The Neo-Fisher Effect: Econometric Evidence from Empirical and Optimizing Models*

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Abstract

This paper presents an econometric assessment of the presence and importance of the neo-Fisher effect in postwar data. It formulates and estimates an empirical model driven by stationary and nonstationary monetary and real shocks. In accordance with conventional wisdom, temporary increases in the nominal interest-rate are found to lead to a decrease in inflation and output and an increase in real rates. The main result of the paper is that permanent monetary shocks that increase the nominal interest rate and inflation in the long run cause short-run dynamics characterized by increasing interest rates, inflation, and output, and decreasing real rates. Permanent monetary shocks are estimated to explain 45 percent of the variance of inflation changes. The paper then estimates a standard new-Keynesian model driven by permanent and stationary but persistent inflation-target shocks as well as a battery of other conventional monetary and real disturbances. It finds that 50 percent of the variance of inflation changes is accounted for by monetary shocks that induce positive short-run comovement in the interest rate and inflation.

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Keywords: Neo-Fisher Effect, Inflation, Monetary Policy, SVAR Models, New-Keynesian Models, Bayesian Estimation.

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1 Introduction

In the past two decades, a number of countries, especially in the developed world, but increasingly in the developing world as well, have been experiencing chronic below-target rates of inflation and near zero nominal rates. According to the classic Fisher effect, nominal rates and inflation move together in the long run. This positive association is a robust empirical regularity. A less studied empirical question, however, is how permanent monetary shocks that increase nominal interest rates and inflation in the long run affect these two variables in the short run. This paper addresses this question from an econometric perspective. To this end, it develops an empirical model driven by transitory and permanent monetary and real shocks, and estimates it using postwar data.

In accordance with conventional wisdom, the estimated model predicts that a transitory increase in the nominal interest rate causes a fall in inflation, a contraction in real activity, and a rise in the real interest rate. The main result of the paper is that in response to a permanent monetary shock that increases the nominal interest rate and inflation in the long run, these two variables increase in the short run, reaching their higher long-run levels within a year. Furthermore, the adjustment to the permanent monetary shock entails no output loss and is characterized by low real interest rates. Permanent monetary shocks are estimated to be the main drivers of inflation, explaining 45 percent of the variance of changes in this variable. This results represents the first econometric assessment of the presence and importance of the neo-Fisher effect in the data.

The paper then introduces permenent and stationary but prsistent inflation-target shocks into a standard new-Keynesian model in which the central bank follows a Taylor-type interest-rate feedback rule. In the model, the permanent and stationary inflation-target shocks compete with standard transitory monetary shocks, permanent and transitory productivity shocks, a preference shock, and a labor supply shock. The goal of this analysis is not theoretical in nature. A number of papers, many of which are cited below, have demonstrated that in the new-Keynesian model sufficiently persistent movements in the inflation target are accommodated through rising interest rates and inflation in the short run. Instead the objective of the analysis is to estimate the importance of shocks that give rise to this type of dynamics. The estimated new-Keynesian model predicts that 50 percent of the variance of inflation changes is explained by monetary shocks that produce neo-Fisherian dynamics. Taken together, the predictions of the estimated empirical and optimizing models suggest that there is a sizable neo-Fisher effect in the data.

A byproduct of the econometric analysis conducted in this paper is the finding that distinguishing temporary and permanent monetary disturbances provides a resolution of the well-known price puzzle, according to which a transitory increase in the nominal interest rate is estimated to cause a short-run increase in inflation.

This paper is related to a number of theoretical and empirical contributions on the effects of interest-rate policy on inflation and aggregate activity. On the empirical front, it is related to papers that estimate the short run effects of permanent monetary shocks. Ritto, Valle e Azevedo, and Teles (2019), using a VECM approach, confirm the results of this paper and add novel additional evidence for the United Kingdom, France, Germany, and the eurozone. Nicolini (2017) estimates time-varying permanent components of inflation and the nominal rate and finds that they comove closely in the short run. De Michelis and Iacoviello (2016) estimate an SVAR model with permanent monetary shocks to evaluate the Japanese experience with Abenomics. They also study the effect of monetary shocks in the context of a calibrated New Keynesian model. The present paper departs from their work in two important dimensions. First, their SVAR model does not include the short-run policy rate. The inclusion of this variable is key in the present paper, because the short-run comovement of the policy rate with inflation is at the core of the neo-Fisher effect. Second, their theoretical model is not estimated and does not include permanent monetary shocks. By contrast, I allow permanent and transitory monetary shocks to compete in the econometric estimation and, as pointed out above, I find that permanent monetary shocks are the main driver of movements in inflation, while the estimated transitory monetary shock plays a relatively small role. Fève, Matheron, and Sahuc (2010) estimate SVAR and dynamic optimizing models with nonstationary inflation-target shocks to study the role of gradualism in disinflation policy. Specifically, they show, by means of counterfactual experiments, that had the European monetary authority been less gradual in lowering its inflation target during the late 2000s, the eurozone would have suffered a milder slowdown in economic growth. The present paper focuses instead on how the short-run comovement of inflation and the policy rate triggered by a monetary disturbance change depending on whether the impulse is permanent or transitory in nature. King and Watson (2012) find that in estimated New-Keynesian models, postwar U.S. inflation is explained mostly by variations in nonstandard shocks, such as random variations in markups. In this paper, I show that once one allows for permanent monetary shocks, almost half of the variance of inflation changes is explained by monetary disturbances. Sims and Zha (2006) estimate a regime-switching model for U.S. monetary policy and find that during the postwar period there were three policy regime switches, but that they were too small to explain the observed increase in inflation of the 1970s or the later disinflation that started with the Volcker chairmanship. The empirical and optimizing models estimated in the present paper attribute much of the movements in inflation in these two episodes to the permanent nominal shock. Cogley and Sargent (2005) use an autoregressive framework to produce estimates of long-run inflationary expectations. The predictions of both models estimated in the present paper are consistent with their estimates of long-run inflation expectations.

This paper is also related to a body of work that incorporates inflation target shocks in the New-Keynesian model. In this regard, the contribution of the present paper is to allow for a permanent component in this source of inflation dynamics. Garín, Lester, and Sims (2018) show that the new-Keynesian model delivers neo-Fisherian effects in response to increases in the inflation target, provided the latter are sufficiently persistent. They also show that the neo-Fisher effect weakens as firms become more backward looking in their pricing behavior. The present investigation is complementary to this work by providing econometric estimates of both, the persistence of the inflation-target shock and the backward-looking component in the price-setting mechanism. It shows that the estimated parameters give rise to neo-Fisherian dynamics in response to innovations in the stationary component of the inflation target. It also finds that this shock explains a sizable fraction of the variance of changes in the inflation rate. Ireland (2007) estimates a new-Keynesian model with a time-varying inflation target and shows that, possibly as a consequence of the Fed's attempt to accommodate supply-side shocks, the inflation target increased significantly during the 1960s and 1970s and fell sharply in the early 2000s. Using a similar framework as Ireland's, Milani (2009) shows that movements in the inflation target become less pronounced if one assumes that agents must learn about the level of the inflation target.

This paper is also related to recent theoretical developments on the neo-Fisher effect. Schmitt-Grohé and Uribe (2010, 2014) show that the neo-Fisher effect obtains in the context of standard dynamic optimizing models with flexible prices. Specifically, they show that a credible increase in the nominal interest rate that is expected to be sustained for a prolonged period of time can give rise to an immediate increase in inflation. Schmitt-Grohé and Uribe (2010, 2014) show that this result also obtains in models with nominal rigidity. Cochrane (2017) shows that if the monetary policy regime is passive, a temporary increase in the nominal interest rate can cause an increase in the short-run rate of inflation. This notion of the neo-Fisher effect is different from the one studied in the present paper, which associates the neo-Fisher effect with the short-run response of inflation to permanent monetary shocks. Williamson (2018) considers a model with flexible-price and sticky-price goods and shows that movements in the interest rate generate movements in expected flexible-price inflation of equal size. Cochrane (2014) and Williamson (2016) provide nontechnical expositions of the neo-Fisher effect. Lukmanova and Rabitsch (2019) extend the analysis in this paper by incorporating imperfect information along the lines of Erceg and Levin (2003). They find that in response to a persistent increase in the inflation target the neo-Fisher effect takes place with some delay. Finally, Aruoba and Schorfheide (2011) estimate a model that combines new Keynesian and monetary frictions. The permanent component of inflation predicted by this model is in line with the one estimated in this paper.

The remainder of the paper is organized as follows: Section 2 presents evidence consistent with the long-run validity of the Fisher effect. Section 3 presents the proposed empirical model and discusses the identification and estimation strategies. Section 4 presents the estimated short-run effects of permanent monetary shocks on inflation, the interest rate, and output. It also reports the importance of these shocks in explaining changes in the rate of inflation. Section 5 presents the New-Keynesian model and discusses its econometric estimation. Section 6 presents the estimated effects of permanent and stationary but persistent innovations in the inflation target on inflation, the interest rate, and output, and their importance in explaining changes in inflation. Section 7 closes the paper with a discussion of actual monetary policy in the ongoing low-inflation era from the perspective of the two estimated models. Data and replication code are available online.[1]

2 Preliminaries: Evidence on the Fisher Effect

What is the effect of an increase in the nominal interest rate on inflation and output? One can argue on theoretical grounds that the answer to this question depends on (a) whether the increase in the interest rate is expected to be permanent or transitory; and (b) whether the horizon of interest is the short run or the long run. Table 1 suggests an answer that summarizes both the starting point and the contribution of this paper.

A large body of empirical and theoretical studies argue that a transitory positive disturbance in the nominal interest rate causes a transitory increase in the real interest rate, which in turn depresses aggregate demand and inflation, entry (1,2) in the table (see, for example, Christiano, Eichenbaum, and Evans, 2005, especially figure 1). Similarly, a property of virtually all modern models studied in monetary economics is that a transitory increase in the nominal interest rate has no effect on inflation in the long run, entry (1,1). By contrast,

[1] http://www.columbia.edu/~mu2166.

Table 1: Effect of an Increase in the Nominal Interest Rate on Inflation

	Long Run Effect	**Short** Run Effect
Transitory shock	0	$\downarrow$
Permanent shock	$\uparrow$	$\boxed{\uparrow ?}$

Note. Entry (2,1): The Fisher effect. Entry (2,2) : The Neo-Fisher effect.

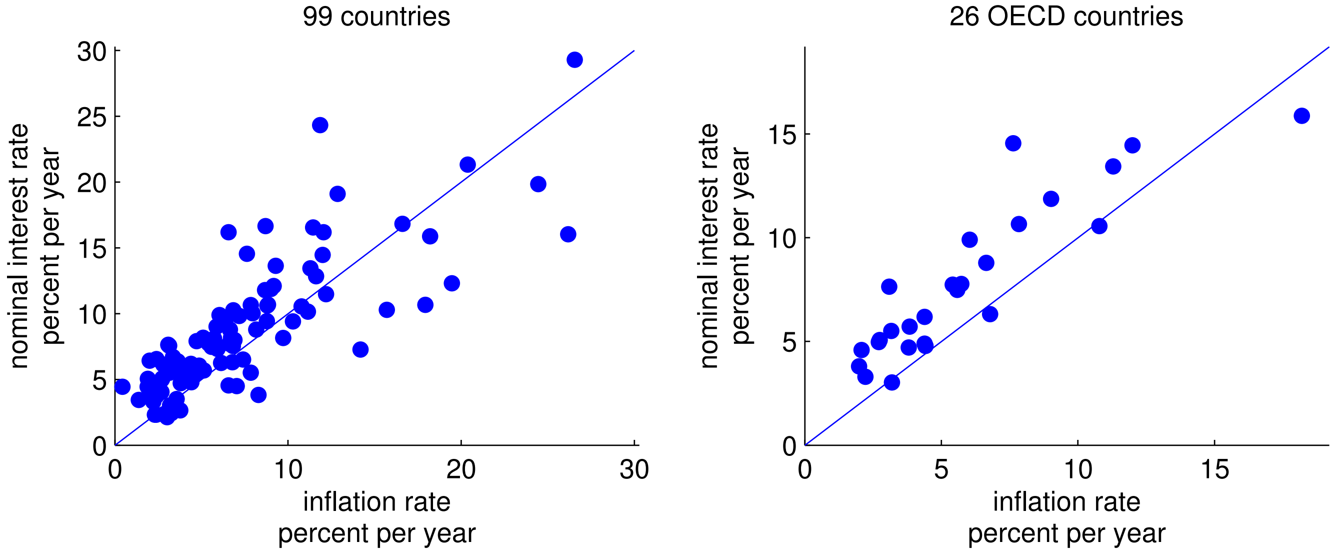
if the increase in the nominal interest rate is permanent, sooner or later, inflation will have to increase by roughly the same magnitude, if the real interest rate, given by the difference between the nominal rate and expected inflation, is not determined by nominal factors in the long run, entry (2,1) in the table. This one-to-one long-run relationship between nominal rates and inflation is known as the Fisher effect. The neo-Fisher effect says that a permanent increase in the nominal interest rate causes an increase in inflation not only in the long run but also in the short run, entry (2,2) in the table. Ascertaining whether the neo-Fisher effect is present in U.S. data is the focus of the present investigation.

