

New evidence on monetary transmission: interest rate versus inflation target shocks*

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Abstract

We present empirical evidence on monetary transmission from estimated New Keynesian and empirical VAR models, that allow for a standard nominal interest rate shock and an inflation target shock. In response to the highly persistent inflation target shock we largely find evidence of a Neo-Fisher effect: the nominal interest rate co-moves positively with inflation and output. In an estimated model version where agents have imperfect information about the nature of monetary shocks, Neo-Fisherian effects arise only with a lagged effect and not in the immediate short-run, because, in such case, inflation expectations do not adjust immediately to the target shock.

Keywords: Monetary policy; Neo-Fisher effect; Time-varying inflation target; DSGE; VAR; full information; imperfect information; learning

JEL-Codes: E12, F31, E52, E58

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1 Introduction

For a long time researchers interested in understanding the monetary transmission mechanism have studied temporary shocks to the nominal interest rate. In theoretical New Keynesian models, monetary policy shocks are typically captured by a temporary shock to the Taylor rule; similarly, in empirical vector autoregressive (VAR), a monetary policy shock is understood as a temporary innovation to the short-term nominal interest in the VAR system. This type of monetary policy shock, however, provides an only incomplete description of the monetary stance. The large and persistent swings in inflation in US post-war data likely reflect also changes in monetary conduct of more permanent and systematic nature, that a current active academic and policy debate on the existence of Neo-Fisher effects deems important in understanding inflation dynamics. The Neo-Fisherian hypothesis postulates that, in response to permanent monetary policy shocks, the nominal interest rate is positively associated with inflation and economic activity, already in the short run. It thus challenges the conventional view that low nominal interest rates are necessarily expansionary and associated with increases in inflation; the argument put forward is that central banks may need to raise interest rates to raise inflation, and that, similarly, extended periods of low interest rates may be deflationary (cf. Cochrane (2016); Williamson (2016); Uribe (2018); Cochrane (2018)).

In the theoretical frameworks of dynamic stochastic general equilibrium models one way to capture such long-term natured monetary policy shifts is to allow for a time-varying inflation target (cf. Ireland (2007); Cogley et al. (2010)). Alternatively, more recent contributions explicitly include permanent nominal interest rate shocks in the theoretical model framework, in addition to the conventional temporary nominal interest rate shocks (cf. Uribe (2018); Cochrane (2018)). We follow the first strand of the literature and estimate the established small-scale New Keynesian model of Ireland (2007) and Cogley et al. (2010) with Bayesian methods to derive impulse responses to the two types of monetary policy shocks: (i) the standard nominal interest rate shock and (ii) a persistent inflation target shock. We do so for a model version where agents have rational expectations and full information about the nature of monetary policy shocks, but also for a model version where agents have imperfect information about the type of the monetary policy shock. In the latter version, private agents have limited information about the central bank's objectives and need to learn the nature of the monetary shock over time to disentangle persistent shifts in the inflation target from transitory disturbances to the monetary policy rule, as in Erceg and Levin (2003). The assumptions on full versus imperfect information have im-

portant bearings for how agents form their inflation expectations, which is at the heart of the question of whether a persistent monetary policy shock like an inflation target increase results in a Neo-Fisher effect. In particular, in the estimated model under full information a target shock raises inflation expectations and thus actual inflation immediately, and the nominal interest rate and economic activity rise, providing evidence in favor of a Neo-Fisher effect. In the case of the estimated model under imperfect information, inflation expectations (and actual inflation) adjust upward only with a lag in response to the target increase, so that interest rates co-move negatively with inflation and output initially, and Neo-Fisherian effects come into play only with a lag of about four to five quarters. In addition to our DSGE-based analysis we provide evidence from empirical VAR models, where we augment a widely-used small-scale monetary VAR on output growth, inflation and the nominal interest rate¹ with a low-frequency measure of inflation, with the goal to capture the inflation target shock. For this purpose we use a number of alternative measures: we consider the off-the-shelf measure of the Federal Reserve Board’s own inflation target estimate (cf. Brayton et al. (2014)); long-run inflation forecasts from the Survey of Professional Forecasters; the DSGE-based implicit inflation target series obtained as a side-product from the Bayesian estimation of our New Keynesian model; or measures of the trend inflation component from purely empirical models. Using this empirical framework, we are, similarly to the theoretical model, able to study the transmission of a persistent monetary shock by looking at the responses to an innovation of our measure that proxies the inflation target – in addition to the standard nominal interest rate shock. For all measures considered, as well as for all different time-splits over subsample periods, we find that, in response to a target shock, inflation and the nominal interest rate both rise, even in the short-run, while output typically expands.

Our paper builds on and connects to a large literature that has deemed a time-varying inflation target important in understanding macroeconomic dynamics, particularly inflation dynamics.² It is also one way to reflect and capture long-term shifts in monetary policy, and, in particular, is an alternative to the route taken by Uribe (2018), who explicitly distinguishes between temporary and permanent interest rate shocks. Our paper thus also more narrowly connects to a new wave of macroeconomic studies on Neo-Fisherian effects

¹See, e.g., Sims (1980); Lütkepohl (1991, 1999); Watson (1994); Waggoner and Zha (1999)

²On the theoretical side, prominent examples include Ireland (2007); Cogley et al. (2010), Erceg and Levin (2003), Smets and Wouters (2003), De Graeve et al. (2009), De Michelis and Iacoviello (2016). On the empirical side Kozicki and Tinsley (2005), Andrieu and Bruha (2014), Mumtaz and Theodoridis (2018) and Bauer and Rudebusch (2017).

(Cochrane (2016); Williamson (2016); Uribe (2018); Schmitt-Grohè and Uribe (2018)). To gain an understanding of the key insights of these studies, let us first review the economic consensus on the monetary transmission mechanism even prior to these studies.

In particular, according to theory, a temporary shock, such as a temporary increase in the short-term interest rate, indisputably decreases inflation in the short run, but has no long run effects. Similarly, it is also quite undisputed that there is empirical evidence for the existence of a Fisher effect, according to which in the long run inflation moves one-to-one with the nominal interest rate, while the real interest rate is determined by non-monetary factors. There is less consensus, and this is the topic of debate of this recent literature whether a permanent monetary policy shock leads to a positive co-movement of the nominal interest rate and inflation *already in the short-run*, which is dubbed the Neo-Fisher effect. The debate up until recently exists mostly on theoretical grounds. Theoretical models where agents have rational expectations typically deliver strong support for a Neo-Fisher effect: agents fully understand when a raise in the interest rate is permanent, and, accordingly, adjust their inflation expectation upwards. Interest rates, actual inflation, and output –because of a drop in real rates– all increase. However, a number of contributions criticize this view and are much more sceptical about the existence of a Neo-Fisher effect (García-Schmidt and Woodford (2018); Evans and McGough (2018); Garin et al. (2018)): if agents do not fully understand that a given interest rate increase reflects a permanent change, but need to learn about the nature of the interest rate increase (temporary or permanent) over time, such as under adaptive learning, inflation expectations may not react the same way.^{3,4}

Given this theoretical ambiguity, we consider it particularly important to provide empirical insights on the matter. Prior to us, there are only few empirical contributions on the Neo-Fisher effect, among which, most prominently, is Uribe (2018). He constructs both an empirical VAR model and a theoretical DSGE model with temporary and permanent monetary shocks (as well as temporary and permanent non-monetary shocks). He finds support for the Neo-Fisher effect, in that a shock that permanently increases the nominal interest rate is associated with a rise in inflation and output.⁵ We obtain similar results in response

³A similar point has been made already in contributions on the period of the Volcker disinflation. In particular, Erceg and Levin (2003) show that in a model where private agents have limited information about the central bank’s objectives and need to disentangle persistent shifts in the inflation target from transitory disturbances to the monetary policy rule, output costs of disinflation are substantially higher.

⁴The theoretical discussion also makes clear that central bank communication has an important role to play. When central banks inform the public about the nature of a policy shift, this should help contribute to affecting inflation expectations accordingly.

⁵Uribe finds permanent monetary policy shocks very important for inflation dynamics, attributing more

to a shock that increases the inflation target, which –for most of our specifications– similarly leads to a rise and positive co-movement of interest rates and inflation and output. While we thus obtain similar results compared to Uribe (2018), we want to emphasize two major differences compared to his approach. The first difference is methodological, but this should be seen as an advantage: reaching similar conclusion despite the different methodological approach corroborates the evidence in favor of the existence of a Neo-Fisher effect. In particular, our methodological approach is to take the inflation target as the measure that captures long-term monetary policy shifts, a conventional approach to understand low-frequency inflation dynamics, following the long tradition of DSGE models with time-varying inflation target. This approach allows us to use very standard and simple methodological frameworks also in the empirical VAR specification, connecting directly to one of the most widely used framework in which monetary transmission has been studied in economics empirically: a VAR in output growth, inflation, and nominal interest rate, now augmented by a proxy for the inflation target process. Instead, Uribe in his empirical model with temporary and permanent monetary (and non-monetary) shocks imposes (and needs to impose) much more structure on the VAR.⁶ The advantage of our approach is that we do not need to impose any assumptions (e.g. on the causality of the long-run Fisher effect running from interest rate to inflation), but are able to let the data speak in a more direct way. A second difference, and a major novel contribution over and above the existing work by Uribe (2018), is that we provide empirical evidence on the Neo-Fisher effect in a framework that explicitly addresses the critical theoretical literature arguing against the existence of a Neo-Fisher effect: in our estimation of the New Keynesian model with imperfect information we explicitly account for the fact that agents in the economy cannot distinguish between different types of monetary shocks (short-term or long-term natured) but need to learn their nature over time. Our findings show that, indeed, this is consequential also for the evidence on the Neo-Fisher effect, as emphasized in the theoretical discussions. A Neo-Fisher effect, in the sense of positive co-movement of nominal interest rates with inflation (and output) does arise in the ‘short-run’, but not immediately, only with a lag of around five quarters, once agents have sufficiently learnt about the monetary disturbance being a target shock.

Our paper is also closely related to the papers by Kozicki and Tinsley (2005), De Miche-

than 40% of the variation in inflation to permanent monetary shocks.

⁶While elegant and plausible, identification in his setup requires much more assumptions, namely that output is cointegrated with the nonstationary non-monetary shock, that inflation and the interest rate are cointegrated with the nonstationary monetary shock, and that temporary monetary policy shocks are allowed to produce only theory-consistent output and price responses via imposing sign restrictions.

lis and Iacoviello (2016) and Mumtaz and Theodoridis (2018). Before the advent of the discussion on the Neo-Fisher effect, Kozicki and Tinsley (2005) propose an empirical model in which they similarly distinguish between target shocks and transitory perturbations to the short-term interest, confirming that sizeable movements in inflation are attributable to (perceptions of) shocks in target inflation. De Michelis and Iacoviello (2016) study Japan’s experience with increasing the inflation target during a liquidity trap, in an empirical and theoretical setting. In their theoretical model, they emphasize the importance of imperfect credibility in explaining the behavior of real and nominal variables. Mumtaz and Theodoridis (2018) study the macroeconomic dynamics of an inflation target shock. In their SVAR, they identify an inflation target shock as VAR innovations that make the largest contribution to future movements in long-horizon inflation expectations. Despite our much simpler setup, the resulting behavior of inflation, nominal interest rate and output (growth) is qualitatively the same.

The paper is organized as follows. In section 2 we provide a brief description of the New Keynesian model that we take to the data, in its full information and in its imperfect information version. We discuss Bayesian impulse responses and implied inflation target series from the estimated models. Section 3 discusses the VAR model and the data used to estimate it, with particular emphasis on the various measures used as a proxy for the central bank’s implicit inflation target. Section 3.4 lays out our main empirical results and extensive sensitivity analysis. Finally, section 4 concludes.

