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

Gernot J. Müller, Martin Wolf and Thomas Hettig

A1. Empirical Analaysis

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

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

Baseline VAR. — In Figure A2 in this appendix, we report impulse responses of all variables to the monetary policy shock in our baseline VAR (see Section I.A). We find that our cleansed measure of Romer and Romer shocks produces sensible results for all variables included in the VAR. The upper-left panel shows that industrial production declines and displays a distinct hump-shaped pattern, familiar from earlier work on the monetary transmission mechanism (Christiano et al., 1999). We observe a maximum effect after about one year, when industrial production has declined approximately 0.7 percent relative to its pre-shock level. The upper-right panel shows the response of the consumer price index. Initially, prices adjust sluggishly. We observe a significant decline of prices only after about 8-10 months, again a familiar finding of earlier studies. However, the price level continues to decline markedly afterwards. The middle-left panel shows the response of the unemployment rate. Unemployment raises markedly after the shock, with a maximum effect of a 0.2 percentage points higher unemployment rate about 1 year after the shock. The middle-right panel shows the commodity price index. It declines markedly following the shock, by about 2 percent after 2 years. In turn, the panels in the last row show the responses of the interest rate differential and the spot exchange rate, and have been discussed in the main text (see Section I.B).

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

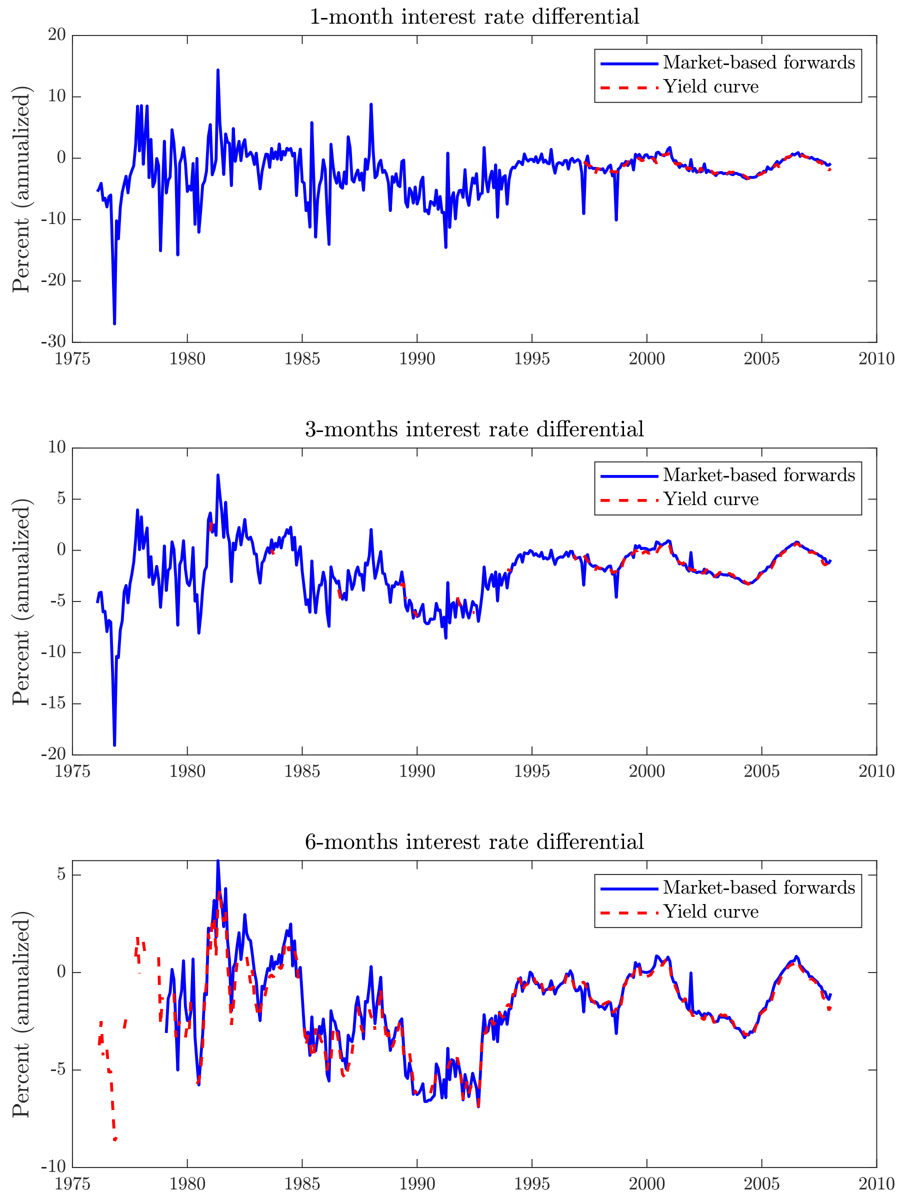

FIGURE A1. COMPARING MARKET-BASED AND YIELD-CURVE-IMPLIED FORWARDS.