Before plunging into an econometric analysis of the neo-Fisher effect, I wish to briefly present evidence consistent with the Fisher effect. The rationale for doing so is that my empirical analysis of the neo-Fisher effect assumes the empirical validity of the Fisher effect, interpreted as a description of the long-run relationship between the nominal interest rate and inflation. The Fisher equation takes the form

$$i_t = R_t + E_t \pi_{t+1}$$

where i_t denotes the nominal interest rate, R_t denotes the real interest rate, π_t denotes the inflation rate, and E_t denotes expectations conditional on information available in period t. This expression says that the nominal interest rate incorporates two types of compensation to lenders. One is a compensation for the loss of purchasing power of money due to expected inflation during the investment period, and the other is a real compensation for postponing

Figure 1: Average Inflation and Nominal Interest Rates: Cross-Country Evidence



Notes. Each dot represents one country. For each country, averages are taken over the longest available uninterrupted sample. The average sample covers the period 1989 to 2012. The solid line is the 45-degree line. Source: World Development Indicators (WDI) available at data.worldbank.org/indicator. Inflation is the CPI inflation rate (code FP.CPI.TOTL.ZG). The nominal interest rate is the treasury bill rate. The WDI database provides this time series not directly, but as the difference between the lending interest rate (code FR.INR.LEND) and the risk premium on lending (lending rate minus treasury bill rate, code FR.INR.RISK). Countries for which one or more of these series were missing as well as outliers, defined as countries with average inflation or interest rate above 50 percent, were dropped from the sample.

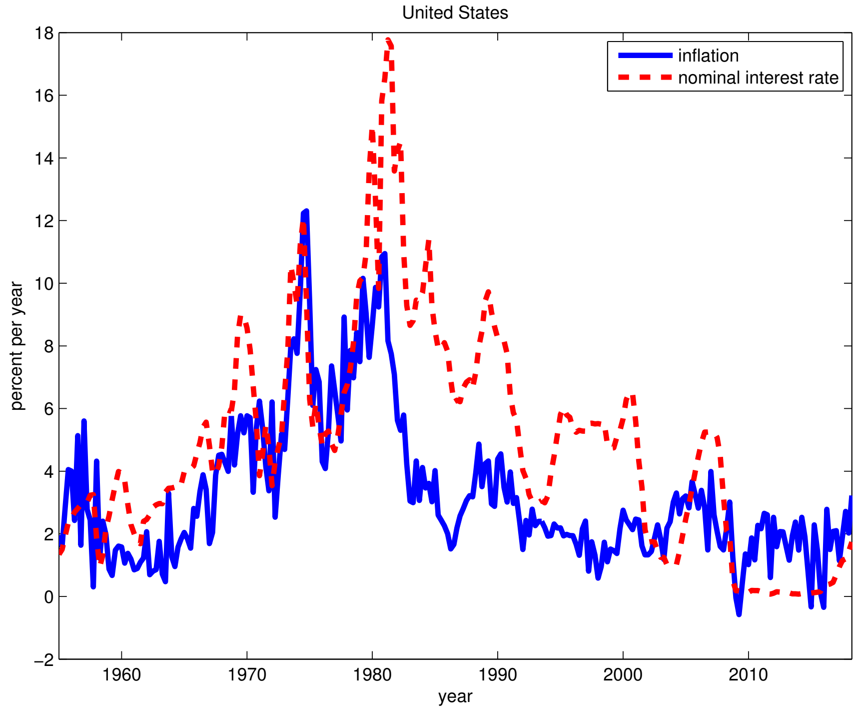
consumption. Assuming that on average expected inflation equals actual inflation, we have that

$$i = R + \pi,$$

where variables without a subscript refer to long-run averages. Further assuming that the average real interest rate is determined mostly by non-monetary factors (such as technology, demographics, distortionary taxes, or economic openness), and that long-run variations in inflation are larger than variations in real rates, the above expression delivers a near one-to-one long-run relationship between the nominal interest rate and the rate of inflation.

The left panel of figure 1 displays times averages of inflation and nominal interest rates across 99 countries. Each dot in the graph corresponds to one country. The typical sample

Figure 2: Inflation and the Nominal Interest Rate in the United States



Notes. Quarterly frequency. Source: See section 3.3.

covers the period 1989 to 2012. The scatter plot is consistent with the Fisher effect in the sense that increases in the nominal interest rate are roughly associated with one-for-one increases in the rate of inflation. This is also the case for the subsample of OECD countries (right panel), which are on average half as inflationary as the group of non-member countries. Figure 2 presents empirical evidence consistent with the Fisher effect from the time perspective. It plots inflation and the nominal interest rate in the United States over the period 1954:Q4 to 2018:Q2. In spite of the fact that the data have a quarterly frequency, it is possible to discern a positive long-run association between inflation and the nominal rate. This relation becomes even more apparent if one removes the cyclical component of both series as in Nicolini (2017), who separates trend and cycle using the HP filter. The high-inflations of the 1970s and 1980s coincided with high levels of the interest rate. Symmetrically, the relatively low rates of inflation observed since the early 1990s have been accompanied by low nominal rates.

The Fisher effect, however, does not provide a prediction of when inflation should be expected to catch up with a permanent increase in the nominal interest rate. It only states that it must eventually do so. A natural question, therefore, is how quickly does inflation adjust to a permanent increase in the nominal interest rate? The remainder of this paper is devoted to addressing this question.

3 An Empirical Model

The empirical model aims to capture the dynamics of three macroeconomic indicators, namely, the logarithm of real output per capita, denoted y_t, the inflation rate, denoted π_t and expressed in percent per year, and the nominal interest rate, denoted i_t and also expressed in percent per year. (Section 4.1 extends the model to include the ten-year spread.) I assume that y_t, π_t, and i_t are driven by four exogenous shocks: a nonstationary (or permanent) monetary shock, denoted X_t^m, a stationary (or transitory) monetary shock, denoted z_t^m, a nonstationary nonmonetary shock, denoted X_t^n, and a stationary nonmonetary shock, denoted z_t^n. The focus of my analysis is the short-run effects of permanent and transitory interest-rate shocks, embodied in the exogenous variables X_t^m and z_t^m. The shocks X_t^n and z_t^n are meant to capture the nonstationary and stationary components of combinations of nonmonetary disturbances of different natures, such as technology shocks, preference shocks, or markup shocks, which my analysis is not intended to individually identify.

I assume that output is cointegrated with X_t^n and that inflation and the nominal interest rate are both cointegrated with X_t^m. Because X_t^m is the permanent component of both inflation and the nominal interest rate, throughout the paper, I refer to it as a permanent monetary shock. The exogenous variable X_t^m admits different interpretations. Under certain conditions, it can be interpreted as an inflation-target shock. For example, I show later that X_t^m fell significantly in the United States in the first half of the 1980s. It is reasonable to interpret this movement in X_t^m as a reduction in the U.S. inflation target. In other contexts, however, movements in X_t^m are less interpretable as changes in the inflation target. For example, the Bank of Japan lowered interest rates to zero in the mid 1990s and continues to keep them at that level to date. At the same time the average Japanese rate of inflation has moved further below its target of 2 percent. Regardless of how X_t^m is interpreted, the focus of the present paper is the short-run behavior of inflation and the nominal interest rate in response to a shock that changes both of them in the long run, independently of whether or not this long-run movement is accompanied by a change in the communicated inflation target.

I define the following vector containing stationary variables

$$\begin{bmatrix} \widehat{y}_t \\ \widehat{\pi}_t \\ \widehat{i}_t \end{bmatrix} \equiv \begin{bmatrix} y_t - X_t^n \\ \pi_t - X_t^m \\ i_t - X_t^m \end{bmatrix}.$$

The variable $\widehat{y}_t$ represents detrended output, and $\widehat{\pi}_t$ and $\widehat{i}_t$ represent the cyclical components of inflation and the nominal interest rate, respectively. Because inflation and the nominal interest rate share a common nonstationary component, they are cointegrated. In other words, the Fisher effect holds, in the sense that shocks that cause a permanent change in the nominal interest rate also cause the same permanent change in the inflation rate. But the assumption that π_t and i_t are cointegrated says nothing about the neo-Fisher effect, that is, about the short-run effect on inflation and output of a permanent monetary shock.

I assume that the law of motion of the vector $\begin{bmatrix} \widehat{y}_t & \widehat{\pi}_t & \widehat{i}_t \end{bmatrix}$ takes the autoregressive form[2]

$$\begin{bmatrix} \widehat{y}_t \\ \widehat{\pi}_t \\ \widehat{i}_t \end{bmatrix} = \sum_{i=1}^{L} B_i \begin{bmatrix} \widehat{y}_{t-i} \\ \widehat{\pi}_{t-i} \\ \widehat{i}_{t-i} \end{bmatrix} + C \begin{bmatrix} \Delta X_t^m \\ z_t^m \\ \Delta X_t^n \\ z_t^n \end{bmatrix} \tag{1}$$

[2]The presentation of the model omits intercepts. A detailed exposition is in Appendix A.

where $\Delta X_t^m \equiv X_t^m - X_{t-1}^m$ and $\Delta X_t^n \equiv X_t^n - X_{t-1}^n$ denote changes in the nonstationary shocks. The objects B_i, for $i = 1, \ldots, L$, are 3-by-3 matrices of coefficients, C is a 3-by-4 matrix of coefficients, and L is a scalar denoting the lag length of the autoregressive block containing endogenous variables.

I assume that the driving forces follow univariate AR(1) laws of motion of the form

$$\begin{bmatrix} \Delta X_{t+1}^m \\ z_{t+1}^m \\ \Delta X_{t+1}^n \\ z_{t+1}^n \end{bmatrix} = \rho \begin{bmatrix} \Delta X_t^m \\ z_t^m \\ \Delta X_t^n \\ z_t^n \end{bmatrix} + \psi \begin{bmatrix} \epsilon_{t+1}^1 \\ \epsilon_{t+1}^2 \\ \epsilon_{t+1}^3 \\ \epsilon_{t+1}^4 \end{bmatrix} \tag{2}$$

where ρ and ψ are 4-by-4 diagonal matrices of coefficients, and ϵ_t^i are i.i.d. disturbances distributed $N(0, 1)$.