2 Evidence from an estimated New Keynesian model

2.1 A model with temporary interest rate and inflation target shocks

To motivate a theoretical New Keynesian model that accounts for a time-varying inflation target consider Figure 1, which plots the time paths of various inflation measures for the U.S. economy over the period 1947-2019. Inflation exhibits large and persistent swings, reaching levels of above 10 percent annually in the period of the Great Inflation in the 1970s and early 1980s, falling to substantially lower levels during the 1980s and 1990s in the Great Moderation, and falling further in and succeeding the period of the Great Recession. Observing these large swings one is reminded of the famous quote by Milton

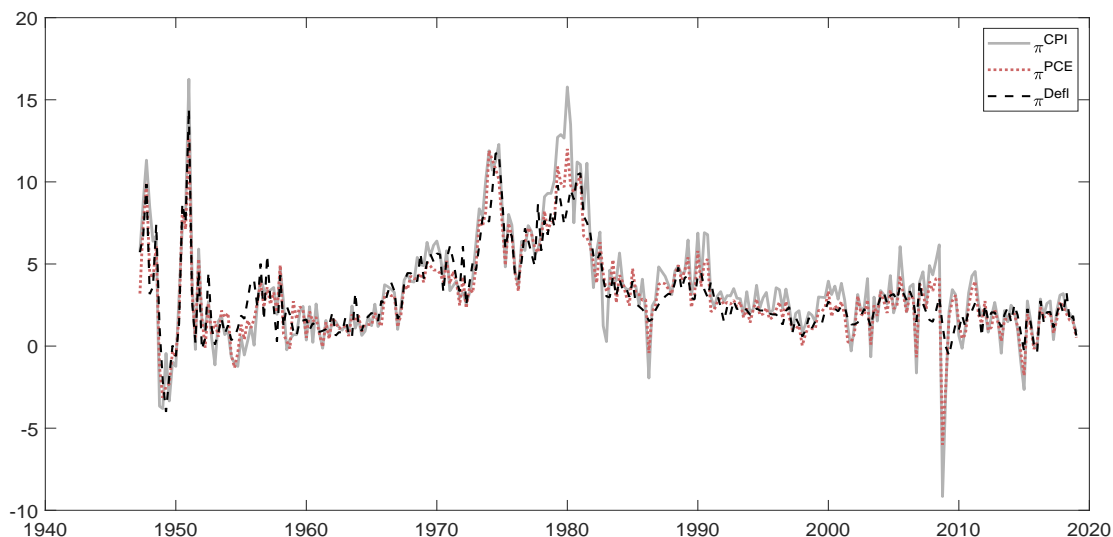


Figure 1: Inflation dynamics for the US economy from 1947Q2 to 2019Q1. Grey line: CPI-based inflation. Red dotted line: PCE-based inflation. Black dashed line: GDP deflator

Friedman (1968, p.39) that "inflation is always and everywhere a monetary phenomenon": while fluctuations in inflation at any point in time may reflect a myriad of factors, such as reactions to purely temporary shocks, large and persistent movements in inflation typically reflect the conduct of monetary policy. The economics discipline has spent considerable efforts to understand these swings in inflation dynamics, estimating an underlying inflation target process or trend inflation, both with theoretical, dynamic stochastic general equilibrium (DSGE), models as well as with empirical models.

This section adopts and extends the influential contribution of Ireland (2007) and Cogley et al. (2010), who model the central bank's inflation target as a time-varying process in a small-scale New Keynesian model. In the model monetary policy shocks thus take on two forms: (i) a temporary interest rate shock, or (ii) an inflation target shocks with a long-lasting effect. We estimate the model with Bayesian methods, to be able to provide empirical evidence on the relevance of the two types of monetary shocks, and on the existence of a Neo-Fisher effect in response to the persistent monetary policy shock. To address the controversies and ongoing discussions on the existence of a Neo-Fisher effect in the theoretical literature, we estimate the model in two versions: in a model version where agents have full information and in a version where agents have imperfect information and need to learn the nature of a monetary policy change. The estimated models are then

used to derive impulse responses to the two types of monetary policy shocks. In addition, we use the model to obtain an estimate for the implicit central bank’s inflation target measure, the main, generally unobserved, determinant in inflation trends, which we later employ, among other measures, in the VAR model of section 3. We choose to stick to a small-scale theoretical model⁷, both for the sake of simplicity but also to be consistent with our later empirical setup, i.e. we only use the same three macroeconomic time series for the estimation of our trend inflation measure from the DSGE model that we will later use in our VAR.

Because the model is standard and has been previously employed in the literature we relegate readers to the Appendix for a complete model description and here focus on laying out the key aspects only (see Appendix A.1). In particular, the model is a standard New Keynesian setting, in which monopolistically competitive firms face nominal rigidities and produce with a labor-only production technology. Households derive utility from consumption –assumed to be of the habit form– and disutility from working. The monetary authority is modelled as setting the short-term nominal interest rate according to a Taylor rule of the form (in log-linearized terms):

$$\widehat{R}_t = \rho_R \widehat{R}_{t-1} + (1 - \rho_R) \left[\rho_\pi (\widehat{\pi}_{4,t} - \widehat{\pi}_t^*) + \rho_Y (\widehat{Y}_t - \widehat{Y}_t^{flex}) \right] + u_t, \quad (1)$$

where for any variable, \widehat{X}_t denotes percentage deviations from its steady state, i.e., $\widehat{X}_t \equiv \log(X_t/X)$. R_t is the nominal interest rate, $\widehat{\pi}_{4,t}$ is actual average inflation over the year, defined as $\widehat{\pi}_{4,t} \equiv (\widehat{\pi}_t + \widehat{\pi}_{t-1} + \widehat{\pi}_{t-2} + \widehat{\pi}_{t-3})/4$, π_t^* is the time-varying inflation target, Y_t is the output level, Y_t^{flex} is the output level in a hypothetical flexible price economy, and u_t captures a (temporary) shock to the policy rate. In the simplest case, as adopted by Cogley et al. (2010), $\rho_u = 0$ and u_t can directly be understood as the disturbance $\varepsilon_{R,t}$. More generally, u_t is described by the exogenous process:

$$u_t = \rho_u u_{t-1} + \varepsilon_{R,t}, \quad \varepsilon_{R,t} \sim N(0, \sigma_R^2). \quad (2)$$

According to the above rule the central bank considers three factors in deciding on the current nominal interest rate: (a) the previous value of the nominal interest rate R_{t-1} , i.e. there is interest rate smoothing; (b) the output gap, defined as the deviation of the actual level of output, Y_t from its potential, i.e. the level of output that would prevail in

⁷Other contributions (e.g. De Graeve et al. (2009) or Smets and Wouters (2003)) use medium-scale DSGE models or more elaborate approach to model the way inflation target counteracts with monetary policy (e.g. Fève et al. (2010))

an economy with flexible prices, Y_t^{flex} ; and (c) the inflation gap, defined as the deviation of inflation, $\bar{\pi}_{4,t}$, from the target inflation, π_t^* .

The key aspect of the Taylor rule described here, and in contrast to the more standard Taylor rule featured in a standard textbook treatment of the New Keynesian model such as, e.g., described in chapter 3 of Galí (2008), the inflation target, π_t^* , is not required to be fixed at a constant level, but is allowed to be time-dependent and vary over time according to following exogenous process for π_t^* :⁸

$$\log \pi_t^* = (1 - \rho_{\pi^*}) \log \pi + \rho_{\pi^*} \log \pi_{t-1}^* + \varepsilon_{\pi^*,t}, \quad \varepsilon_{\pi^*,t} \sim N(0, \sigma_{\pi^*}^2). \quad (3)$$

To introduce the full information versus the imperfect information version of the model, let us rewrite the above Taylor rule, equation (1), slightly as:

$$\widehat{R}_t = \rho_R \widehat{R}_{t-1} + (1 - \rho_R) \left[\rho_{\pi} (\widehat{\pi}_{4,t}) + \rho_Y (\widehat{Y}_t - \widehat{Y}_t^*) \right] + \varepsilon_t, \quad (4)$$

and define

$$\varepsilon_t \equiv (1 - \rho_R) (-\rho_{\pi}) \widehat{\pi}_t^* + u_t. \quad (5)$$

When agents are rational and have full information, agents in the economy observe both $\widehat{\pi}_t^*$ and u_t individually, and fully understand what is behind an interest rate movement at any point in time. Under imperfect information, while agents are still rational, they are only able to observe ε_t , but cannot observe $\widehat{\pi}_t^*$ and u_t individually. However, they learn over time what is behind a particular observed movement in ε_t , that varies the interest rate. In particular, their learning problem is a linear problem, featuring an observation equation, $o_t = H' \xi_t$, and a state transition equation, $\xi_{t+1} = F \xi_t + B \varepsilon_{t+1}$, so that the learning problem can be described using the Kalman filter:

$$\underbrace{\begin{pmatrix} \varepsilon_t \\ o_t \end{pmatrix}}_{o_t} = \underbrace{\begin{bmatrix} (1 - \rho_R) & (-\rho_{\pi}) & 1 \end{bmatrix}}_{H'} \underbrace{\begin{pmatrix} \widehat{\pi}_t^* \\ u_t \end{pmatrix}}_{\xi_t}, \quad (6)$$

$$\underbrace{\begin{pmatrix} \widehat{\pi}_{t+1}^* \\ u_{t+1} \end{pmatrix}}_{\xi_{t+1}} = \underbrace{\begin{bmatrix} \rho_{\pi^*} & 0 \\ 0 & \rho_u \end{bmatrix}}_F \underbrace{\begin{pmatrix} \widehat{\pi}_t^* \\ u_t \end{pmatrix}}_{\xi_t} + \underbrace{\begin{pmatrix} \varepsilon_{\pi^*,t+1} \\ \varepsilon_{R,t+1} \end{pmatrix}}_{\varepsilon_{t+1}}, \quad (7)$$

⁸In particular, in the standard New Keynesian model of, e.g., Galí (2008), the central bank aims at eliminating the distance between the actual inflation and a constant inflation target. Moreover, the steady state inflation is often assumed to be constant at a net rate of zero. However, this does not have a direct correspondence in practice. The setting in equations (1)-(3) provide an empirically more suitable generalization.

where we denote with Q the variance-covariance matrix of the innovation $B\epsilon_{t+1}$, $Q = BB' = \begin{bmatrix} \sigma_{\pi^*}^2 & 0 \\ 0 & \sigma_R^2 \end{bmatrix}$.

We estimate the DSGE model using Bayesian methods using three observable time series: real output growth, inflation, expressed as the quarterly change in the consumer price index, and the 3-months Treasury Bill rate. We use U.S. data from 1947Q2 to 2019Q1, taken from the Federal Reserve Bank of St. Louis database. We refer the reader to Appendix A.4 for a table that summarizes prior choice (where we largely follow Cogley et al. (2010)) and the parameter estimates of both the full information and imperfect information versions of our New Keynesian model. Here, we only want to briefly comment on the estimation results of the inflation target process. In both model versions we find a very high autoregressive coefficient, ρ_{π^*} , equal to 0.9908 (0.9918) and a low standard deviation, σ_{π^*} , of 0.1146 (0.0828) in the full (imperfect) information version.⁹ These statistical properties of our inflation target process imply that target shocks can indeed be viewed as long-term natured monetary policy shifts, even though it should be noted that, unlike in Uribe (2018), shocks to the inflation target are not, strictly speaking, permanent but only highly persistent.