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

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

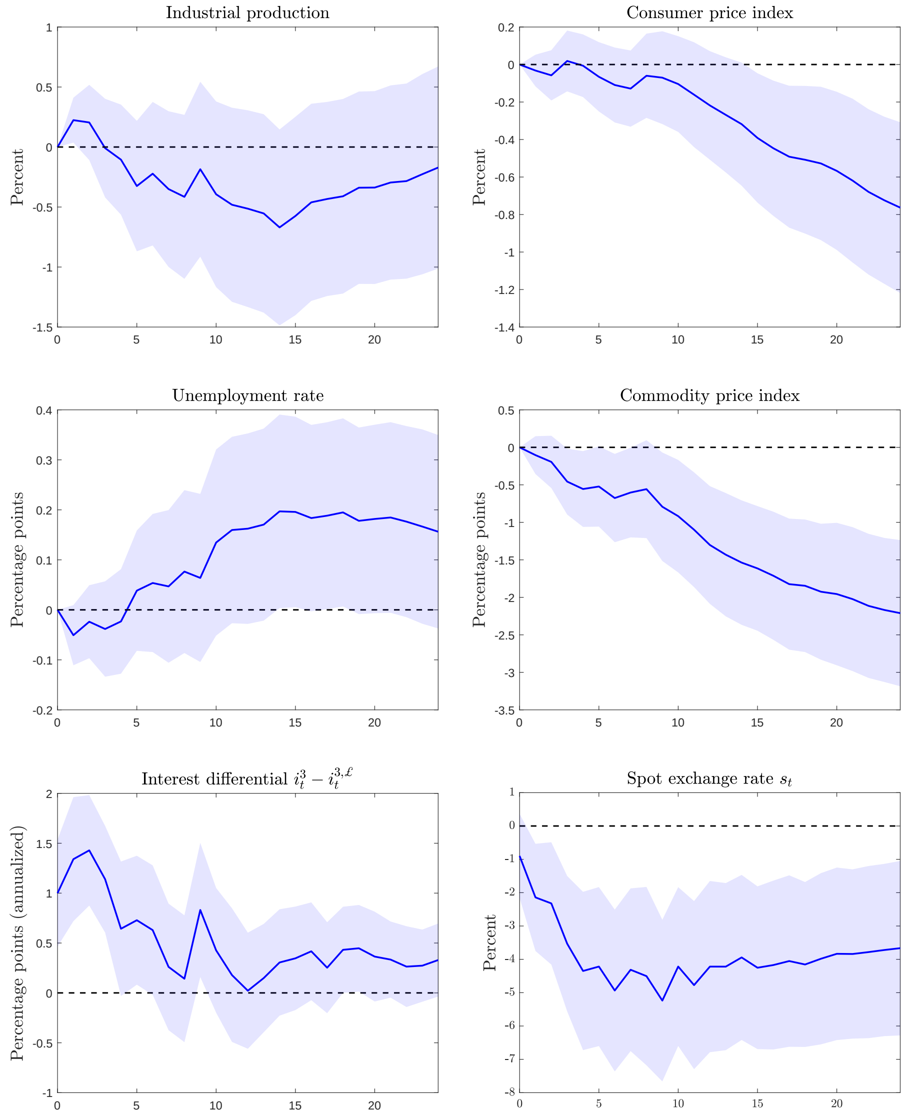

Figure A2. Responses to Monetary Policy Shocks

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

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

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

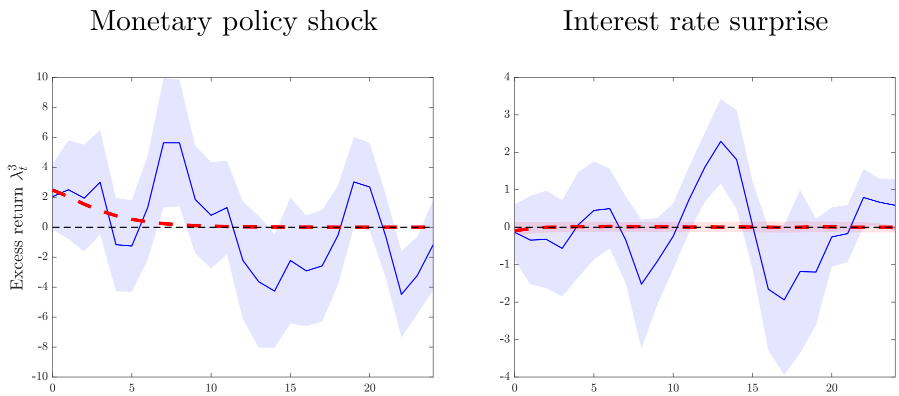

Figure A3. Response of Excess Return

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

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

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

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

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

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

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

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

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

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

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

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

where we denote $a_t = \log(A_t)$. The signal is the same for all firms, in line with our assumption that firms have common information.

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

Phillips curve

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Combining this with (A.11), we obtain

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

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

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

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

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

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

To derive the uncovered interest parity (UIP) condition, **equation** (11), from the main text, first combine (A.8) and (A.9) to obtain a relationship between c_t, p_t^C and s_t

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

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

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

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

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

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

Combining both yields equation (13).

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

The Taylor rule, **equation** (12), is given by the linear expression defined in the main text.

We assume that u_t and y_t^n, where y_t^n is defined in equation (A.12), follow the stochastic processes given in **equations** (15) **and** (16).

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

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

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

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

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

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

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

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

The signal $\varsigma_{1,t}$, which is **equation** (18) in the main text, is given by combining equations (A.3) and (A.12)

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

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

Finally, the signal $\varsigma_{2,t}$, which is **equation** (19) in the main text, is a direct implication of combining equations (12) and (17), both of which we derived before.

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