3.1 Identification Restrictions

Thus far, I have introduced three identification assumptions, namely, that output is cointegrated with X_t^n and that inflation and the interest rate are cointegrated with X_t^m. In addition, to identify the transitory monetary shock, I adopt a methodology pioneered by Uhlig (2005) and impose sign restrictions on the impact effect of these disturbances on endogenous variables. Specifically, I assume that

$$C_{12} \leq 0 \text{ and } C_{22} \leq 0,$$

where C_{ij} denotes the (i, j) element of C. These two conditions restrict transitory exogenous increases in the interest rate to have nonpositive impact effects on output and inflation. The results are robust to assuming that monetary shocks have no impact effect on output and inflation (Christiano, Eichenbaum, and Evans, 2005). Finally, without loss of generality, I introduce the normalizations $C_{32} = C_{14} = 1$.

To establish the identifiability of the estimated parameters of the model I apply the test proposed by Iskrev (2010). This procedure consists in calculating the derivative of the predicted autocovariogram of the observables with respect to the vector of estimated parameters. Identifiability obtains if the matrix of derivatives has rank equal to the length of the vector of estimated parameters. Evaluating the parameters of the model at their posterior mean, I find that the rank condition is satisfied. This means that in a neighborhood of the posterior mean, the predicted covariogram is uniquely determined by the value of the vector of estimated parameters.

3.2 Observables, Priors, and Estimation Method

All variables in the system (1)-(2) are unobservable. To estimate the parameters of the matrices defining this system, I use observable variables for which the model has precise predictions. Specifically, I use observations of output growth, Δy_t, the change in the nominal interest rate, Δi_t, and the interest-rate-inflation differential,

$$r_t \equiv i_t - \pi_t.$$

These three variables are stationary by the maintained long-run identification assumptions. The following equations link the observables to variables included in the unobservable system (1)-(2):

$$\begin{aligned} \Delta y_t &= \widehat{y}_t - \widehat{y}_{t-1} + \Delta X_t^n, \\ r_t &= \widehat{i}_t - \widehat{\pi}_t, \\ \Delta i_t &= \widehat{i}_t - \widehat{i}_{t-1} + \Delta X_t^m \end{aligned} \tag{3}$$

I assume that Δy_t, r_t, and Δi_t are observed with measurement error. Formally, letting o_t be the vector of variables observed in quarter t, I assume that

$$o_t = \begin{bmatrix} \Delta y_t \\ r_t \\ \Delta i_t \end{bmatrix} + \mu_t \tag{4}$$

where μ_t is a 3-by-1 vector of measurement errors distributed i.i.d. $N(\emptyset, R)$, and R is a diagonal variance-covariance matrix.

To compute the likelihood function, it is convenient to use the state-space representation of the model. Define the vector of endogenous variables $\widehat{Y}_t \equiv [\widehat{y}_t \quad \widehat{\pi}_t \quad \widehat{i}_t]'$ and the vector of driving forces $u_t \equiv [\Delta X_t^m \quad z_t^m \quad \Delta X_t^n \quad z_t^n]'$. Then the state of the system is given by

$$\xi_t \equiv \begin{bmatrix} \widehat{Y}_t \\ \widehat{Y}_{t-1} \\ \vdots \\ \widehat{Y}_{t-L+1} \\ u_t \end{bmatrix},$$

and the system composed of equations (1)-(4) can be written as follows:

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

$$o_t = H'\xi_t + \mu_t,$$

where the matrices F, P, and H are known functions of B_i, $i = 1, \dots L$, C, ρ, and ψ and are presented in Appendix A. This representation allows for the use of the Kalman filter to evaluate the likelihood function, which facilitates estimation.

I estimate the model on quarterly data using Bayesian techniques. I include 4 lags in

Table 2: Prior Distributions

Parameter	Distribution	Mean.	Std. Dev.
Main diagonal elements of B_1	Normal	0.95	0.5
All other elements of B_i, $i = 1, \ldots, L$	Normal	0	0.25
C_{21}, C_{31}	Normal	-1	1
$-C_{12}, -C_{22}$	Gamma	1	1
All other estimated elements of C	Normal	0	1
ψ_{ii}, $i = 1, 2, 3, 4$	Gamma	1	1
ρ_{ii}, $i = 1, 2, 3$	Beta	0.3	0.2
ρ_{44}	Beta	0.7	0.2
R_{ii}	Uniform $\left[0, \frac{\text{var}(o_t)}{10}\right]$	$\frac{\text{var}(o_t)}{10\times 2}$	$\frac{\text{var}(o_t)}{10\times\sqrt{12}}$

equation (1) ($L = 4$), which is a lag length commonly adopted in the related literature (e.g., Christiano, Eichenbaum, and Evans, 2005). Table 2 displays the prior distributions of the estimated coefficients. The prior distributions of all elements of B_i, for $i = 1, \ldots, L$, are assumed to be normal. In the spirit of the Minnesota prior (MP), I assume a prior parameterization in which at the mean of the prior parameter distribution the elements of $\widehat{Y}_t$ follow univariate autoregressive processes. So when evaluated at their prior mean, only the main diagonal of B_1 takes nonzero values and all other elements of B_i for $i = 1, \ldots, L$ are nil. Because the system (1)-(2) is cast in terms of stationary variables, I deviate from the random-walk assumption of the MP and instead impose an autoregressive coefficient of 0.95 in all equations, so that all elements along the main diagonal of B_1 take a prior mean of 0.95. I assign a prior standard deviation of 0.5 to the diagonal elements of B_1, which implies a coefficient of variation close to one half (0.5/0.95). As in the MP, I impose lower prior standard deviations on all other elements of the matrices B_i for $i = 1, \ldots, L$, and set them to 0.25.

The coefficient C_{21} takes a normal prior distribution with mean -1 and standard deviation 1. The value assigned to the mean of this distribution implies a prior belief that the impact effect of a permanent interest rate shock on inflation, given by $1 + C_{21}$, can be positive or negative with equal probability. I make the same assumption about the impact effect of permanent monetary shocks on the nominal interest rate itself, therefore assigning to C_{31} a normal prior distribution with mean -1 and standard deviation 1. As explained above, $-C_{12}$ and $-C_{22}$ are restricted to be nonnegative. I assume that these objects have Gamma prior distributions with mean and standard deviations equal to one. Thus, identification of the transitory monetary shock is achieved via restrictions of prior distributions. All other parameters of the matrix C, except C_{32} and C_{14}, which are normalized to unity, are assigned a normal prior distribution with mean 0 and standard deviation 1.[3]

The parameters ψ_{ii}, for $i = 1, \ldots, 4$, representing the standard deviations of the four exogenous innovations in the AR(1) process (2) are all assigned Gamma prior distributions with mean and standard deviation equal to one. I impose nonnegative serial correlations on the four exogenous shocks ($\rho_{ii} \in (0, 1)$ for $i = 1, \ldots, 4$), and adopt Beta prior distributions for these parameters. I assume relatively small means of 0.3 for the prior serial correlations of the two monetary shocks and the nonmonetary nonstationary shock and a relatively high mean of 0.7 for the stationary nonmonetary shock. The small prior mean serial correlations for the monetary shocks reflect the usual assumption in the related literature of serially uncorrelated monetary shocks. The relatively small prior mean serial correlation for the nonstationary nonmonetary shock reflects the fact that the growth rate of the stochastic trend of output is typically estimated to have a small serial correlation. Similarly, the relatively high prior mean of the serial correlation of the stationary nonmonetary shock

[3]One might wonder whether a rationale like the one I used to set the prior mean of C_{21} could apply to C_{13}, the parameter governing the impact output effect of a nonstationary nonmonetary shock, X_t^n, which is given by $1 + C_{13}$. To see why a prior mean of 0 for C_{13} might be more reasonable, consider the effect of an innovation in the permanent component of TFP, which is perhaps the most common example of a nonstationary nonmonetary shock in business-cycle analysis. Specifically, consider a model with the Cobb-Douglas production function $y_t = X_t^n + z_t^n + \alpha k_t + (1 - \alpha)h_t$ expressed in logarithms. Consider first a situation in which capital and labor, denoted k_t and h_t, do not respond contemporaneously to changes in X_t^n. In this case, the contemporaneous effect of a unit increase in X_t^n on output is unity, which implies that a prior mean of 1 for $1+C_{13}$, or equivalently a prior mean of 0 for C_{13} is the most appropriate. Now consider the impact effect of changes in X_t^n on k_t and h_t. It is reasonable to assume that the stock of capital, k_t, is fixed in the short run. The response of h_t depends on substitution and wealth effects. The former tends to cause an increase in employment, and the latter a reduction. Which effect will prevail is not clear, giving credence to a prior of 0 for C_{13}. One could further think about the role of variable input utilization. An increase in X_t^n is likely to cause an increase in utilization, further favoring a prior mean of 0 over one of -1 for C_{13}.

reflects the fact that typically these shocks (e.g., the stationary component of TFP) are estimated to be persistent. The prior distributions of all serial correlations are assumed to have a standard deviation of 0.2. The variances of all measurement errors are assumed to have a uniform prior distribution with lower bound 0 and upper bound of 10 percent of the sample variance of the corresponding observable indicator.

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

3.3 Data and Unit Root Tests

I estimate the empirical model on quarterly U.S. data spanning the period 1954:Q3 to 2018:Q2. The proxy for y_t is the logarithm of real GDP seasonally adjusted in chained dollars of 2012 minus the logarithm of the civilian noninstitutional population 16 years old or older. The proxy for π_t is the growth rate of the implicit GDP deflator expressed in percent per year. In turn, the implicit GDP deflator is constructed as the ratio of GDP in current dollars and real GDP both seasonally adjusted. The proxy for i_t is the monthly Federal Funds Effective rate converted to quarterly frequency by averaging and expressed in percent per year. The source for nominal and real GDP is the Bureau of Economic Analysis (bea.gov), the source for population is the Bureau of Labor Statistics (bls.gov), and the source for the Federal Funds rate is the Board of Governors of the Federal Reserve System (federalreserve.gov). The ten-year rate used in the expanded model of section 4.1.4 is from FRED (series GS10, 10-Year Treasury Constant Maturity Rate).

Before presenting the predictions of the empirical model, I briefly report standard unit-root tests based on univariate representations of the data. The augmented Dickey-Fuller (ADF) test, which is a commonly used test of the null hypothesis of a unit root, fails to reject the null hypothesis for y_t, i_t, and π_t, and rejects it for $i_t - \pi_t$ at standard confidence levels of 10 percent or less.[4] These results are in line with the assumption that the interest rate, inflation, and output, all possess unit roots, and that the interest-inflation differential is stationary.