2.2 Impulse responses

Figure 2 reports impulse responses to the standard nominal interest rate shock, $\epsilon_{R,t}$, and to the inflation target shock, $\epsilon_{\pi^*,t}$, for the model version under full information. The responses to the nominal interest rate shock, displayed in row 1 of Figure 2, summarize the conventional wisdom from decades of New Keynesian macro models: a contractionary monetary shock ($\epsilon_{R,t} \uparrow$) that temporarily raises the nominal interest rate, translates, because of sticky prices, into an increase also in the real interest rate. This decreases consumption demand, as agents increase their saving and delay their consumption to future periods. As a result of the temporarily depressed demand, firms sell less of their goods produced (output falls), despite lowering their prices to attract customers (inflation falls). That is, the short-term dynamics generated are that the nominal interest rate (\widehat{R}_t) co-moves negatively with output (\widehat{Y}_t) and inflation ($\widehat{\pi}_t$). In contrast, the short-run co-movement properties

⁹Cogley et al. (2010) do not estimate ρ_{π^*} but set it close to a unit root, 0.995. Ireland (2007) even considers a unit coefficient on lagged inflation target values, π_{t-1}^* . We performed sensitivity checks of our Bayesian estimation, adding ρ_{π^*} to the list of calibrated parameters, following Cogley et al. (2010) in setting $\rho_{\pi^*} = 0.995$. Results are essentially unaffected.

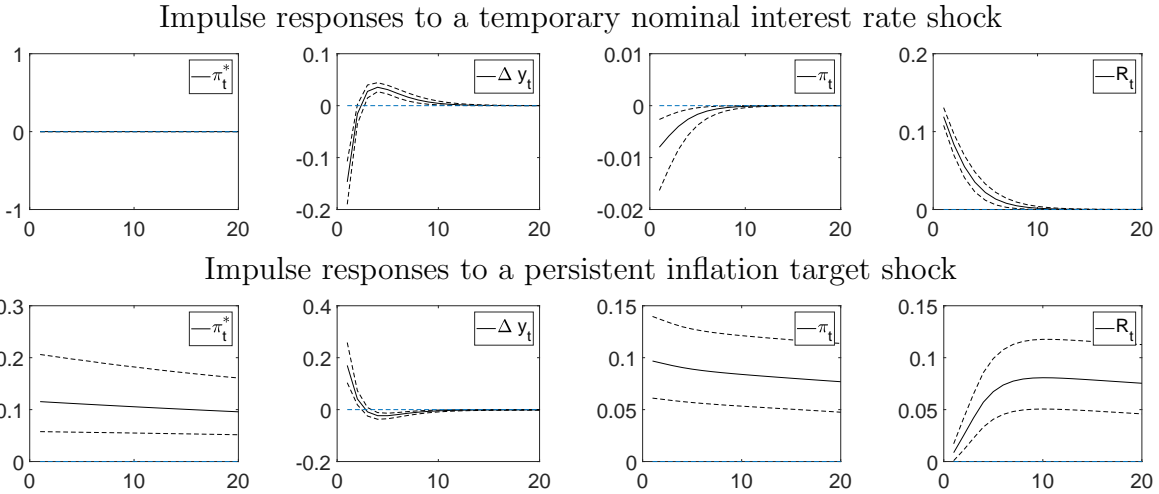


Figure 2: Impulse responses in the full information model. The Figure plots Bayesian impulse responses (at the posterior mean of the estimated parameters and at their 10% and 90% percentiles) of inflation target (π_t^*), output growth (Δy_t), inflation (π_t), and nominal interest rate (R_t). Row 1: responses to a temporary monetary shock, $\varepsilon_{R,t}$. Row 2: responses to an inflation target shock, $\varepsilon_{\pi^*,t}$.

of the nominal interest rate with output and inflation differ markedly in response to an inflation target shock, displayed in row 2 of Figure 2. In response to the target shock the inflation target rises persistently. Because agents fully understand the nature of this monetary policy shock (under full information), they adjust their inflation expectations on impact, leading to a fall in the real interest rate and an expansionary effect on output¹⁰. The jump in inflation expectations, together with the expansion in output imply that actual inflation jumps up strongly as well. Finally, the nominal interest rate responds positively to the inflation gap and the output gap: while the former is actually slightly negative (because the inflation target goes up by more than actual inflation), the strongly positive output gap implies that the central bank responds with a nominal interest rate increase. Summarizing, in response to the inflation target shock, the short-term dynamics of the nominal interest rate (\widehat{R}_t) are positively related with output (\widehat{Y}_t) and inflation ($\widehat{\pi}_t$), in support of a Neo-Fisher effect and in contrast to the co-movement properties of \widehat{R}_t and $\widehat{\pi}_t$ in response to the conventional temporary interest rate shock.

Figure 3 moves on to report the same impulse responses in our model version where

¹⁰Note that what is plotted in Figure 2 is not the *level* of output, but output growth, Δy_t . The effect on the level of output is undoubtedly expansionary and the response of output (in % deviation from its steady state) never falls below zero in response to the target shock.

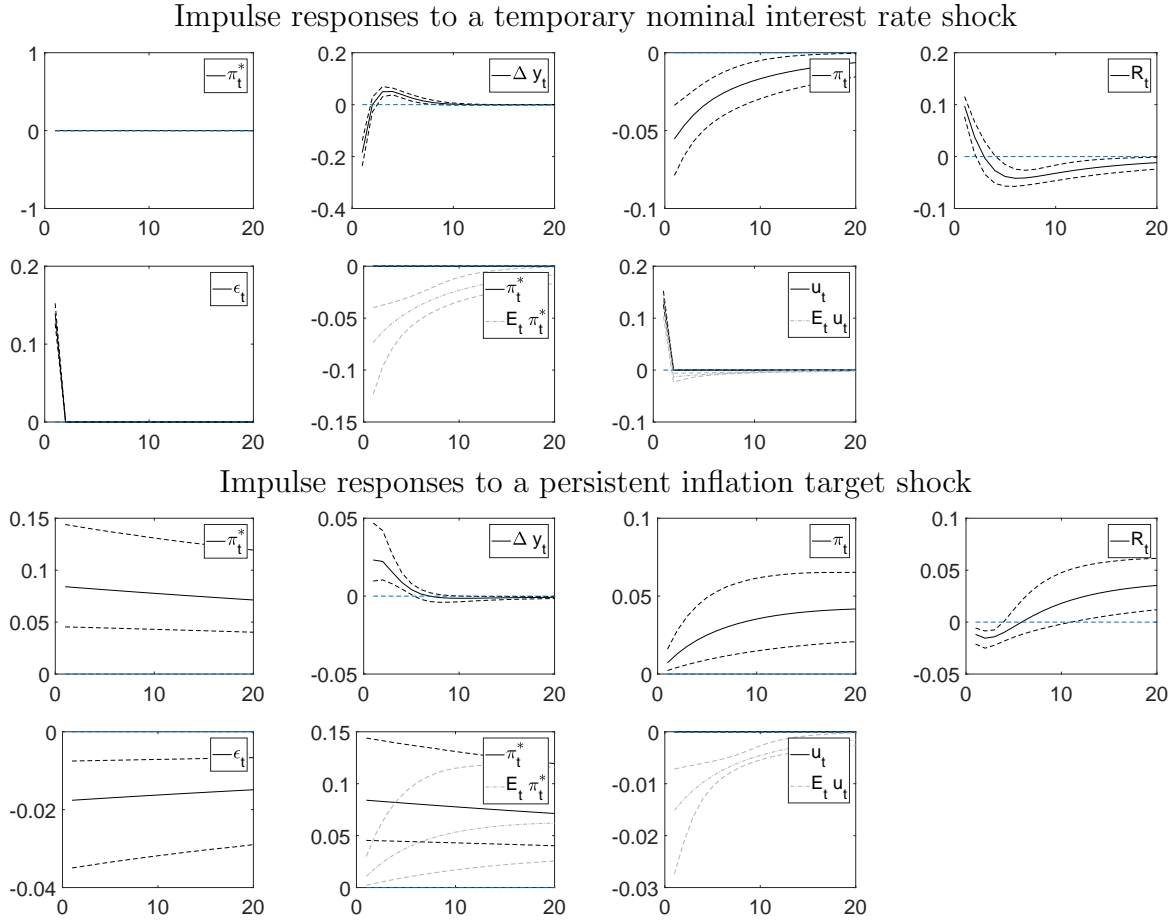


Figure 3: Impulse responses in the imperfect information model. The figure plots Bayesian impulse responses (at the posterior mean of the estimated parameters and at their 10% and 90% percentiles) of (π_t^*) , output growth (Δy_t) , inflation (π_t) , and nominal interest rate (R_t) , as well as the observed (composite) monetary shock (ε_t) , the target shock and perceived target $(\pi_t^*$ and $E_t \pi_t^*)$, and the temporary interest rate shock and the perceived temporary shock $(u_t$ and $E_t u_t)$. Row 1-2: responses to a temporary monetary shock, $\varepsilon_{R,t}$. Row 3-4: responses to an inflation target shock, $\varepsilon_{\pi^*,t}$.

agents do not have full knowledge about the type of monetary policy shock, but only can observe ε_t , which could move either because the economy was subjected to a temporary interest rate shock or because of a persistent target shock. In particular, at the heart of the discussion of theoretical contributions on the existence of the Neo-Fisher effect stands the exactly this question, and several contributions have cast doubts on agents fully being able to understand the nature of a monetary shock (García-Schmidt and Woodford (2018); Evans and McGough (2018); Garin et al. (2018); De Michelis and Iacoviello (2016); Erceg and Levin (2003)). Our estimation results from the imperfect information model version indeed show that the transmission of monetary policy shocks is sensitive to this assumption. The upper panels of Figure 3 report again the case of a temporary nominal interest rate rise: in row 1, the responses to the inflation target, output growth, inflation and the nominal rate; row 2 reports also the response of ε_t , the only thing agents can in fact observe, as well as the responses of the actual and perceived inflation target and temporary shock, on impact and as agents learn over time. As can be seen, the interest rate shock in the imperfect information model continues to give rise to a short-term negative co-movement of nominal interest rate (\widehat{R}_t) with output (\widehat{Y}_t) and inflation ($\widehat{\pi}_t$) in the very short-run, however, a few quarters after the shock hit the nominal interest rate turns negative (in terms of deviations from its steady state value), suggesting that even such traditional monetary policy shock may be able to give rise to a positive co-movement of the nominal interest rate with inflation and economic activity. Most importantly, the lower panels of Figure 3, rows 3-4, display the responses to the inflation target increase in the imperfect information setup. As the increase in $\widehat{\pi}_t^*$ is unobserved, and agents only observe a drop in ε_t (implied by the increase in $\widehat{\pi}_t^*$), they may mistake a target increase with a temporary expansionary shock, believing that a drop in the temporary component u_t could be behind the drop in ε_t . That is, instead of reacting to an inflation target increase, they react to a perceived temporary expansionary interest rate decrease. As a result, agents do not update their inflation expectations and the rise in inflation is very modest initially. Since the inflation gap is now strongly negative in the first couple of quarters after the target shock, the nominal interest rate falls. Summarizing, the imperfect information assumption and the fact that agents need to learn the nature of the monetary policy shock indeed implies that we do not observe a Neo-Fisher effect in the very short-term, with \widehat{R}_t co-moving negatively with with output (\widehat{Y}_t) and inflation ($\widehat{\pi}_t$) for the first 5 quarters. Only thereafter, agents have sufficiently learned the nature of the shock (i.e. that it was indeed an inflation target shock) and respond accordingly, so that a Neo-Fisher effect is present

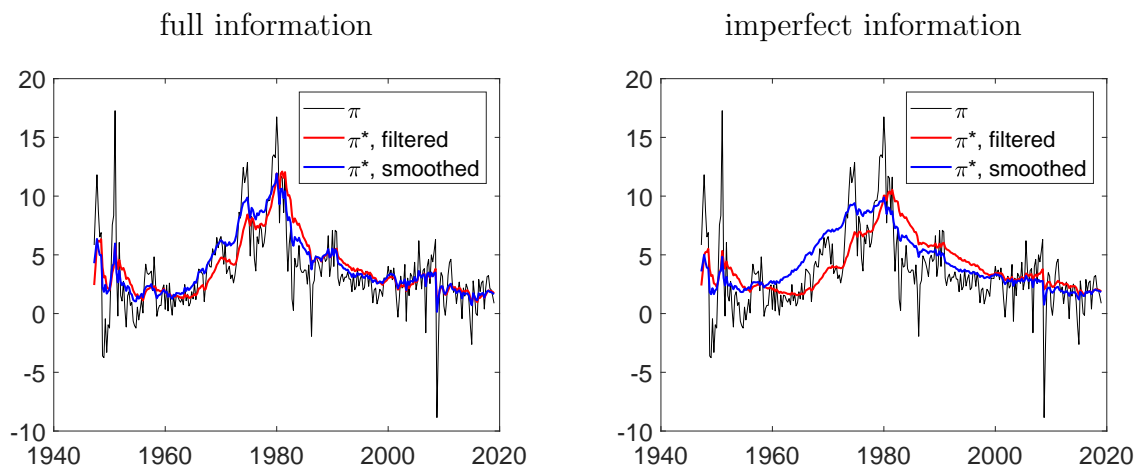


Figure 4: Dynamics of the inflation target series from the estimated New Keynesian DSGE model and actual inflation. Left panel: case of full information. Right panel: case of imperfect information. Black line: actual inflation. Blue line: smoothed inflation target estimate. Red line: filtered inflation target estimate.

from around period five onwards.

