected months to reach 10bps)



Notes: The figure presents the responses of "time-to-lift-off" for the ECB and the Federal Reserve to a relative QE shock that expands the ECB's balance sheet relative to that of the Federal Reserve by one percentage point. See also the note to Figure 2.

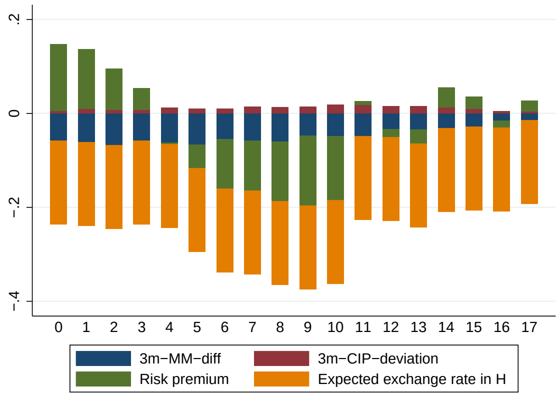
Figure 7: Impulse responses of the CIP deviation to a relative QE shock

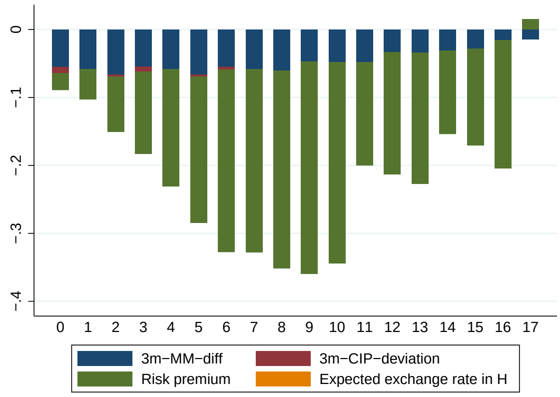
CIP deviation
$(\lambda_t = f^{3m}_{t,t+1} - s_t + r^{€,3m}_t - r^{\$,3m}_t)$
(deviation from baseline in %-age points)



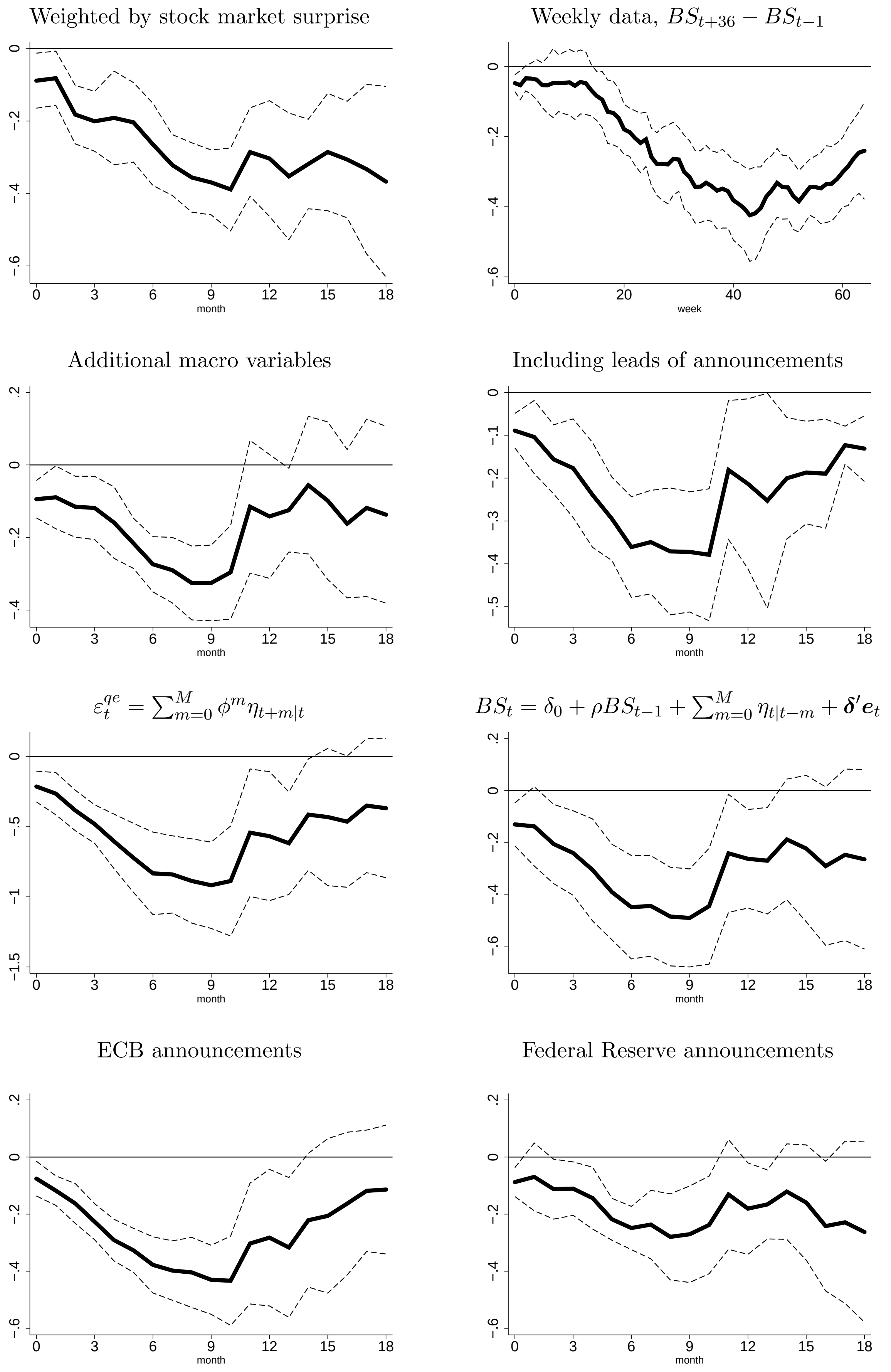
Note: See the note to Figure 2.

Figure 8: Decomposition of exchange rate response to QE shocks





Notes: The panels show the decomposition of the exchange rate effect of a relative QE shock that increases the difference between the growth rates of the ECB's and the Federal Reserve's balance sheets by one percentage point into the transmission channels according to Equation (12). The left-hand side panel presents the decomposition based on the point estimates of the relevant responses, regardless of whether these are statistically significant or not. The right-hand side panel presents the decomposition using only the estimates of the relevant impulse responses which are statistically significant at the 90% significance level, replacing the estimates which are not statistically significant by zero.



Note: See the note to Figure 2.

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