4 Effects of Permanent and Transitory Monetary Shocks in the Empirical Model

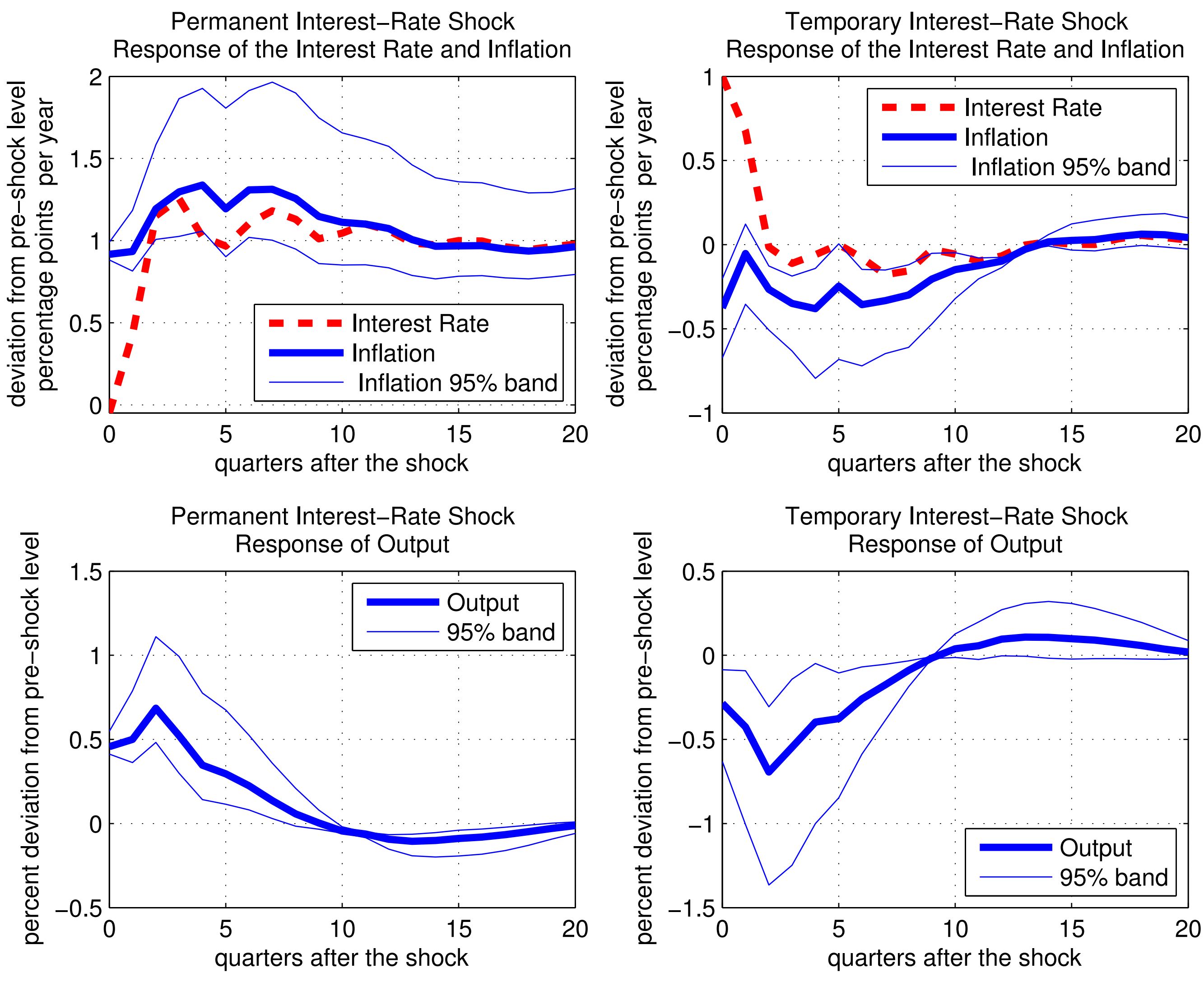
Figure 3 displays mean posterior estimates of the responses of inflation, output, and the nominal interest rate to permanent (left panels) and temporary (right panels) interest-rate shocks, along with asymmetric 95-percent error bands constructed using the method proposed by Sims and Zha (1999). The size of the permanent interest-rate shock is set to ensure that on average it leads to a 1 percent increase in the nominal interest rate in the long run, where the average is taken over the posterior distribution of impulse responses. Because inflation is cointegrated with the nominal interest rate, it also is expected to increase by 1 percent in the long run. The main result conveyed by figure 3 is that the adjustment of inflation to its higher long-run level takes place in the short run. In fact, inflation increases by 1 percent on impact and remains around that level thereafter.

On the real side of the economy, the permanent increase in the nominal interest rate does not cause a contraction in aggregate activity. Indeed, output exhibits a transitory expansion.[5] This effect could be the consequence of low real interest rates resulting from

[4] Specifically, for a random variable x_t, the ADF test considers the null hypothesis that $x_t = x_{t-1} + \eta_0 + \sum_{i=1}^{I} \eta_i \Delta x_{t-i} + \epsilon_t$, where ϵ_t is white noise, against the alternative hypothesis that $x_t = \delta x_{t-1} + \gamma t + \eta_0 + \sum_{i=1}^{I} \eta_i \Delta x_{t-i} + \epsilon_t$, with $\delta < 1$. For i_t and π_t, I restrict γ to be zero (no time trend), and for $i_t - \pi_t$, I restrict γ and η_0 to be zero (no time trend or drift). I include 4 lags of Δx_t ($I = 4$). The p values for $x_t = y_t, i_t, \pi_t, i_t - \pi_t$ are, respectively, 0.604, 0.131, 0.135, and 0.0351.

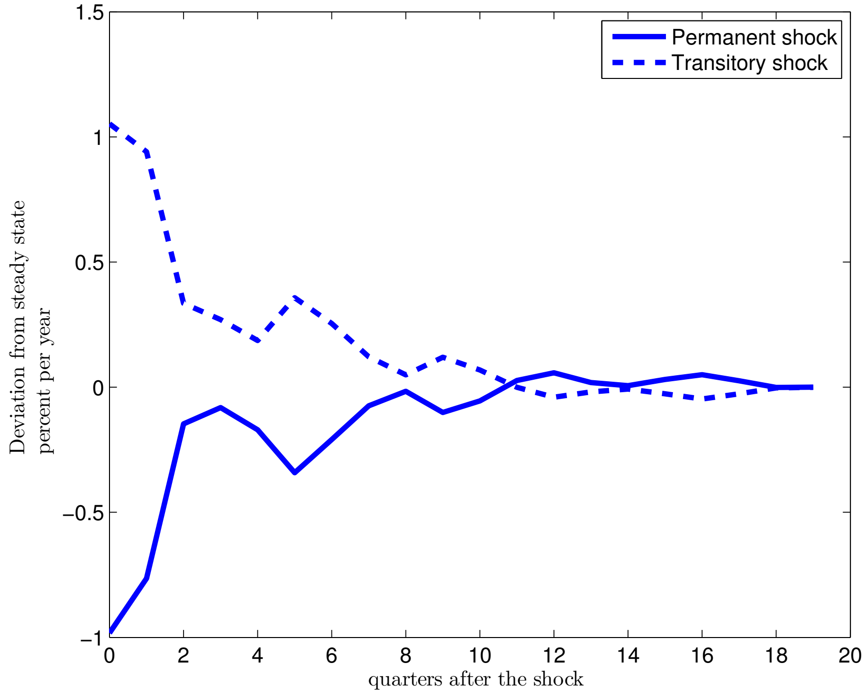
[5] In period 11, the error band narrows to 3 basis points. This is not an uncommon feature of error bands of the type proposed by Sims and Zha (see, for example, the applications in their paper). It is a reflection of little uncertainty about the position of the impulse response in that period. Additional uncertainty may remain about other features of the impulse response in that period, such as its shape. A similar comment applies for the responses of inflation and output to a temporary monetary shock.

Figure 3: Impulse Responses to Permanent and Temporary Interest-Rate Shocks: Empirical Model



Notes. Impulse responses are posterior mean estimates. Asymmetric error bands are computed using the Sims-Zha (1999) method. Replication code: `plot_ir_chain.m` in `empirical_model.zip`.

Figure 4: Response of the Real Interest Rate to Permanent and Transitory Interest-Rate Shocks: Empirical Model

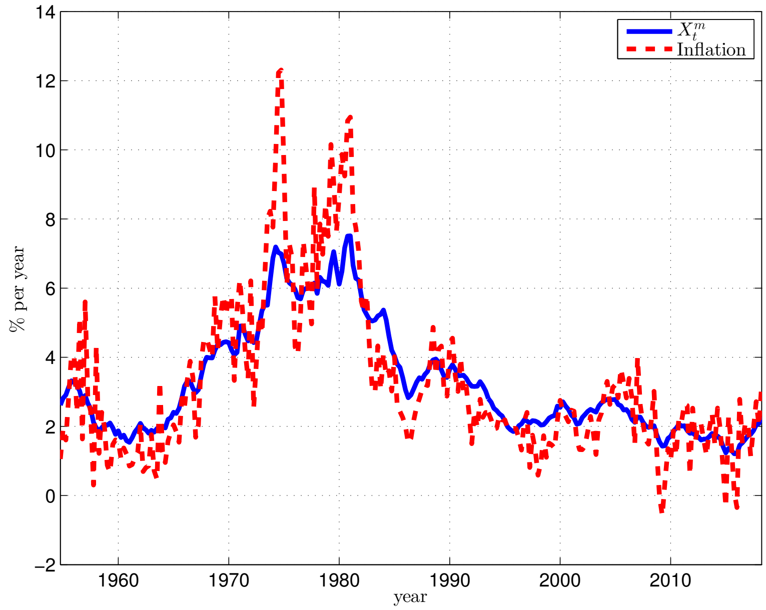


Notes. Posterior mean estimates. The real interest rate is defined as $i_t - E_t\pi_{t+1}$. Replication code: `real_interest_rate.m` in `empirical_model.zip`.

the swift reflation of the economy following the permanent interest-rate shock. Figure 4 displays with a solid line the response of the real interest rate, defined as $i_t - E_t\pi_{t+1}$, to a permanent interest-rate shock. Because of the faster response of inflation relative to that of the nominal interest rate, the real interest rate falls by almost 1 percent on impact and converges to its steady-state level from below, implying that the entire adjustment to a permanent interest-rate shock takes place in the context of low real interest rates.

The responses of nominal and real variables to a transitory interest-rate shock, shown in the right panels of figure 3 are quite conventional. Both inflation and output fall below trend and remain low for a number of quarters. The real interest rate, whose impulse response is shown with a broken line in figure 4, increases on impact and remains above its long-run value during the transition, which is in line with the contractionary effect of the transitory increase in the interest rate.

Figure 5: Inflation and Its Permanent Component: Empirical Model



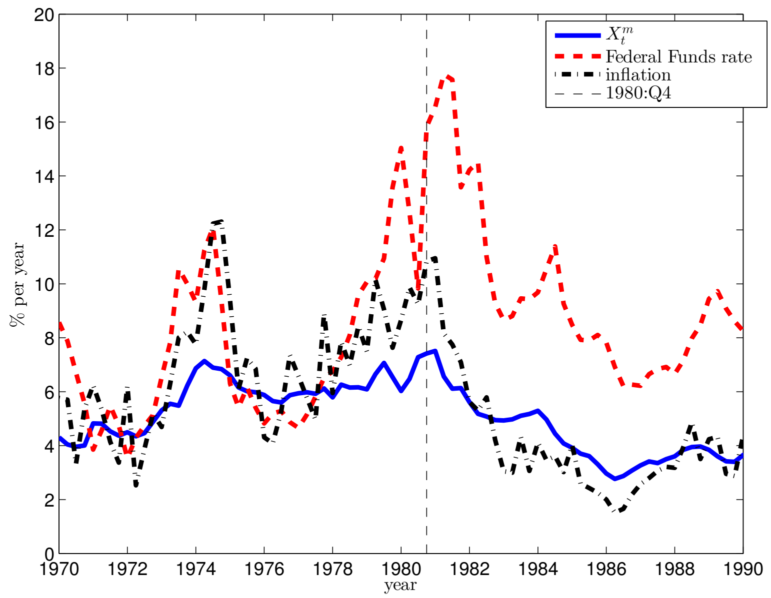
Note. Quarterly frequency. The inferred path of the permanent component of inflation, X_t^m, was computed by Kalman smoothing and evaluating the empirical model at the posterior mean of the estimated parameter vector. The initial value of X_t^m was normalized to make the average value of X_t^m equal to the average rate of inflation over the sample period, 1954:Q4 to 2018:Q2. Replication code: `plot_xm.m` in `empirical_model.zip`.

Interestingly, the model does not suffer from the price puzzle, which plagues empirical models with only stationary monetary shocks, pointing to the importance of explicitly distinguishing between temporary and permanent shocks.

What does the permanent component of U.S. inflation look like according to the estimated empirical model? Figure 5 displays the actual rate of inflation along with its permanent component, given by the nonstationary monetary shock, X_t^m, over the estimation period (1954:Q4 to 2018:Q2). The path of X_t^m resembles the estimate of long-run inflation expectations reported in much of the related empirical literature, see, for example, Cogley and Sargent (2005) and the references cited therein. This result is reassuring because it shows that the short-run effects of temporary and permanent monetary shocks reported in figure 3 are not based on an estimate of the permanent component of inflation that is at odds with those obtained in the related literature.