2.3 Implicit inflation target series from estimated DSGE-model

We also make use of our estimated New Keynesian model to derive model-implied time series of the latent series of the implicit central bank’s inflation target, a main variable of interest also for our empirical VAR analysis. Figure 4 presents the estimated smoothed and filtered series of the inflation target, plotted on the actual inflation series, for both the full information model version (left panel) and the imperfect information learning model version (right panel). In both cases, the inflation target is much smoother than actual inflation, largely following its patterns, mimicking the high inflation episode of the 1980s, and becoming relatively stable after the 1990s. The inflation target is also quite stable in the low inflation episode that followed the 2007/08 financial crisis and its aftermath, reflecting the strong dedication of the Federal Reserve to avoid deflation and bring inflation back up again quickly.

Our estimates are consistent with the literature. As we closely follow Ireland (2007) and Cogley et al. (2010) to derive the inflation target, our full information inflation-target measure also looks fairly similar to theirs, and the small differences that do arise stem mostly from a consideration of different time periods of estimation. Our full information

inflation-target measure also squares well with other rational expectations (full information) DSGE-based estimations that we are aware of, such as the also small-scale New Keynesian model of Bjørnland et al. (2011) or the medium-scale model of De Graeve et al. (2009). It also bears a close resemblance to both the permanent component of inflation estimated by Uribe’s empirical SVAR or in his theoretical model (Figure 5 and 7 in Uribe (2018)). A similar statement can be made about the estimated inflation target of a recent contribution by Mumtaz and Theodoridis (2018), depicted in Figure 5 of Mumtaz and Theodoridis (2018). Contrasting the estimated inflation target from full information and imperfect information model versions, the latter similarly tracks actual inflation realizations, but to a somewhat more lagged degree, reflecting agents’ learning process.¹¹. The common feature of DSGE-based estimates for the inflation target is that the resulting inflation target series are all slow-moving, highly persistent measures that track (and to some degree lag) the big trends in actual inflation, but are substantially smoother than actual inflation. This is consistent with the nature of an inflation target, as it represents a long-term objective of the Fed. Although the inflation target is time-dependent, we do not expect it to react to short-term economic shocks, but to be subject to changes only infrequently.

3 VAR model

This section presents the empirical model. A major goal is to keep the framework simple and tractable. Our baseline model directly connects to one of the most widely used frameworks to study monetary transmission: a three-variable VAR model in output growth, inflation and the nominal interest rate. Our baseline model is precisely this three-variable VAR, augmented by a measure of low-frequency inflation dynamics, which is closely related to the implicit inflation target of the theoretical model. This set-up allows us to examine the transmission of monetary policy shocks, both in terms of the standard shock to the nominal interest rate, but also in terms of more persistent monetary policy shifts from the inflation target shock.

¹¹We are not aware of any other inflation target estimates from rational expectations imperfect information models. Deviating from the assumption of rational expectations, the working paper version of Milani (2007), Milani (2005), or the estimate of Kozicki and Tinsley (2005) report inflation target series estimated within an adaptive learning setting

3.1 Data

We use U.S. data from 1947Q2 to 2019Q1 taken from the Federal Reserve Bank of St. Louis as our baseline period. All data is on quarterly basis. The variables in our VAR include the growth rate of real GDP, inflation, expressed as the rate of change of the consumer price index, and the 3-month Treasury bill rate¹², as well as a proxy for the central bank’s inflation target. Section 3.2 discusses the various measures we use as a proxy in detail.

We experiment with alternative time samples. In addition to our baseline period of 1947Q2 to 2019Q1, we estimate the VAR for the following periods: we start in 1979Q3 (as to start from the period of the Volcker chairmanship of the Fed) and end in 2008Q2 (to exclude the period of interest rates at the zero lower bound) or in 2019Q1.¹³ We choose the breakpoint at the end of 1979 as it marks the period of Volcker’s disinflation. Some studies (Primiceri, 2005; Cogley and Sargent, 2005; Cogley et al., 2010) point towards a decline in inflation gap persistence from 1980 onwards. By looking at different subsample periods, we are able to conclude that the dynamics of the identified nominal interest rate and inflation target shocks are similar across the postwar period and the shorter subsample periods.

3.2 Measures of long-run inflation

We consider several alternative measures that capture long-term inflation trends and serve as a suitable proxy for the central bank’s inflation target: (i) the Federal Reserve Board of Governors’ own inflation target estimate (PTR), (ii) long-run inflation expectations, (iii) our DSGE-based estimates of the implicit inflation target process, and (iv) empirical estimates of trend inflation. Figure 5 plots these time series, together with the actual inflation time series.

The Federal Reserve Board’s *PTR* measure (the acronym being an abbreviation for ‘perceived inflation target rate’) is displayed in the left panel of Figure 5, and corresponds to the FRB’s own inflation target estimate from the FRB/US-model, described in (Brayton

¹²Real GDP was calculated using nominal GDP and the GDP deflator, the CPI index is Consumer Price Index for All Urban Consumers All Items, CPIAUCSL, and the treasury bill rate is 3-Month Treasury Bill Secondary Market Rate, TB3MS, an average of monthly time series over each quarter. The data used in our VAR models thus corresponds to the data used for the Bayesian estimation of the theoretical models of section 2.

¹³It could be argued that our use of the 3-month T bill series for the nominal interest rate ignores possible problems related to the zero lower bound. We therefore re-estimate our VAR models with samples until 2019Q1 also with the alternative measure of the shadow interest rate of Wu and Xia (2016), and obtain virtually identical results.

et al., 2014). The time series is publicly available on a quarterly basis from 1962Q1, taken from the website of the Boards of Governors of the Federal Reserve System.¹⁴

An alternative measure proxying for the central bank’s inflation target is long-run inflation expectations, which is conceptually very close to the central bank’s target when inflation expectations are well anchored in the long-run. Our measure is inflation forecasts taken from the Survey of Professional Forecasters (Livingstone survey), denoted as *SPF*, and depicted in the center panel of Figure 5. Specifically, we use the 10-year ahead inflation forecast which starts in 1991Q4. To extend the number of observations we augment the forecast with observations from the Blue Chip Economic Indicators, a survey of top business economists, available from 1979.¹⁵ Apart for the shorter time period covered, the *SPF* measure closely resembles the *PTR* measure.

The implicit inflation target series obtained as a side-product from the Bayesian estimation of our New Keynesian model of section 2 constitutes another set of measures to employ in our VAR. We have already presented the evolution of these time series in Figure 4, plotting the smoothed and filtered versions of the estimates for the model-based π_t^* process, both with with full and imperfect information. The DSGE-based measures also show a clear resemblance to the two previous measures, indicating that they all capture well low-frequency inflation dynamics.

Finally, we also consider trend inflation estimates proposed in the empirical literature, reported in the right panel of Figure 5. Measures of trend inflation similarly reflect the long-term low-frequency movements in inflation dynamics. Stock and Watson (2007) is a key reference in decomposing inflation dynamics into trend and cyclical components, using an unobserved components stochastic volatility model. In addition we look at the contribution of Chan et al. (2018), who build on Stock and Watson (2007).¹⁶ It turns out that the Stock and Watson measure of trend inflation captures much higher frequencies in inflation dynamics compared to our other proxies of inflation target measures, resembling much more closely the actual inflation series. This leaves us to conclude that the Stock and Watson trend inflation measure may not be a good proxy for the inflation target. However, Chan et al. (2018) estimate trend inflation in a similar set-up as Stock and Watson (2007), but augment the Stock and Watson trend inflation measure by considering actual infla-

¹⁴Mumtaz and Theodoridis (2018) also employ the *PTR* measure in VAR estimations.

¹⁵The Blue Chip Economic Indicators are available on biannual basis, the missing observations were interpolated.

¹⁶We estimate trend inflation based on Stock and Watson (2007) using inflation based on the quarterly CPI index, for the period of 1947Q2 to 2019Q1. Trend inflation as in Chan et al. (2018) is taken from Joshua Chan’s website; it starts in 1960Q2.

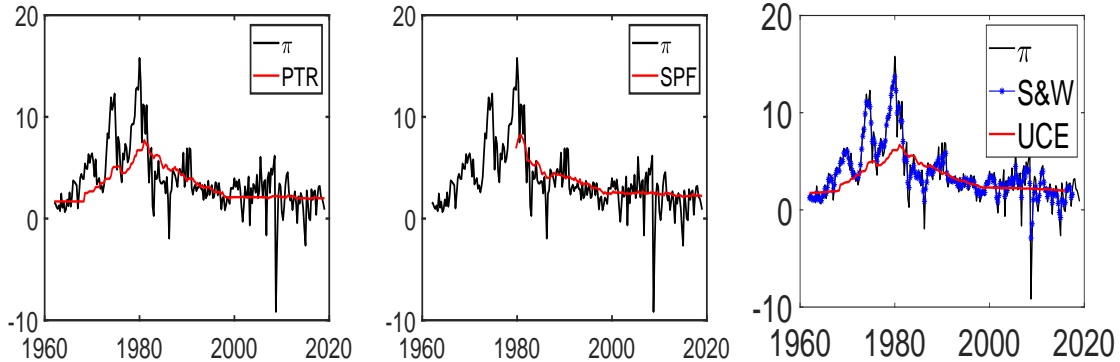


Figure 5: Measures serving as proxy for the inflation target, plotted on actual inflation. Left panel: Federal Reserve Board’s perceived inflation target rate (*PTR*) measure. Center panel: Survey of Professional Forecasters (*SPF*) long-run inflation expectations. Right panel: trend inflation as in Stock and Watson (2007) (*S&W*) and trend inflation as in Chan et al. (2018) (*UCE*).

tion, together with the *PTR* measure of long-run inflation expectations in the estimation process. The additional information of forward-looking inflation expectations gives rise to an estimated trend inflation that is considerably less volatile and more persistent than the trend inflation measure of Stock and Watson, and, again, resembles our other, earlier presented measures.

To sum up, the measures of low-frequency inflation dynamics introduced in this section and used, in the following, as our proxy variable for the central bank’s inflation target in our VAR models all share similar characteristics: high persistence and low volatility. From a macroeconomic perspective, long-term inflation trends and long-term inflation expectations are conceptually closely related to the concept of a time-varying perceived inflation target. We think of a shock to these measures, in a VAR setting, as reflecting a systematic shift in monetary policy, much like a shift in the Fed’s preferences over an inflation target.