Figure 5 reveals a number of features of the low-frequency drivers of postwar inflation in

Figure 6: The Volcker Disinflation



Note. See note to figure 5.

the United States. First, inflationary factors began to build up much earlier than the oil crisis of the early 1970s. Indeed, the period 1963 to 1972, corresponding to the last seven years in office of Fed Chairman William M. Martin and the first three years of Chairman Arthur F. Burns, were characterized by a continuous increase in the permanent component of inflation, from about 2 percent per year to about 5 percent per year. Second, the high inflation rates associated with the oil crises of the mid 1970s were not entirely due to nonmonetary shocks. The Fed itself contributed by maintaining X_t^m at the high level it had reached prior to the oil crisis. Third, the figure indicates that the normalization of rates that began in 2015 and put an end to seven years of near-zero nominal rates triggered by the global financial crisis is interpreted by the empirical model as having a significant permanent component.

It is of interest to zoom in on the Volcker era, which arguably represents the largest disinflation episode in the postwar United States. Figure 6 displays the nominal interest rate, the inflation rate, and the permanent monetary shock X_t^m over the period 1970 to 1990. The vertical broken line indicates 1980:Q4, which according to Goodfriend and King (2005) represents the beginning of the "deliberate disinflation." The graph suggests that

Table 3: Variance Decomposition: Empirical Model

	Δy_t	$\Delta \pi_t$	Δi_t
Permanent Monetary Shock, ΔX_t^m	9.1	44.6	21.9
Transitory Monetary Shock, z_t^m	2.1	6.2	10.9
Permanent Non-Monetary Shock, ΔX_t^n	49.8	27.9	13.5
Transitory Non-Monetary Shock, z_t^n	39.1	21.4	53.7

Note. Posterior means. The variables Δy_t, $\Delta \pi_t$, and Δi_t denote output growth, the change in inflation, and the change in the nominal interest rate, respectively. Replication code: `table_vardecomp.m` in `empirical_model.zip`.

according to the estimated model the Volcker policy was a combination of a large transitory increase in the policy rate and a gradual decrease in its permanent component. The impulse responses shown in figure 3 suggest that both of these measures are deflationary. This is consistent with the fact that, as shown in figure 6, inflation fell faster than its permanent component. Specifically, at the beginning of the stabilization program, 1980:Q4, inflation was about 3 percentage points above its permanent component, whereas by 1983 it was already below it, in spite of the fact that the permanent component continued to fall. In fact, one of the most remarkable features of the Volcker disinflation is the speed at which inflation fell. This transition toward low inflation was characterized by depressed economic activity, which is consistent with the enormous magnitude of the hike in the transitory component of the interest rate. According to the empirical model, a decrease in the permanent component of the interest rate would have sufficed to bring about low inflation without unemployment.[6]

How important are nonstationary monetary shocks? The relevance of the neo-Fisher effect depends not only on whether it can be identified in actual data, which has been the focus of this section thus far, but also on whether permanent monetary shocks play a significant role in explaining short-run movements in the inflation rate. If nonstationary monetary shocks played a marginal role in explaining cyclical movements in nominal variables, the neo-Fisher effect would just be an interesting curiosity. To shed light on this question, table 3

[6]This statement is, of course, subject to the Lucas critique. However, it is confirmed by the optimizing model I study in section 5.

displays the variance decomposition of the three variables of interest, output growth, the change in inflation, and the change in the nominal interest rate, predicted by the estimated empirical model. The table shows that the nonstationary monetary shock explains 45 percent of the change in inflation, 22 percent of changes in the nominal interest rate, and 9 percent of the growth rate of output. Thus, the empirical model assigns a significant role to this type of monetary disturbance, especially in explaining movements in nominal variables. In comparison, the stationary monetary shock explains a relatively small fraction of movements in the three macroeconomic indicators included in the model. These results suggest that the neo-Fisher effect emanates from a relevant driver of nominal variables. More generally, in light of the fact that the majority of studies in Monetary Economics limits attention to the study of stationary nominal shocks, the results reported in table 3 call for devoting more attention to understanding the effects of nonstationary monetary disturbances.

4.1 Robustness

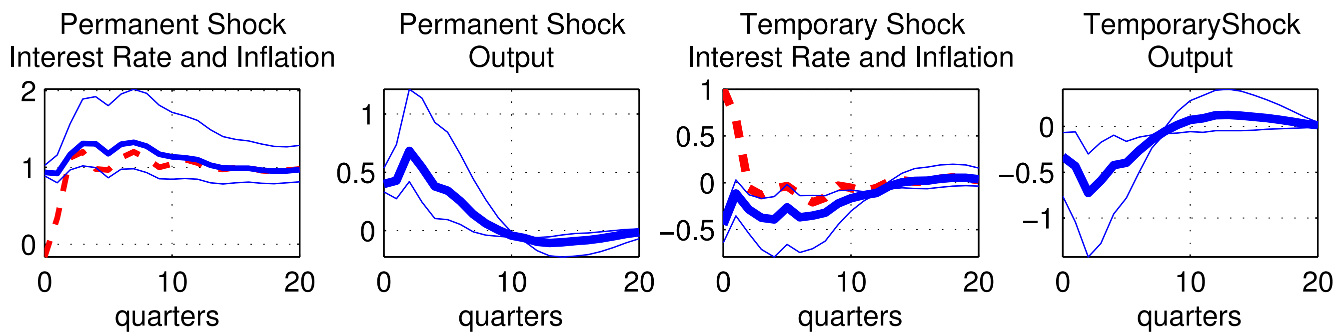
This section considers a number of modifications of the baseline empirical model aimed at gauging the sensitivity of the results. The robustness tests include truncating the sample at the beginning of the zero-interest-rate period; estimating the model on Japanese data; a specification in which the interest-rate-inflation differential is nonstationary; and including the ten-year rate.

4.1.1 Dropping the ZLB Period

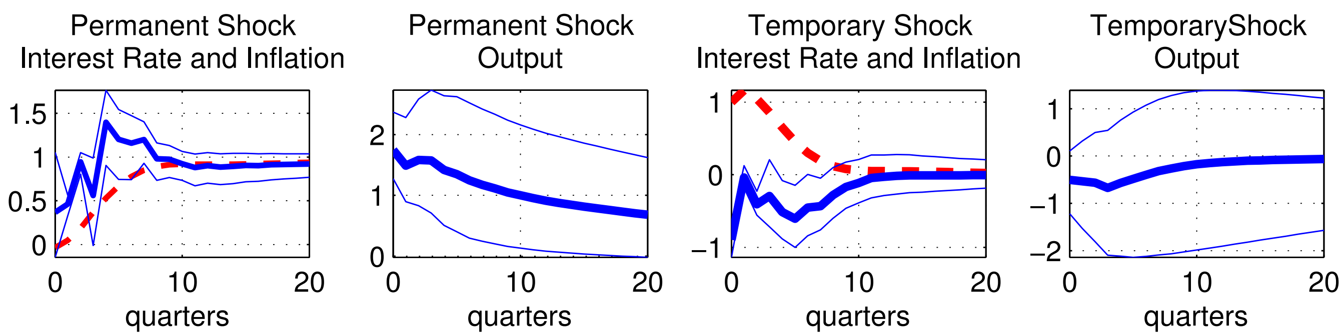
Between 2009 and 2015, the Federal Funds rate was technically nil, and interest-rate policy was said to have hit the zero lower bound (ZLB). The zero lower bound on nominal rates may introduce nonlinearities that the linear empirical model may not be able to capture. Formulating and estimating a nonlinear model is beyond the scope of this paper. As an imperfect alternative, I estimate the linear model truncating the sample in 2008:Q4. The results are shown in the top panels of figure 7. The impulse responses are qualitatively

Figure 7: Robustness Checks: Empirical Model

Truncating the Sample at the Beginning of the ZLB Period (2008:Q4)



Estimation on Japanese Data (1955:Q3 to 2016:Q4)



Notes. Thick lines are posterior means. Thick broken lines correspond to the nominal interest rate. Thin lines are 95% asymmetric error bands computed using the Sims-Zha (1999) method.

similar to those obtained with the longer sample.

4.1.2 Estimation on Japanese Data

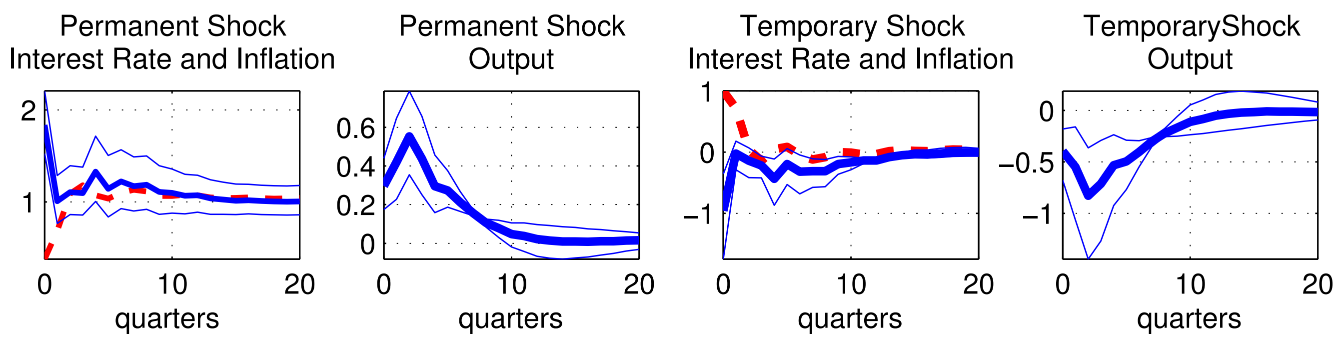
As a second robustness check, I estimate the model on Japanese data from 1955.Q3 to 2016.Q4. I rely on the results of the previous robustness check in deciding not to truncate the zero-rate period that started in 1995. There are two additional benefits of keeping the period 1995-2016. First, this period might provide valuable information on the effect of permanent monetary shocks, as it involves more than two decades of highly stable rates. Second, excluding the period 1995-2016 results in a relatively short sample of slightly over 20 years, which might make it difficult to distinguish the transitory and permanent components of monetary disturbances. The estimated impulse responses appear in the bottom panel of figure 7. The figure suggests that the main results obtained using U.S. data carry over to employing Japanese data.

4.1.3 Nonstationarity of the Interest-Rate-Inflation Differential

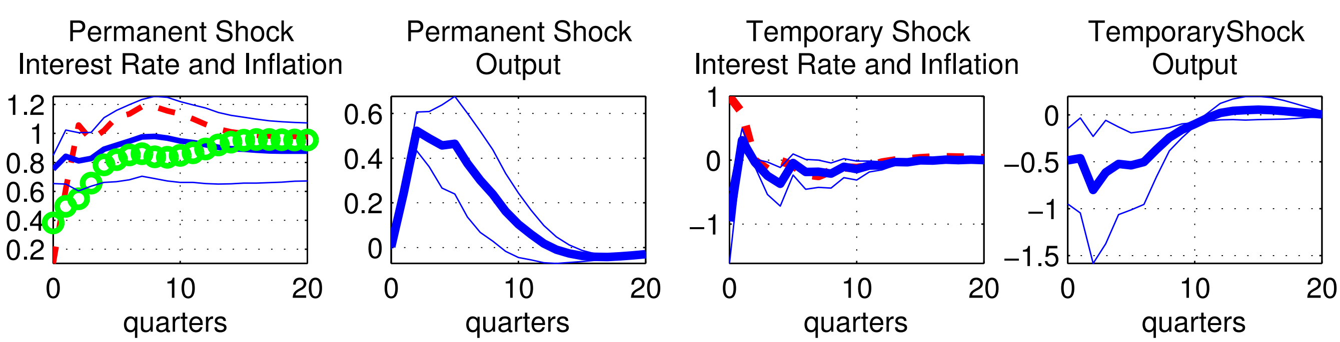
The baseline model assumes that the policy rate, i_t, and inflation, π_t, are both cointegrated with the permanent monetary shock, X_t^m. Under this assumption, i_t and π_t are themselves cointegrated with cointegration vector $[1 \;\; -1]$. This implies that $i_t - \pi_t$ is a stationary variable. Here, I adopt a more flexible specification in which i_t continues to be cointegrated with X_t^m, but π_t is cointegrated with αX_t^m, where α is a parameter to be estimated. Under this specification, the interest rate inflation differential, $i_t - \pi_t$, is nonstationary.For this reason, in the vector of observables, I replace it with the change in inflation, $\Delta\pi_t$, which retains its stationarity. The other two observables continue to be Δy_t and Δi_t. I assume that the parameter α has a normal prior distribution with mean 1 and standard deviation 0.15. Its estimated posterior distribution has a mean of 0.9401, a standard deviation of 0.1263, and a 95-percent confidence interval of $[0.7323, 1.1513]$. One cannot reject the hypothesis that the cointegration vector is $[1, -1]$, as in the baseline case. The top panel of Figure 8

Figure 8: Robustness Checks: Empirical Model (cont.)

Nonstationarity of the Interest-Rate-Inflation Differential

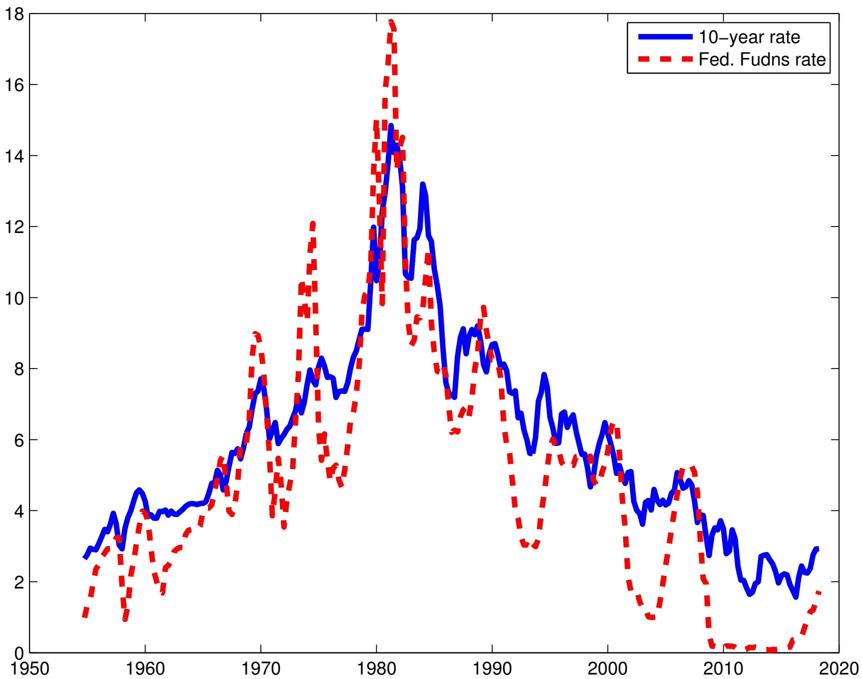


Including the Ten-Year Spread



Notes. Thick lines are posterior means. Thick broken lines correspond to the nominal interest rate. In the bottom-left panel, the response of the ten-year rate is displayed with circles. Thin lines are 95% asymmetric error bands computed using the Sims-Zha (1999) method.

Figure 9: The Ten-Year Rate nd the Federal Funds Rate



Notes. Quarterly frequency. Source: See section 3.3.

displays the impulse responses of inflation, the policy rate, and output to transitory and permanent monetary shocks. Overall, the key predictions of the baseline model continue to hold under this specification. In particular, the permanent shock generates a quick reflation without output loss, whereas the transitory shock causes a fall in inflation and a contraction in aggregate activity.

4.1.4 Including the Ten-Year Spread

To facilitate the estimation of the permanent monetary shock, X_t^m, it is of interest to include a long-term rate. Figure 9 plots the ten-year rate and the federal funds rate. Over the long run, the two series track each other. In the short run, the longer rate appears to follow the short rate with some delay.

The empirical model considered here extends the model of section 4.1.3 to include the ten-year rate, denoted i_t^{10}. Specifically, the unobservable autoregressive system includes the variable $\hat{i}_t^{10} \equiv i_t^{10} - X_t^m$, and the observation equation includes the ten-year spread, $i_t^{10} - i_t$.

All other aspects of the model are as in section 4.1.3. The bottom panel of Figure 8 displays the impulse responses of output, inflation, the short rate, and the ten-year rate to transitory and permanent monetary shocks. The main predictions of the baseline model extend to the expanded model. In particular, a monetary shock that increases inflation and interest rates in the long run causes an increase in inflation in the short run. As in the raw data, the ten-year rate tracks the short rate with a delay.

5 An Estimated New-Keynesian Model with Permanent Trend-Inflation Shocks

This section presents an econometric estimation of a small-scale new-Keynesian model augmented with permanent and stationary but persistent movements in the inflation target of a Taylor-type interest-rate feedback rule. These shocks complete with other monetary and real shocks. The objective of this analysis is not theoretical in nature. A number of papers cited in the introduction have shown that in models of this type, permanent and stationary but persistent changes in the inflation target are implemented via rising interest rates and inflation in the short run. Instead, the goal of this section is to measure the importance of this class of shocks in the context of an optimizing model.

The empirical model estimated in the first part of this paper allows for the identification of two types of monetary shock, namely, a nonstationary shock and a stationary one. The optimizing nature of the new-Keynesian model can accommodate a second stationary monetary shock, interpretable as a stationary disturbance in the inflation target and differing from the other stationary monetary shock in its persistence and possibly in its variance. This possibility is of interest because it gives the data a chance to gauge the importance of stationary movements in the inflation target that give rise to positive short-run co movement in interest rates and inflation (Garín, Lester, and Sims, 2018) . As it turns out, this source of neo-Fisherian effects is significant.

The model features price stickiness and habit formation and is driven by four real shocks in addition to the aforementioned three monetary shocks: permanent and transitory productivity shocks, a preference shock, and a labor-supply shock. This section presents the main building blocks of the model. Appendix B offers a detailed derivation of the equilibrium conditions .

The economy is populated by households with preferences defined over streams of consumption and labor effort and exhibiting external habit formation. The household's lifetime utility function is

$$E_0 \sum_{t=0}^{\infty} \beta^t e^{\xi_t} \left\{ \frac{\left[(C_t - \delta \widetilde{C}_{t-1})(1 - e^{\theta_t} h_t)^{\chi} \right]^{1-\sigma} - 1}{1-\sigma} \right\}, \tag{5}$$

where C_t denotes consumption in period t, $\widetilde{C}_t$ denotes the cross sectional average of consumption, h_t denotes hours worked in period t, ξ_t and θ_t denote exogenous preference shocks, E_t denotes the expectations operator conditional on information available in period t, and $\beta, \delta \in (0,1)$ and $\sigma, \chi > 0$ are parameters.

The preference shocks are assumed to follow AR(1) processes of the form

$$\xi_{t+1} = \rho_\xi \xi_t + \sigma_\xi \epsilon^\xi_{t+1}$$

and

$$\theta_{t+1} - \theta = \rho_\theta(\theta_t - \theta) + \sigma_\theta \epsilon^\theta_{t+1},$$

where ϵ^ξ_t and ϵ^θ_t are i.i.d. innovations distributed $N(0,1)$, and $\rho_\xi, \rho_\theta \in (-1,1)$, $\sigma_\xi, \sigma_\theta > 0$, and θ are parameters.

Households are subject to the budget constraint

$$P_t C_t + \frac{B_{t+1}}{1+I_t} + T_t = B_t + W^n_t h_t + \Phi_t, \tag{6}$$

where P_t denotes the nominal price of consumption, B_{t+1} denotes a one-period nominal discount bond purchased in t and paying the nominal interest rate I_t in $t+1$, T_t denotes nominal lump-sum taxes, W_t^n denotes the nominal wage rate, and Φ_t denotes nominal profits received from firms.

The consumption good C_t is assumed to be a composite of a continuum of varieties C_{it} indexed by $i \in [0,1]$. The aggregation technology is assumed to be of the Dixit-Stiglitz form

$$C_t = \left[\int_0^1 C_{it}^{1-1/\eta} di\right]^{\frac{1}{1-1/\eta}}, \tag{7}$$

where the parameter $\eta > 0$ denotes the elasticity of substitution across varieties.

The firm producing variety i operates in a monopolistically competitive market and faces quadratic price adjustment costs à la Rotemberg. The production technology uses labor and is buffeted by stationary and nonstationary productivity shocks. Specifically, output of variety i is given by

$$Y_{it} = e^{z_t} X_t^n h_{it}^{\alpha}, \tag{8}$$

where Y_{it} denotes output of variety i in period t, h_{it} denotes labor input used in the production of variety i, and z_t and X_t^n are stationary and nonstationary productivity shocks, respectively. The transitory productivity shock and the growth rate of the nonstationary productivity shock, $g_t \equiv \ln(X_t^n/X_{t-1}^n)$, are assumed to follow AR(1) processes of the form

$$z_{t+1} = \rho_z z_t + \sigma_z \epsilon_{t+1}^z$$

and

$$g_t - g = \rho_g(g_{t-1} - g) + \sigma_g \epsilon_t^g,$$

where ϵ_t^z and ϵ_t^g are exogenous disturbances distributed i.id. $N(0,1)$, and $\sigma_z, \sigma_g > 0$, $\rho_z, \rho_g \in (0,1)$, and g are parameters.

The expected present discounted value of profits of the firm producing variety i is given by

$$E_0 \sum_{t=0}^{\infty} q_t \left[\frac{P_{it}}{P_t} C_{it} - W_t h_{it} - \frac{\phi}{2} X_t^n \left(\frac{P_{it}/P_{it-1}}{1+\widetilde{\Pi}_t} - 1 \right)^2 \right], \tag{9}$$

where $1+\widetilde{\Pi}_t = (1+\widetilde{\Pi}_{t-1})^{\gamma_m}(1+\Pi_t)^{1-\gamma_m}$ denotes the average level of inflation around which price-adjustment costs are defined, and $\Pi_t \equiv P_t/P_{t-1} - 1$ denotes the inflation rate. The parameter $\phi > 0$ governs the degree of price stickiness, and the parameter $\gamma_m \in [0,1]$ the backward-looking component of the inflation measure at which price adjustment costs are centered. Both parameters are estimated. Allowing for a backward-looking component in firms' price-setting behavior is in order in the present context because, as pointed out by Garín, Lester, and Sims (2018), the larger is this component, the less likely it will be that stationary but persistent movements in the inflation target are implemented with rising interest rates and inflation in the short run. The variable $q_t \equiv \beta^t \frac{\Lambda_t}{\Lambda_0}$, denotes a pricing kernel reflecting the assumption that profits belong to households. The price adjustment cost in the profit equation (9) is scaled by the output trend X_t^n to keep nominal rigidity from vanishing along the balanced growth path.

The monetary authority follows a Taylor-type interest-rate feedback rule with policy smoothing, as follows

$$\frac{1+I_t}{\Gamma_t} = \left[A \left(\frac{1+\Pi_t}{\Gamma_t} \right)^{\alpha_\pi} \left(\frac{Y_t}{X_t^n} \right)^{\alpha_y} \right]^{1-\gamma_I} \left(\frac{1+I_{t-1}}{\Gamma_{t-1}} \right)^{\gamma_I} e^{z_t^m},$$

where Y_t denotes aggregate output, z_t^m denotes a stationary interest-rate shock, Γ_t is the inflation-target, and A, α_π, α_y and $\gamma_I \in [0,1)$ are parameters.