3.3 Estimation

We estimate the VAR with Bayesian methods using an independent Normal-Wishart prior.¹⁷ This prior family allows priors on the autoregressive parameters of the VAR to be specified independently of priors on the covariance. We do not impose a strong belief on the values of the autoregressive coefficients, setting the prior for the autoregressive coef-

¹⁷We also explore other priors, in particular, data-driven prior suggested by Giannone et al. (2015) and receive very similar results.

ficients at zero, with a value of the prior precision of 10. This way we leave it up to the data to identify the non-zero coefficients important to capture the dynamics of our four variables. The prior for the covariance matrices is set equal to an identity matrix, similarly uninformative. As there is no analytical solution for this choice of prior distributions, we employ a Gibbs-sampler for the estimation of posterior densities (Koop and Korobilis (2010) provide an extensive discussion on this topic). Our baseline model includes two lags, as, e.g. in Mumtaz and Theodoridis (2018), but we also perform robustness checks with four lags. The model set up consists of:

$$x_t = A_0 + \sum_{j=1}^p A_j x_{t-j} + e_t, \quad (8)$$

$$e_t \sim \mathcal{N}(0, \Sigma).$$

where x_t is a vector of four macroeconomic time series: a proxy for the inflation target, π_t^* , output growth, Δy_t , inflation, π_t , and the nominal interest rate, R_t . A_0 is a vector of intercepts, p is the number of lags, A_j is the matrix of autoregressive coefficients of lag j , and Σ is the covariance matrix of the residuals.

In order to identify structural shocks we employ sign restrictions. This allows us to identify the nominal interest rate shock consistently with the predictions of the DSGE model. In particular, the nominal interest rate shock is restricted to lead to an increase in the nominal interest rate and a decline in both output growth and inflation. These restrictions are imposed for 4 quarters after the shock and are common in the VAR literature, (see, e.g., Uhlig (2005)). In order to identify the inflation target shock we impose only one restriction, namely that the shock leads to an increase in the measure of long-run inflation (expectations). We leave the remaining variables unrestricted as we are interested in their responses. As an additional robustness check we also consider an alternative identification strategy, employing a Cholesky identification, as it remains one of the most widely used identification strategies; in this case, the variables in the VAR are ordered as π_t^* , Δy_t , π_t , and R_t .

3.4 Results

3.4.1 Results from the baseline model with the PTR inflation target measure

Our baseline empirical specification is the VAR model in output growth, inflation and interest rate, augmented with the *PTR* measure, the FRB’s estimate of the perceived

inflation target. This setting allows us, like in the theoretical model of section 2, to look at the two types of monetary policy shocks: the temporary monetary policy shock to the short-term nominal interest rate, as standard in the literature; and, the inflation target shock, a persistent shock to the long-run inflation goal of the Fed, identified as the shock to an innovation to the PTR variable. We show that both shocks have significant effects over various time samples, proving to be important channels for monetary policy transmission into the US economy.

Figure 6 presents posterior impulse responses of the baseline model estimated over the full horizon, starting in 1962Q1 and ending in 2019Q1. The responses to the nominal interest rate shock are summarized in row 1 of Figure (6). By imposing sign restrictions, we accept only responses that, up to 4 quarters after the shock, positively affect the nominal interest rate, and negatively affect output growth and inflation. The intuition behind these restrictions comes from transitional dynamics generated by theoretical New Keynesian models, such as the one discussed in detail in section 2. In particular, a positive nominal interest rate shock leads to an increase in the nominal rate and, due to sticky prices, to an increase in the real rate. The higher real rate translates into a drop in demand and a corresponding drop in output and inflation. We place no restrictions on the reaction of the inflation target variable in response to the nominal interest rate shock. There is no theoretical reason to expect that the central bank would adjust its inflation target in response to a temporary interest shock; however, our VAR suggests that the perceived target declines. We do not consider this finding to be troubling though, as, on the one hand, the magnitude of the target response is small compared to the macroeconomic variables. On the other hand, the drop in the perceived target in response to the interest rate shock is actually consistent with the imperfect information version of our theoretical New Keynesian model, where we similarly observe a fall in the perceived target, despite the actual target remaining constant (cf. Figure 3).

Row 2 of Figure 6 displays impulse responses to a positive inflation target shock. In response to this persistent monetary policy shock, we observe an increase in inflation, the nominal interest rate and output growth. This is in line with the results from the theoretical model, the dynamics of our VAR model corresponding closely to the dynamics of Figure 2, the full information New Keynesian model. In particular, in our VAR model, we do not find that the nominal interest rate responds positively only with a lag, as we find in the imperfect information New Keynesian model. The VAR results thus more clearly indicate support for Neo-Fisher like effects, i.e. persistent changes in the inflation target

induce a positive co-movement of inflation and nominal interest rate dynamics already in the short-run, at no output cost. The theoretical model of section 2 helps us interpreting the transmission mechanism economically. There, an outcome of the shock is a decline in the real rate, which stimulates output and inflation. This seems to be consistent with the data. The effects of the inflation target shock are also found to be very persistent. Even 20 quarters after the shock the responses of inflation and the interest rate do not die out.¹⁸ This is due to the high persistence of the inflation target shock, but also due to the nature of the shock: as it moves forward-looking variables, long-term inflation expectations, it creates long-lasting effects. The effect on output growth is least persistent, starting to die out after the first year. This is consistent with the Fisher equation: as the dynamics between inflation and the interest rate adjust and reach similar levels, the real rate becomes unaffected by changes in these nominal variables. As a result, output growth returns to its pre-shock value.

Our results are qualitatively in line with the results from other related empirical studies. Uribe (2018) finds that, in response to a permanent nominal interest rate raise, inflation and the interest rate increase. Mumtaz and Theodoridis (2018) study the effects of an inflation target shock using a SVAR model and similarly report an increase in nominal rate and inflation. Both Uribe (2018) and Mumtaz and Theodoridis (2018) also find evidence in favour of an increase in economic activity. The particular shape of our post-shock dynamics of inflation and the interest rate is different from Uribe (2018) and more in line with Mumtaz and Theodoridis (2018), reflecting the differences in modeling a long-lasting change in monetary policy through an inflation target shock or a permanent monetary policy shock.

¹⁸As our variables are stationary, their reactions die out eventually. However, the effects are long-lasting.

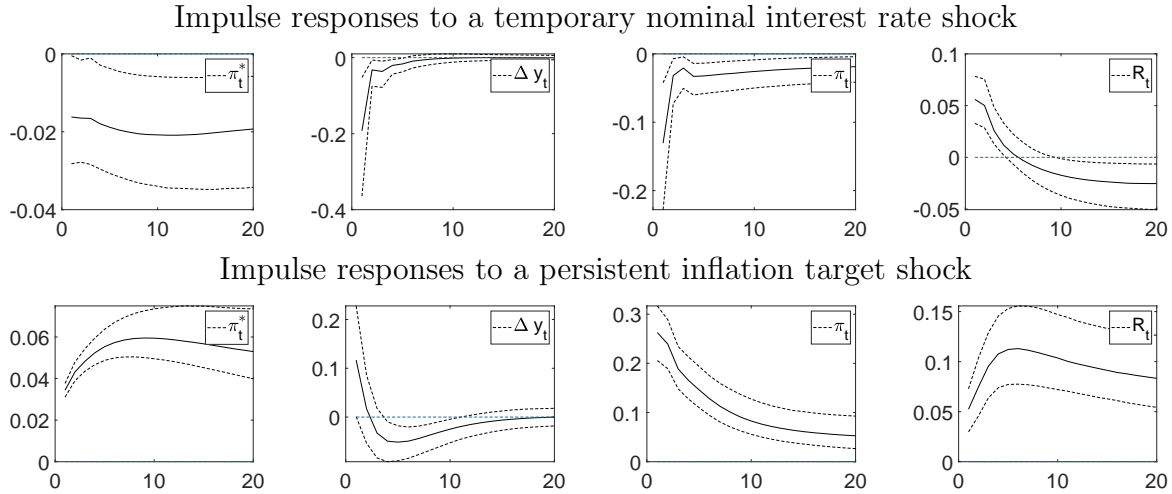


Figure 6: Baseline model with perceived inflation target rate (*PTR*) measure from the FRB/US model (Brayton, Laubach, Reifschneider, 2014). First row: 90% confidence interval to a nominal interest rate shock. Second row: 90% confidence interval to a persistent inflation target shock. Sample: 1962Q1 to 2019Q1. Horizontal axis: periods after the shock. Vertical axis: percentage change.

We also consider different time samples, to study if our findings on the presence of Neo-Fisher effects are robustly found also for more recent time periods. Appendix B.2 contains impulse responses of our VAR model estimated over various time horizons: 1962Q1 to 2008Q2, 1979Q2 to 2019Q1 and 1979Q2 to 2008Q2. Arguably, with the beginning of the Volcker chairmanship, US monetary policy become much more committed to the goal of price stability, under the chairmanship of Bernanke even adopted an explicit, publicly announced inflation target. As a result, the inflation target became more credible. We indeed find that the effects of an inflation target shock are dependant on the monetary style adopted by the Federal Reserve, i.e. on the 'era' of its chairmanship. In the more recent sample periods of 1979Q2-2019Q1 and 1979Q2-2008Q2, the inflation target shock and its effects on inflation and the nominal interest rate are quantitatively less pronounced and less persistent compared to the entire postwar period. Also, the responses of output are no longer significantly positive. These results suggests the policy implication that a long-run commitment to an inflation target helps reducing inflation persistence, making the implementation of monetary policy more effective. Nonetheless, short-run effects of inflation target shocks remain significant, and continue to introduce inflation and nominal interest rate dynamics in line with the Neo-Fisher effect, which stand in contrast to the

dynamics in response to a standard temporary shock to the nominal interest rate.

3.4.2 Sensitivity: models with alternative inflation target measures

In this section we discuss robustness of our results of the baseline model of section 3.4.1, by substituting the *PTR* measure with our other inflation target proxy measures: the survey-based inflation forecasts of professional forecasters (*SPF*), the estimated inflation target series from our full and imperfect information versions of the DSGE model, and the Chan et al. (2018) trend inflation measure (*UCE*). To save space, we relegate all impulse responses for these alternative VAR models to Appendix B.1.¹⁹

The VAR models with all alternative measures deliver robust results, with dynamics similar to our baseline model. In response to the nominal interest rate shock, inflation and output contract, while the inflation target measure goes down after the shock – this reaction being small quantitatively, however, as in the baseline. In response to the inflation target shock, inflation, output growth and nominal rate all typically increase. There are only a few noteworthy differences across the VAR models with different target measures. In the model with the *SPF* measure, the reaction of inflation is smaller in magnitude compared to our baseline model, and the interest rate increase is not significant on impact. The models with the DSGE-based inflation target measures produce strong Neo-Fisherian effects; surprisingly, even the version with the inflation target estimated from the imperfect information model. The model with the *UCE* measure, again, produces responses that are quantitatively less pronounced as in the baseline model, and the inflation response is insignificant on impact. Nonetheless, the differences across the specifications with with alternative inflation target measures are minor. We thus conclude that with respect to the inflation target shock, our result about dynamics in line with Neo-Fisherian effect persists.

4 Conclusions

This paper presents new empirical evidence on monetary policy transmission by distinguishing between long-run and short-run monetary policy shocks. We do so both by estimating a theoretical New Keynesian DSGE model and by studying empirical VAR models. Both approaches suggest that the two shocks are important sources of fluctuations in inflation, interest rates and output growth in the close aftermath of the shock, but each

¹⁹The impulse responses reported are for the full sample period. We again check robustness with respect to a higher number of lags and subsample periods.

shock represents a different channel through which the central bank affects the economy and implies different co-movement properties of the nominal interest rate with inflation and output. In response to a temporary nominal interest rate shock, a rise in the interest rate is associated with a fall in inflation and economic activity, as is the conventional wisdom of generations of monetary macro models. In response to a persistent inflation target increase, we tend to find evidence that the nominal interest rate, inflation, and economic activity all rise, in line with a recent literature on Neo-Fisherian effects. A key novel aspect of our paper is that we also estimate a version of the New Keynesian model in which agents have imperfect information about the nature of a monetary policy shock, and need to learn over time if a change in monetary policy reflects a temporary interest rate shock or a shock to the inflation target. We show that this is indeed consequential, as agents do not adjust their inflation expectations upwards immediately in response to a target increase. We find that, in such case, Neo-Fisherian effects arise only with a lagged effect and not in the immediate short-run.