The inflation target is assumed to have a permanent component denoted X_t^m and a transitory component denoted z_t^{m2}. Formally,

$$\Gamma_t = X_t^m e^{z_t^{m2}}.$$

The growth rate of the permanent component of the inflation target, $g_t^m \equiv \ln\left(\frac{X_t^m}{X_{t-1}^m}\right)$, and the stationary disturbances z_t^m, and z_t^{m2}, are assumed to follow AR(1) processes of the form

$$g_t^m = \rho_{gm} g_{t-1}^m + \sigma_{gm}\epsilon_t^{gm}$$

$$z_t^m = \rho_{zm} z_{t-1}^m + \sigma_{zm}\epsilon_t^{zm},$$

and

$$z_t^{m2} = \rho_{zm2} z_{t-1}^{m2} + \sigma_{zm2}\epsilon_t^{zm2},$$

where ϵ_t^{gm}, ϵ_t^{zm}, and ϵ_t^{zm2} are exogenous i.i.d. innovations distributed $N(0,1)$, and $\rho_{gm}, \rho_{zm}, \rho_{zm2} \in (0,1)$ and $\sigma_{gm}, \sigma_{zm}, \sigma_{zm2} > 0$ are parameters. As explained in more detail in section 5.1 below, the identification of the two stationary monetary shocks, z_t^m and z_t^{m2}, is achieved by imposing restrictions on the prior distribution of their serial correlations.

Government consumption is assumed to be nil at all times. Thus, the fiscal authority faces the budget constraint

$$T_t + \frac{B_{t+1}}{1+I_t} = B_t.$$

Fiscal policy is assumed to be Ricardian, in the sense that the government sets the lump-sum tax T_t to ensure intertemporal solvency independently of the paths of the price level or the nominal interest rate.

5.1 Data, Priors, and Estimation

As in much of the DSGE literature, I estimate a subset of the parameters of the model and calibrate the remaining ones using standard values in business-cycle analysis. The set of estimated parameters includes those that play a central role in determining the model's implied short-run dynamics, such as those defining price adjustment costs, habit formation, monetary policy, and the stochastic properties of the underlying sources of uncertainty.

Table 4 displays the values assigned to the calibrated parameters. I set the subjective discount factor, β, equal to 0.9982, which implies a growth-adjusted discount factor, $\beta e^{-\sigma g}$

Table 4: Calibrated Parameters in the New Keynesian Model

Parameter	Value	Description
β	0.9982	subjective discount factor
σ	2	inverse of intertemp. elast. subst.
η	6	intratemporal elast. of subst.
α	0.75	labor semielast. of output
g	0.004131	mean output growth rate
θ	0.4055	preference parameter
χ	0.625	preference parameter

Note. The time unit is one quarter.

equal to 0.99, the reciprocal of the intertemporal elasticity of substitution, σ, to 2, the intratemporal elasticity of substitution across varieties of intermediate goods, η, to 6, which implies a steady-state markup of price over marginal cost of 20 percent (Galí, 2008), the labor semi elasticity of the production function, α, to 0.75, the unconditional mean of per capita output growth, g, to 0.004131 (1.65 percent per year), which matches the average growth rate of real GDP per capita in the United States over the estimation period (1954:Q4 to 2018:Q2), and the parameters θ and χ to ensure, given all other parameter values, that in the steady state households allocate one third of their time to work, $h = 1/3$ and a unit Frisch elasticity of labor supply, $(1 - e^{\theta} h)/(e^{\theta} h) = 1$ (Galí, 2008).

The remaining parameters of the model are estimated using the same observables as in the estimation of the empirical model of section 3, namely, per-capita output growth, the interest-rate-inflation differential, and the change in the nominal interest rate. The data sources are as described in subsection 3.3. As in the case of the empirical model, the econometric estimation employs Bayesian techniques. Table 5 displays means and standard deviations of the prior distributions of the estimated parameters. All estimated parameters have relatively loose priors. The parameter ϕ governing the degree of price stickiness has a Gamma prior distribution with a mean of 50 and a standard deviation of 20. The assumed mean prior value of ϕ ensures that, given the calibrated values of η, α, and θ, the output coefficient of the linearized Phillips curve (κ in equation (19) appearing in Appendix B) is 0.043, as

Table 5: Prior and Posterior Parameter Distributions: New-Keynesian Model

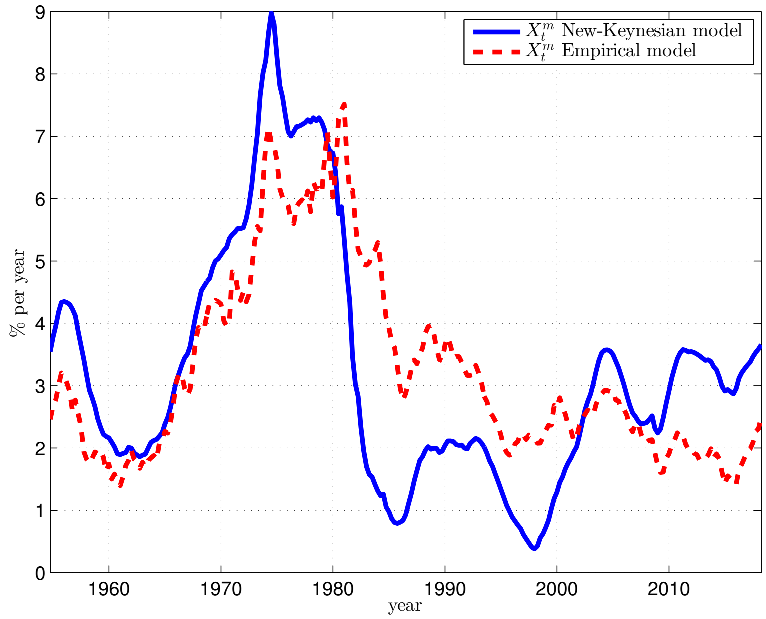
	Prior Distribution			Posterior Distribution			
Parameter	Distribution	Mean	Std	Mean	Std	5%	95%
ϕ	Gamma	50	20	146	31.9	96.8	201
α_π	Gamma	1.5	0.25	2.32	0.221	1.98	2.7
α_y	Gamma	0.125	0.1	0.188	0.123	0.0336	0.422
γ_m	Uniform	0.5	0.289	0.606	0.0762	0.475	0.724
γ_I	Uniform	0.5	0.289	0.242	0.142	0.053	0.517
δ	Uniform	0.5	0.289	0.258	0.0531	0.173	0.348
ρ_ξ	Beta	0.7	0.2	0.915	0.0234	0.874	0.95
ρ_θ	Beta	0.7	0.2	0.708	0.21	0.317	0.98
ρ_z	Beta	0.7	0.2	0.7	0.214	0.302	0.978
ρ_g	Beta	0.3	0.2	0.221	0.108	0.0557	0.41
ρ_{gm}	Beta	0.3	0.2	0.248	0.166	0.0295	0.562
ρ_{zm}	Beta	0.3	0.2	0.306	0.184	0.0526	0.654
ρ_{zm2}	Beta	0.7	0.2	0.796	0.205	0.33	0.975
σ_ξ	Gamma	0.01	0.01	0.0287	0.00602	0.0212	0.0398
σ_θ	Gamma	0.01	0.01	0.00164	0.00138	0.000115	0.00435
σ_z	Gamma	0.01	0.01	0.00122	0.000974	8.66e-05	0.00312
σ_g	Gamma	0.01	0.01	0.00758	0.000944	0.00593	0.00905
σ_{gm}	Gamma	0.0025	0.0025	0.000848	0.000474	8.48e-05	0.00159
σ_{zm}	Gamma	0.0025	0.0025	0.000832	0.000465	7.96e-05	0.00152
σ_{zm2}	Gamma	0.0025	0.0025	0.00131	0.000733	0.000138	0.00248
R_{11}	Gamma	3.78e-06	2.18e-06	4.46e-06	2.59e-06	1.22e-06	9.46e-06
R_{22}	Gamma	2.08e-06	1.2e-06	4.55e-06	4.88e-07	3.79e-06	5.4e-06
R_{33}	Gamma	2.36e-07	1.36e-07	1.74e-07	9.95e-08	4.82e-08	3.62e-07

Note. The time unit is one quarter. Growth rates and log-deviations from trend are expressed in per one (1 percent is denoted 0.01). Replication code: `table_param.m` in `optimizing_model.zip`.

in Galí (2008). The parameter $\gamma_m \in (0,1)$, governing the backward looking component in price setting, takes a uniform distribution with support $[0,1]$. The inflation and output coefficients of the Taylor rule, α_π and α_y, have Gamma prior distributions with means equal to 1.5 and 0.125 (two commonly used values) and standard deviations equal to 0.25 and 0.1, respectively. The parameter $\gamma_I \in [0,1]$ measuring the smoothness of monetary policy has a uniform prior distribution with support $[0,1]$. The degree of external habit formation, given by $\delta \in [0,1)$, adopts a uniform prior distribution with support $[0,1]$. Echoing the priors imposed in the empirical model, the serial correlation of the nonstationary monetary and real shocks, ρ_g and ρ_{gm}, have Beta distributions with mean equal to 0.3 and standard deviation equal to 0.2. The transitory interest rate shock, z_t^m, and the transitory inflation-target shock, z_t^{m2}, are identified by imposing different prior distributions for their serial correlations. Specifically, ρ_{zm} and ρ_{zm2} have Beta prior distributions with means equal to 0.3 and 0.7, respectively, and standard deviations equal to 0.2. The serial correlations of all stationary nonmonetary shocks (ρ_ξ, ρ_θ, and ρ_z) have Beta distributions with mean 0.7 and standard deviation 0.2. Also in line with the empirical model, the standard deviations of the three monetary shocks, σ_{gm} σ_{zm}, and σ_{zm2}, take Gamma distributions with mean and standard deviation equal to 1/400, the standard deviation of the permanent nonmonetary shock, σ_g, has a Gamma distribution with mean and standard deviation equal to 1/100, and the standard deviations of all stationary nonmonetary shocks (σ_ξ, σ_θ, and σ_z) have Gamma distributions with mean and standard deviation equal to 1/100. Finally, as in the empirical model, the observables are assumed to contain measurement error. The variances of the measurement errors have uniform distribution with lower bound equal to zero and upper bound equal to 10 percent of the variance of the data.