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Appendix A The DSGE model

A.1 Brief model description

This section presents the DSGE model which we employ to estimate the unobserved time series for the inflation target. We intend to stay within a simple and commonly acknowledged framework. We follow closely the approach taken by Cogley et al. (2010): a standard New Keynesian model (Boivin and Giannoni, 2006) with a time-varying inflation target process as in (Ireland, 2007). We give a brief description of the model below.

Our economy is populated by households who consume, supply their labor services in the labor market and decide on their savings. Imperfectly competitive firms supply goods to the market and face nominal rigidities in their price setting decisions. Monetary policy is described by a central bank that follows a Taylor rule in setting the nominal interest rate every period.

The household's faces habit preferences in consumption, that is, period utility depends positively on consumption relative to past consumption with a weight h , and negatively on labor effort, with ν being the inverse Frisch elasticity of labor supply. The representative household solves the following maximization problem:

$$\max E_t \sum_{s=0}^{\infty} \beta^s b_{t+s} \left[\log(C_{t+s} - hC_{t+s-1}) - \psi \int_0^1 \frac{L_{t+s}(i)^{1+\nu}}{1+\nu} di \right], \quad (\text{A.1})$$

subject to the budget constraint:

$$\int_0^1 P_t(i) C_t(i) di + B_t + T_t \leq R_{t-1} B_{t-1} + \Pi_t + \int_0^1 W_t(i) L_t(i) di. \quad (\text{A.2})$$

L_t is the household's labor supply, W_t the nominal wage rate, B_t indicate holdings of government bonds, R_t is the nominal gross interest rate, T_t are taxes and transfers received. b_t represents a preference shock. C_t is a final consumption index, modelled as a Dixit-Stiglitz aggregator over the different varieties of consumption goods, that are substitutable with each other at elasticity of substitution θ_t :

$$C_t = \left[\int_0^1 C_t(i)^{\frac{1}{1+\theta_t}} di \right]^{1+\theta_t}$$

The substitution elasticity θ_t is allowed to vary over time according to an exogenous process, which gives rise to fluctuations in firms' markup over marginal cost. The exogenous

processes of the preference shock, b_t , and the markup shock, θ_t , evolve according to the following stochastic processes:

$$\log(b_t) = \rho_b \log(b_{t-1}) + \varepsilon_{b,t}, \quad (\text{A.3})$$

$$\log(\theta_t) = (1 - \rho_\theta) \log(\theta) + \rho_\theta \log(\theta_{t-1}) + \varepsilon_{\theta,t},$$

The production side is represented by monopolistically competitive firms. Each firm i produces a differentiated good taken as given the demand for its variety from households and facing a linear production function, $Y_t(i)$:

$$Y_t(i) = A_t L_t(i), \quad (\text{A.4})$$

where A_t is the level of aggregate total factor productivity. The level of productivity is allowed to grow over time, and the growth rate of the economy, defined as $z_t \equiv \log \frac{A_t}{A_{t-1}}$, follows an exogenous process and is subject to stochastic shocks:

$$z_t = (1 - \rho_z)\gamma + \rho_z z_{t-1} + \varepsilon_{z,t}. \quad (\text{A.5})$$

Firm i optimally sets the price for its variety, but cannot do so every period, following the setup of staggered prices as in Calvo (1983). In particular, each period only a fraction of $1 - \zeta$ of firms is allowed to optimally re-set their price, while the remaining fraction ζ of firms is not allowed to re-optimize their prices. In setting the price the firm aims to maximize the lifetime expected discounted stream of profits (revenue minus costs) subject to the demand schedule from households, and subject to its production technology:

$$\max E_t \sum_{s=0}^{\infty} \zeta^s \Lambda_{t,t+s} \left[\tilde{P}_t(i) \pi Y_{t+s}(i) - W_{t+s}(i) L_{t+s}(i) \right], \quad (\text{A.6})$$

where $\Lambda_{t+s} = \beta^s \frac{\lambda_{t+s}}{\lambda_t}$ is the household's discount factor (the appropriate discount factor for firms' decision as firms are owned by households), and π is the steady state gross inflation rate.

Finally, the monetary authority sets the gross nominal interest rate according to the following Taylor rule:

$$\frac{R_t}{R} = \frac{R_{t-1}}{R}{}^{\rho_R} \left[\left(\frac{\bar{\pi}_{4,t}}{(\pi_t^*)^4} \right)^{\rho_\pi} \left(\frac{Y_t}{Y_t^*} \right)^{\rho_Y} \right]^{1-\rho_R} e^{\varepsilon_{R,t}}, \quad (\text{A.7})$$

where R is the steady state level of the nominal interest rate, and where $\varepsilon_{R,t}$ is an exogenous disturbance meant to capture (temporary) nominal interest rate shock to the

policy rate. According to the rule the central bank considers three factors in deciding on the current level of the nominal interest rate: (1) the previous level of the nominal interest rate R_{t-1} , i.e. there is interest rate smoothing; (2) the output gap, defined as the deviation of the actual level of output, Y_t from its potential, i.e. the level of output that would prevail in an economy with flexible prices, Y_t^* ; and (3) the inflation gap, defined as the deviation of inflation, $\bar{\pi}_{4,t}$, from the level of target inflation. In particular, it is defined as $\bar{\pi}_{4,t} \equiv (\pi_t + \pi_{t-1} + \pi_{t-2} + \pi_{t-3})/4$. In contrast to the more standard Taylor rule featured in a standard New Keynesian model such as, e.g., described in chapter 3 of Galí (2008), the inflation target, π_t^* , is not required to be fixed at a constant level, but is allowed to be time dependent and vary over time according to following exogenous process for π_t^* :

$$\log \pi_t^* = (1 - \rho_{\pi^*}) \log \pi + \rho_{\pi^*} \log \pi_{t-1}^* + \varepsilon_{\pi^*,t}. \quad (\text{A.8})$$

A.2 List of log-linearized first order and equilibrium conditions

This section lists the system of first order and equilibrium conditions to be coded.

First-order and equilibrium conditions of the sticky price economy:

Phillips curve:

$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \hat{\lambda}_{P,t} + \frac{(1 - \beta\zeta)(1 - \zeta)}{\zeta \left(1 - \nu \left(1 + \frac{1}{\lambda_P}\right)\right)} \hat{w}_t, \quad (\text{A.9})$$

Marginal utility of consumption

$$(\gamma - h\beta)(\gamma - h)\hat{\lambda}_t + (\gamma^2 + \beta h^2)\hat{Y}_t = \left[\begin{array}{c} (\gamma h\beta) E_t \hat{Y}_{t+1} + \gamma h \hat{Y}_{t-1} + \\ (\gamma - h\beta\rho_b)(\gamma - h)\hat{b}_t + (\beta h\gamma\rho_z - h\gamma)\hat{z}_t \end{array} \right], \quad (\text{A.10})$$

Euler equation

$$\hat{\lambda}_t = \beta E_t \hat{\lambda}_{t+1} + \hat{R}_t - \hat{\pi}_{t+1} - \rho_z \hat{z}_t \quad (\text{A.11})$$

Labor supply equation

$$\hat{w}_t + \hat{\lambda}_t = \hat{b}_t + \nu \hat{Y}_t \quad (\text{A.12})$$

Monetary policy rule

$$\hat{R}_t = \rho_R \hat{R}_{t-1} + (1 - \rho_R) \left[\rho_\pi \left(\frac{\hat{\pi}_t + \hat{\pi}_{t-1} + \hat{\pi}_{t-2} + \hat{\pi}_{t-3}}{4} \right) + \rho_Y (\hat{Y}_t - \hat{Y}_t^{flex}) \right] + \varepsilon_t, \quad (\text{A.13})$$

First-order and equilibrium conditions of the flexible price economy:

Marginal utility of consumption

$$(\gamma - h\beta)(\gamma - h)\widehat{\lambda}_t^{flex} + (\gamma^2 + \beta h^2)\widehat{Y}_t^{flex} = \begin{bmatrix} (\gamma h\beta) E_t \widehat{Y}_{t+1}^{flex} + \gamma h \widehat{Y}_{t-1}^{flex} + \\ (\gamma - h\beta\rho_b)(\gamma - h)\widehat{b}_t + (\beta h\gamma\rho_z - h\gamma)\widehat{z}_t \end{bmatrix}, \quad (\text{A.14})$$

Euler equation

$$\widehat{\lambda}_t^{flex} = \beta E_t \widehat{\lambda}_{t+1}^{flex} + \widehat{R}_t^{flex} - \rho_z \widehat{z}_t, \quad (\text{A.15})$$

Labor supply equation

$$\widehat{w}_t^{flex} + \widehat{\lambda}_t^{flex} = \widehat{b}_t + \nu \widehat{Y}_t^{flex}, \quad (\text{A.16})$$

Observables

$$o_\Delta Y_t = \gamma^{100} + \widehat{Y}_t - \widehat{Y}_{t-1} + \widehat{z}_t, \quad (\text{A.17})$$

$$o_\pi \pi_t = \pi^{100} + \widehat{\pi}_t, \quad (\text{A.18})$$

$$o_R R_t = (\pi^{100} + r^{100}) + \widehat{R}_t. \quad (\text{A.19})$$

Exogenous processes

$$\widehat{z}_t = \rho_z \widehat{z}_{t-1} + \varepsilon_{z,t}, \quad (\text{A.20})$$

$$\widehat{b}_t = \rho_b \widehat{b}_{t-1} + \varepsilon_{b,t}, \quad (\text{A.21})$$

$$\widehat{\theta}_t = \rho_\theta \widehat{\theta}_{t-1} + \varepsilon_{\theta,t}, \quad (\text{A.22})$$

$$\widehat{\pi}_t^* = \rho_{\pi^*} \widehat{\pi}_{t-1}^* + \varepsilon_{\pi^*,t}, \quad (\text{A.23})$$

$$u_t = \rho_u u_{t-1} + \varepsilon_{R,t} \quad (\text{A.24})$$

Definition of ε_t

$$\varepsilon_t \equiv (1 - \rho_R)(-\rho_\pi)\widehat{\pi}_t^* + u_t. \quad (\text{A.25})$$

A.3 The solution in the imperfect information setup

Solving and estimating the model version under full information is straightforward, the system of equations in section A.2, equations (A.9)-(A.25) needs to be coded up and solved with any of the many available packages to solve linear rational expectation systems.²⁰ It can be shown, that in the model solution of the full information model version, the policy

²⁰E.g., Dynare is particularly convenient.

functions are a function of the state vector $x_t = \left[\widehat{R}_{t-1}, \widehat{\pi}_{t-1}, \widehat{\pi}_{t-2}, \widehat{\pi}_{t-3}, \widehat{Y}_{t-1}, \widehat{Y}_{t-1}^{flex}, \widehat{z}_t, \widehat{b}_t, \widehat{\theta}_t, \widehat{\pi}_t^*, u_t \right]$.

Obtaining a solution to the model version under imperfect information and learning is somewhat more involved, and the steps needed to derive a solution are laid out in detail below.²¹ Recall from the main text that the Taylor rule describing the central banks's policy actions could be written as:

$$\widehat{R}_t = \rho_R \widehat{R}_{t-1} + (1 - \rho_R) \left[\rho_\pi (\widehat{\pi}_{4,t}) + \rho_Y (\widehat{Y}_t - \widehat{Y}_t^*) \right] + \varepsilon_t,$$

where we defined

$$\varepsilon_t \equiv (1 - \rho_R) (-\rho_\pi) \widehat{\pi}_t^* + u_t.$$

Under imperfect information, agents are only able to observe ε_t , but cannot observe the components $\widehat{\pi}_t^*$ and u_t individually. However, they learn over time what is behind a particular movement of ε_t . In particular, their learning problem is a linear problem and features an observation equation, $o_t = H' \xi_t$, and a state transition equation, $\xi_{t+1} = F \xi_t + B \epsilon_{t+1}$, so that the learning problem can be described using the Kalman filter:

$$\underbrace{(\varepsilon_t)}_{o_t} = \underbrace{\begin{bmatrix} (1 - \rho_R) & (-\rho_\pi) & 1 \end{bmatrix}}_{H'} \underbrace{\begin{bmatrix} \widehat{\pi}_t^* \\ u_t \end{bmatrix}}_{\xi_t},$$

$$\underbrace{\begin{bmatrix} \widehat{\pi}_{t+1}^* \\ u_{t+1} \end{bmatrix}}_{\xi_{t+1}} = \underbrace{\begin{bmatrix} \rho_{\pi^*} & 0 \\ 0 & \rho_u \end{bmatrix}}_F \underbrace{\begin{bmatrix} \widehat{\pi}_t^* \\ u_t \end{bmatrix}}_{\xi_t} + \underbrace{\begin{bmatrix} \varepsilon_{\pi^*,t+1} \\ \varepsilon_{R,t+1} \end{bmatrix}}_{\epsilon_{t+1}},$$

where we denote with Q the variance-covariance matrix of the innovation $B \epsilon_{t+1}$, $Q =$

²¹An excellent exposition of a imperfect information and learning model is in chapter 5 of Schmitt-Grohé and Uribe (2017) (despite being on the very different application of a small open economy needing to learn the source of technology disturbances, temporary versus permanent). Our solution approach follows the same steps. Since obtaining the model solution is non-standard, we cannot use Dynare for estimation. Instead, for estimating the imperfect information model, we adopt (and adapt) the Bayesian estimation codes that accompany the example model of chapters 1 and 2 of Herbst and Schorfheide (2016, <https://web.sas.upenn.edu/schorf/files/2017/07/DSGE-Estimation-ueds33.zip>) to our model. Rigorous checks for correct implementation were successful, e.g., we also implement the full information model version in the Herbst and Schorfheide (2016) set of Bayesian estimation codes; we verify that our implementation and Dynare yields (for a particular draw of parameters) identical policy function coefficients and model log-likelihood, as well as virtually the same estimated parameters from the Metropolis-Hastings MCMC.

$BB' = \begin{bmatrix} \sigma_{\pi^*}^2 & 0 \\ 0 & \sigma_u^2 \end{bmatrix}$. The Kalman filter yields

$$\begin{aligned} E_t o_{t+1} &= H' E_t \xi_{t+1}, \\ E_t \xi_{t+1} &= F E_{t-1} \xi_t + \kappa (o_t - H' E_{t-1} \xi_t), \end{aligned}$$

where κ is the Kalman gain matrix, $\kappa \equiv FPH(H'PH)^{-1}$, and P is implicitly given by the Riccati equation $P = F [P - PH(H'PH)^{-1}H'P] F' + Q$, and represents the steady state mean square error of the forecast of ξ_{t+1} , that is $P = E [(\xi_{t+1} - E_t \xi_{t+1})(\xi_{t+1} - E_t \xi_{t+1})']$.

Given this setup, the model version with imperfect information and learning can be solved in two stages. In the first stage, one needs to code up equations (A.9) to (A.22), that is, all model equations apart from the ones describing the exogenous processes of $\hat{\pi}_t^*$ and u_t , and the definition of ε_t . In addition, the variable ε_t (the observable) is treated as a state variables, and expectations in period t are taken, given the agent's information in period t , which does not include $\hat{\pi}_t^*$ and u_t . In particular, agents only know $E_{t-1} \hat{\pi}_t^*$ and $E_{t-1} u_t$. Defining auxiliary (state) variables $\eta_{1t} = E_{t-1} \hat{\pi}_t^*$ and $\eta_{2t} = E_{t-1} u_t$, we can write their law of motion as:

$$\begin{bmatrix} \eta_{1t+1} \\ \eta_{2t+1} \end{bmatrix} = (F - \kappa H') \begin{bmatrix} \eta_{1t} \\ \eta_{2t} \end{bmatrix} + \kappa [\varepsilon_t], \quad (\text{A.26})$$

and the conditional expectation of ε_{t+1} is given by

$$[E_t \varepsilon_{t+1}] = H' \begin{bmatrix} \eta_{1t+1} \\ \eta_{2t+1} \end{bmatrix}. \quad (\text{A.27})$$

Solving system (A.9)-(A.22) together with (A.26) and (A.27) yields a solution as a function of the state vector $x_t = [\hat{R}_{t-1}, \hat{\pi}_{t-1}, \hat{\pi}_{t-2}, \hat{\pi}_{t-3}, \hat{Y}_{t-1}, \hat{Y}_{t-1}^{flex}, \hat{z}_t, \hat{b}_t, \hat{\theta}_t, \eta_{1t}, \eta_{2t}, \varepsilon_t]$, and concludes the first step in the solution procedure. This is not the end of the computation algorithm though, because in equilibrium, the variable ε_t is not a primitive exogenous state variable, but a control variable, determined by the truly exogenous states $\hat{\pi}_t^*$ and u_t . Luckily, this second step of the solution is easily done and consists of rewriting the solution obtained in step 1 as a function of $x_t = [\hat{R}_{t-1}, \hat{\pi}_{t-1}, \hat{\pi}_{t-2}, \hat{\pi}_{t-3}, \hat{Y}_{t-1}, \hat{Y}_{t-1}^{flex}, \hat{z}_t, \hat{b}_t, \hat{\theta}_t, \eta_{1t}, \eta_{2t}, \hat{\pi}_t^*, u_t]$ (by using the solution of ε_t from the first step), and appending equations $\xi_{t+1} = F\xi_t + B\varepsilon_{t+1}$ and $o_t = H'\xi_t$ to the system.

A.4 Prior setup and posterior estimates

Table A.1 presents estimation results for the model parameters of the New Keynesian model described in Appendix A.1, reporting information on the chosen prior distributions, prior means and variances, as well as the estimated posterior means and 10% and 90% intervals.

param.	prior density	prior mean	prior var.	Full information		Imperfect information	
				post. mean	10% and 90% intervals	post. mean	10% and 90% intervals
γ^{100}	Normal	0.475	0.025	0.482	[0.451,0.514]	0.483	[0.452,0.514]
π^{100}	Normal	0.500	0.100	0.511	[0.386,0.635]	0.520	[0.396,0.645]
$\frac{1}{\beta} - 1$	Gamma	0.250	0.100	0.147	[0.079,0.225]	0.151	[0.080,0.232]
h	Beta	0.500	0.100	0.469	[0.405,0.532]	0.457	[0.393,0.521]
ζ	Beta	0.660	0.100	0.768	[0.703,0.831]	0.783	[0.718,0.843]
ρ_π	Normal	1.700	0.200	1.260	[1.005,1.525]	1.193	[0.941,1.458]
ρ_Y	Gamma	0.300	0.150	1.110	[0.829,1.410]	1.252	[0.948,1.577]
ρ_R	Beta	0.600	0.200	0.877	[0.840,0.910]	0.825	[0.761,0.880]
ρ_z	Beta	0.400	0.200	0.608	[0.507,0.707]	0.545	[0.450,0.640]
ρ_θ	Beta	0.600	0.200	0.507	[0.431,0.581]	0.538	[0.465,0.610]
ρ_b	Beta	0.600	0.200	0.940	[0.907,0.967]	0.935	[0.901,0.964]
ρ_{π^*}	Beta	0.980	0.015	0.991	[0.984,0.997]	0.992	[0.986,0.997]
σ_R	Inv.Gam.	0.150	1.000	0.139	[0.130,0.148]	0.139	[0.129,0.149]
σ_z	Inv.Gam.	1.000	1.000	0.709	[0.587,0.834]	0.807	[0.696,0.921]
σ_θ	Inv.Gam.	0.150	1.000	0.260	[0.222,0.299]	0.253	[0.213,0.294]
σ_b	Inv.Gam.	1.000	1.000	4.142	[3.032,5.528]	3.973	[2.836,5.392]
σ_{π^*}	Inv.Gam.	0.100	0.050	0.115	[0.065,0.177]	0.084	[0.051,0.125]

Table A.1: Prior parameters and posterior estimates

Appendix B Sensitivity checks in empirical models

B.1 Sensitivity checks: alternative inflation target measures

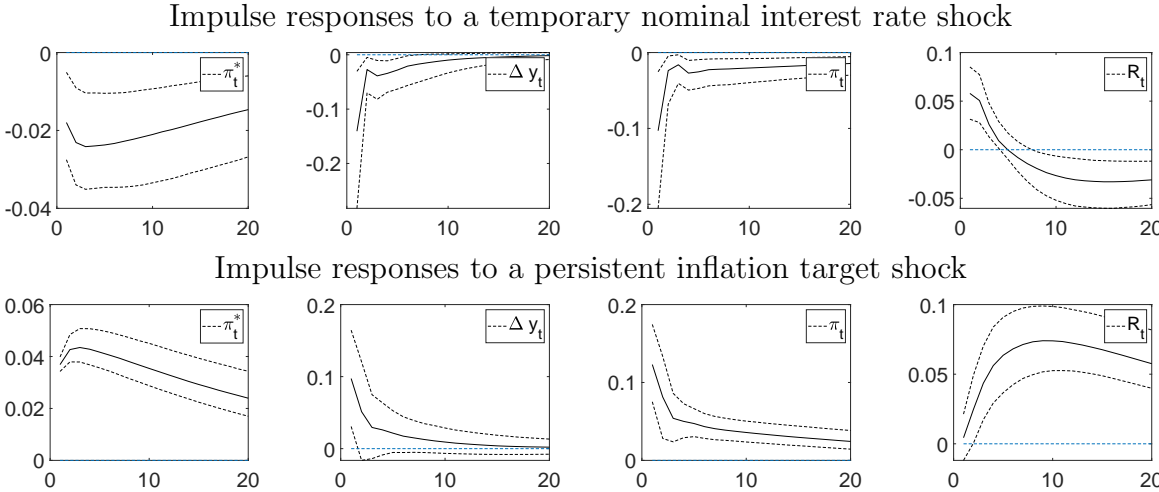


Figure B.1: Model with inflation forecasts taken from the Survey of Professional Forecasters, *SPF*. First row: 90% confidence interval to a nominal interest rate shock. Second row: 90% confidence interval to a persistent inflation target shock. Sample: 1979Q4 to 2019Q1. Horizontal axis: periods after the shock. Vertical axis: percentage change.

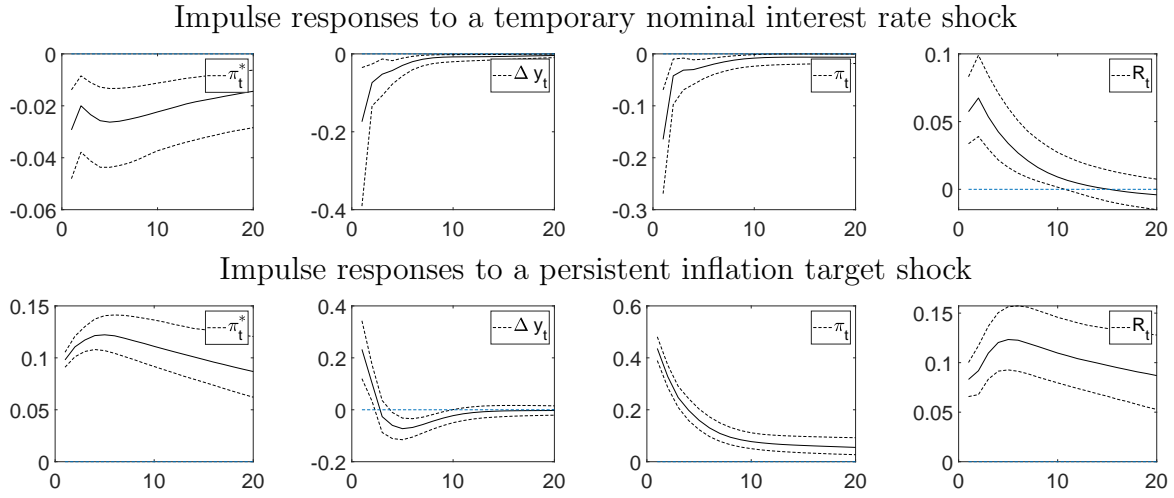


Figure B.2: Model with inflation target estimated from the DSGE model with full information. First row: 90% confidence interval to a nominal interest rate shock. Second row: 90% confidence interval to a persistent inflation target shock. Sample: 1947Q2 to 2019Q1. Horizontal axis: periods after the shock. Vertical axis: percentage change.

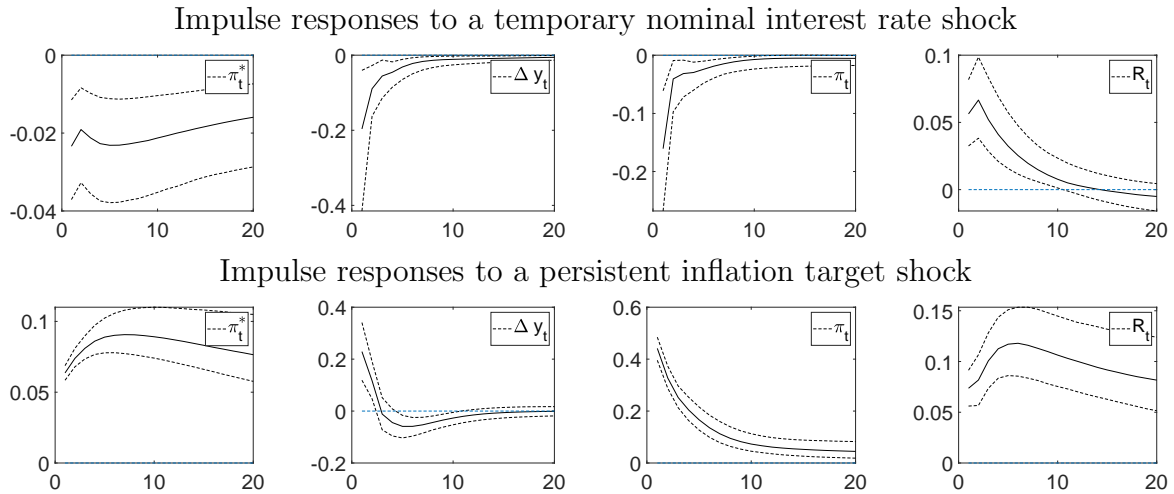


Figure B.3: Model with inflation target estimated from the DSGE model with imperfect information. First row: 90% confidence interval to a nominal interest rate shock. Second row: 90% confidence interval to a persistent inflation target shock. Sample: 1947Q2 to 2019Q1. Horizontal axis: periods after the shock. Vertical axis: percentage change.

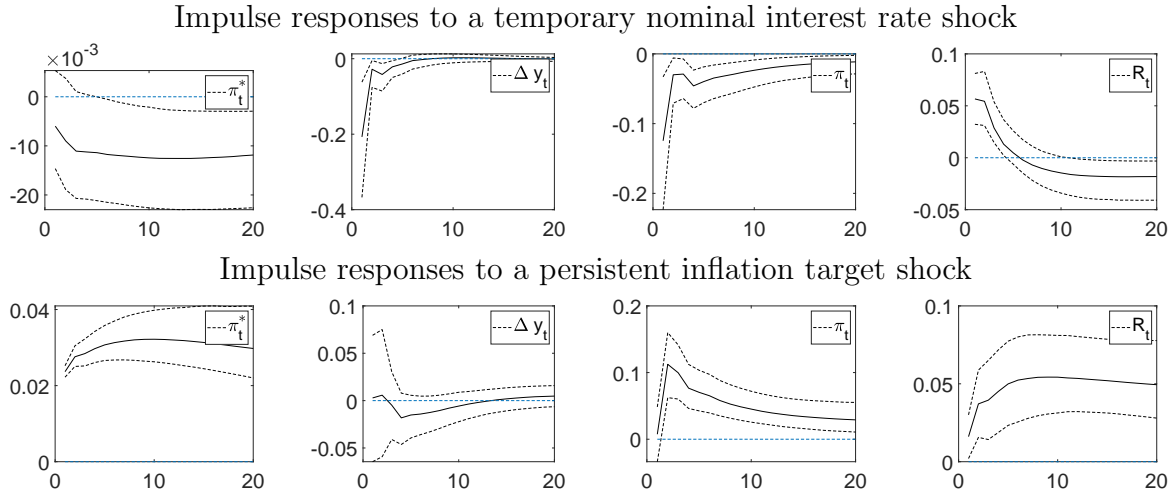


Figure B.4: Model with trend inflation taken from Chan et al. (2018), *UCE*. First row: 90% confidence interval to a nominal interest rate shock. Second row: 90% confidence interval to a persistent inflation target shock. Sample: 1962Q1 to 2016Q1. Horizontal axis: periods after the shock. Vertical axis: percentage change.

B.2 Sensitivity checks: different time samples

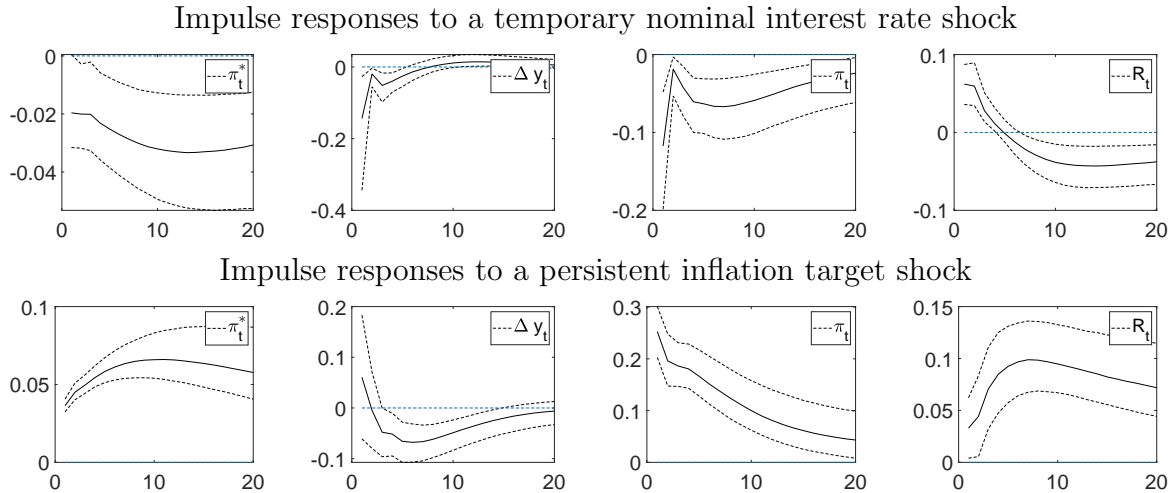


Figure B.5: Model with *PTR* measure from the FRB/US model (Brayton, Laubach, Reifschneider, 2014). First row: 90% confidence interval to a nominal interest rate shock. Second row: 90% confidence interval to a persistent inflation target shock. Sample: 1962Q1 to 2008Q2. Horizontal axis: periods after the shock. Vertical axis: percentage change.

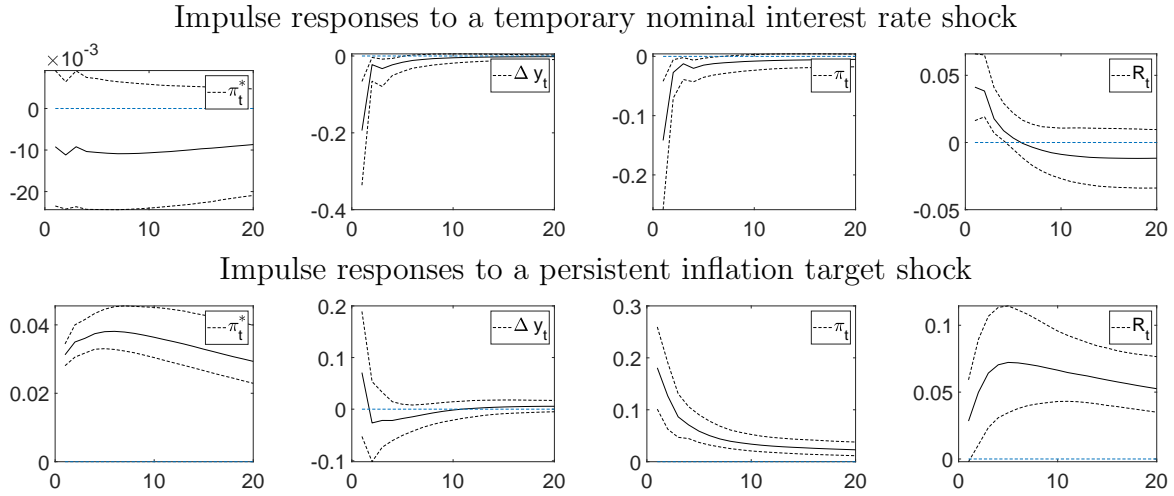


Figure B.6: Model with *PTR* measure from the FRB/US model (Brayton, Laubach, Reifschneider, 2014). First row: 90% confidence interval to a nominal interest rate shock. Second row: 90% confidence interval to a persistent inflation target shock. Sample: 1979Q2 to 2019Q1. Horizontal axis: periods after the shock. Vertical axis: percentage change.

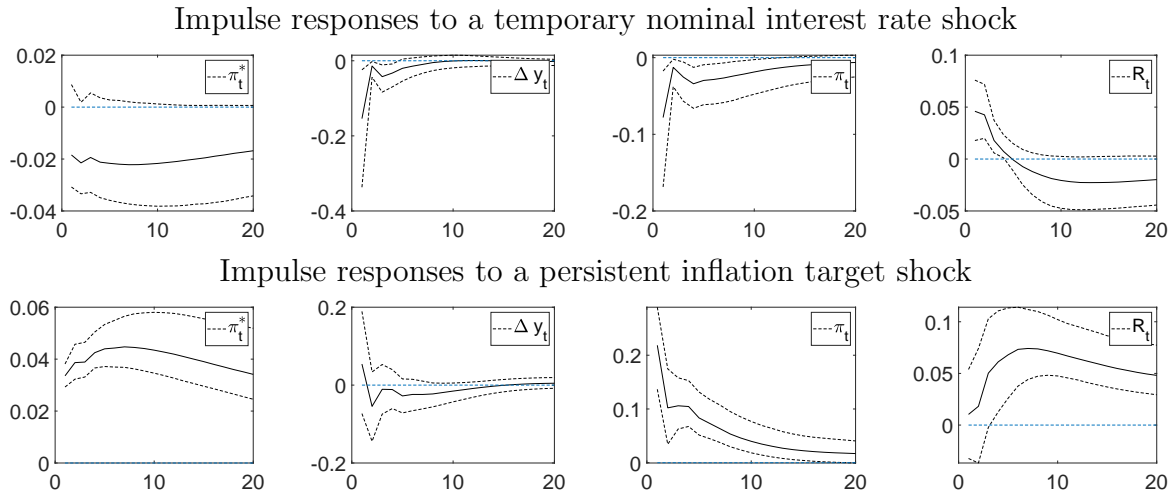


Figure B.7: Model with *PTR* measure from the FRB/US model (Brayton, Laubach, Reifschneider, 2014). First row: 90% confidence interval to a nominal interest rate shock. Second row: 90% confidence interval to a persistent inflation target shock. Sample: 1979Q2 to 2008Q2. Horizontal axis: periods after the shock. Vertical axis: percentage change.