The last four columns of table 5 displays means, standard deviations, and 5 and 95 percent intervals of the estimated posterior distributions, based on a Random Walk Metropolis Hastings MCMC chain of length one million after discarding 100 thousand burn-in draws. Most parameters are estimated with significant uncertainty, a feature that is common in es-

Figure 10: The Permanent Component of Inflation: New Keynesian Model

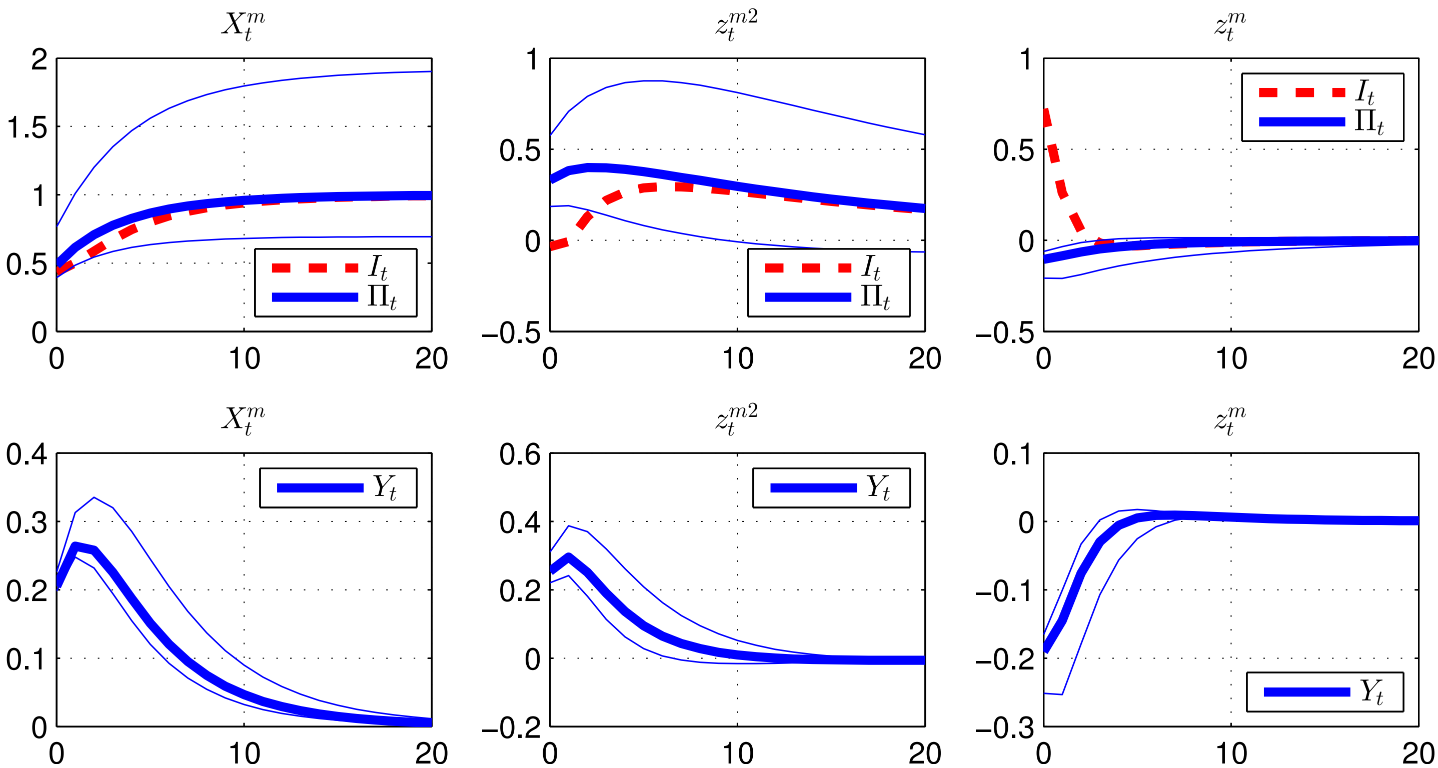


Note. Quarterly frequency. The inferred path of the permanent component of inflation, X_t^m, IS computed by Kalman smoothing and evaluating the model at the posterior mean of the estimated parameter vector. The initial value of X_t^m is normalized to make the average value of X_t^m equal to the average rate of inflation over the sample period, 1954:Q4 to 2018:Q2. Replication code: `plot_xm.m` in `optimizing_model.zip`.

timates of small-scale New Keynesian models (Ireland, 2007). Nonetheless, the data speaks with a strong voice on the parameters ϕ and δ, governing price stickiness and habit formation, which are key determinants of the propagation of nominal and real shocks.

Furthermore, it is reassuring, given the focus of this paper, that the estimated path of the nonstationary monetary shock, the latent variable X_t^m, resembles its counterpart in the empirical model. This is shown in Figure 10, which displays the inferred paths of X_t^m from the New-Keynesian and empirical models. Overall, the nonstationary monetary shock implied by the optimizing model tracks the one stemming from the empirical model relatively well. The sample correlation of the two series is 0.7. The path of X_t^m implied by the New-Keynesian model is more volatile than the one coming from the empirical model, perhaps due to the fact that the empirical model has a richer lag structure.

Figure 11: Estimated Impulse Responses to Inflation-Target and Interest-Rate Shocks in the New-Keynesian Model



Notes. Impulse responses are posterior mean estimates. Inflation, Π_t, and the nominal interest rate, I_t, are deviations from pre-shock levels and expressed in percentage points per year. output, Y_t, is measured in percent deviations from trend. Thin lines represent 95% confidence intervals for inflation (top panels) and output (bottom panels). Asymmetric error bands are computed using the Sims-Zha (1999) method. Replication code: `plot_ir_chain.m` in `optimizing_model.zip`.

6 Relevance and Short-Run Effects of Inflation-Target Shocks

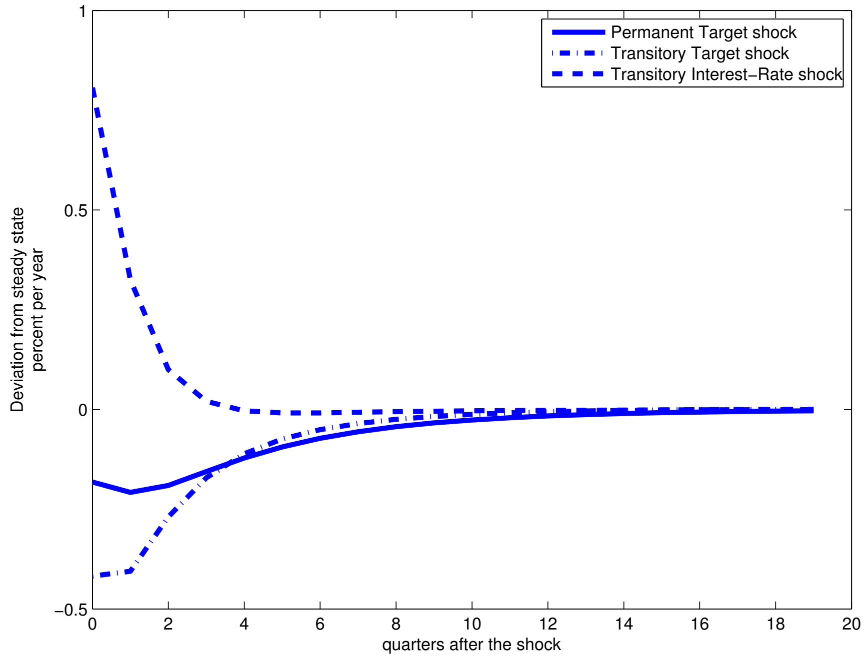
How important are shocks that induce neo-Fisherian dynamics according to the new-Keynesian model? To address this question, this section begins by examining the estimated response of the interest rate, inflation, and output to the three monetary shocks, X_t^m, z_t^{m2}, and z_t^m. It then documents the role of each of these sources of uncertainty in accounting for observed movements in the inflation rate.

Figure 11 displays the estimated impulse responses of inflation, the policy rate, and output to inflation-target shocks (X_t^m and z_t^{m2}) and interest-rate shocks (z_t^m) implied by the estimated New-Keynesian model. The main message conveyed by the figure is that qualitatively the responses implied by the New-Keynesian model concur with those implied by the empirical model of sections 3 and 4. In the estimated new-Keynesian model, a permanent increase in the inflation target, X_t^m, is implemented with a gradual increase in the nominal interest rate, which reaches its higher long-run level in about 10 quarters. In response to this policy innovation, inflation increases monotonically to its new steady-state value, without loss of aggregate activity. Similarly, an increase in the transitory component of the inflation target, z_t^{m2}, causes rising interest rates, an elevation in the rate of inflation, and no contraction in output.

The estimated response of inflation and the interest rate to a stationary increase in the inflation target provides econometric support to the theoretical finding of Garín, Lester, and Sims (2018) that stationary trend shocks can produce neo-Fisherian effects if sufficiently persistent. It is worth noting that although ρ_{zm2} is estimated with significant uncertainty, the data picks a mean posterior value higher than its prior counterpart (0.8 versus 0.7). By contrast, the standard transitory interest-rate shock, z_t^m, is estimated to cause a fall in inflation and a contraction in aggregate activity.

Figure 11 shows that in response to either a permanent or a transitory but persistent increase in the inflation target inflation not only begins to increase immediately, but does so at a rate faster than the nominal interest rate. As a result, the real interest rate falls, as shown in Figure 12. By contrast, a short-lived increase in the nominal interest rate causes a fall in inflation and an increase in the real interest rate. A natural question is why inflation moves faster than the interest rate in the short run when the monetary shock is expected to be permanent or transitory but persistent. The answer has to do with the presence of nominal rigidities and with the way the central bank conducts monetary policy. In response to an increase in the inflation target, the central bank raises the short-run policy rate quickly but gradually. At the same time, firms know that, by the classic Fisher effect, the consumer price level and the nominal wage will increase down the road. They therefore realize that

Figure 12: Estimated Response of the Real Interest Rate to Inflation-Target and Interest-Rate Shocks in the New-Keynesian Model



Notes. Posterior mean estimates. The real interest rate is defined as $i_t - E_t\pi_{t+1}$. Replication code: `real_interest_rate.m` in `optimizing_model.zip`.

if they don't follow suit they will face ever increasing losses as time goes by, since they would sell their product increasingly cheaply relative to other firms while facing elevated labor costs. Since firms face quadratic costs of adjusting prices, they find it optimal to begin increasing their price immediately. And since all firms do the same, inflation itself begins to increase as soon as the shock occurs.

The central contribution of this section is to ascertain the importance of X_t^m and z_t^{m2} in explaining movements in the inflation rate. Table 6. displays this information. The permanent monetary shock, X_t^m, explains more than 30 percent of the variance of changes in the rate of inflation. Thus, like the empirical model, the new-Keynesian model assigns a significant role to permanent innovations in monetary policy. Transitory movements in the inflation target, embodied in the shock z_t^{m2}, explain 22 percent of changes in the rate of inflation. Thus, trend-inflation shocks (X_t^m and z_t^{m2}) jointly explain more than 50 percent of the variance of changes in the inflation rate. Also, as in the empirical model, in the new-

Table 6: Variance Decomposition: New Keynesian Model

	Δy_t	$\Delta \pi_t$	Δi_t
Permanent Trend-Inflation Shock, g_t^m	2.4	30.1	7.6
Transitory Trend-Inflation Shock, z_t^{m2}	4.3	22.2	5.1
Transitory interest-Rate Shock, z_t^m	1.2	1.2	14.2
Permanent Productivity Shock, g_t	79.5	0.8	1.6
Transitory Productivity Shock, z_t	0.5	2.8	2.6
Preference Shock, ξ_t	11.5	40.0	66.3
Labor-Supply Shock, θ_t	0.6	2.8	2.6

Notes. Posterior means. The variables Δy_t, $\Delta \pi_t$, and Δi_t denote output growth, the change in inflation, and the change in the nominal interest rate, respectively. Replication code: `table_vardecomp.m` in `optimizing_model.zip`.

Keynesian model the stationary interest-rate shock, z_t^m, accounts for a relatively small share of movements in the rate of inflation. Taken together, these results indicate that monetary shocks that induce neo-Fisherian dynamics appear to have a significance presence in the data.

With respect to the role played by nonmonetary shocks, a further similarity between the empirical and the optimizing model is that in both the nonstationary nonmonetary shock, X_t^n, explains a significant fraction of variations in output growth, although in the New Keynesian model this role is estimated to be much larger. Finally, in both models nonmonetary stationary shocks are the main drivers of changes in the nominal interest rate. However, thanks to its more structural nature, the optimizing model is able to say more about which specific nonmonetary stationary sources of uncertainty are the most relevant. Specifically, while the empirical model encapsulates all stationary nonmonetary disturbances in a single shock, z_t^n, the New Keynesian model can distinguish finer categories and suggests that it is a demand shock, namely, the preference shock ξ_t, that has the largest impact on changes in the nominal interest rate.

Table 7: Variance Decomposition: New Keynesian Model Without a Stationary Inflation-Target Shock

	Δy_t	$\Delta \pi_t$	Δi_t
Permanent Monetary Shock, g_t^m	4.4	51.3	12.4
Transitory Monetary Shock, z_t^m	1.7	1.8	18.6
Permanent Productivity Shock, g_t	80.0	1.0	1.7
Transitory Productivity Shock, z_t	0.7	2.7	2.4
Preference Shock, ξ_t	12.5	40.5	62.5
Labor-Supply Shock, θ_t	0.7	2.7	2.4

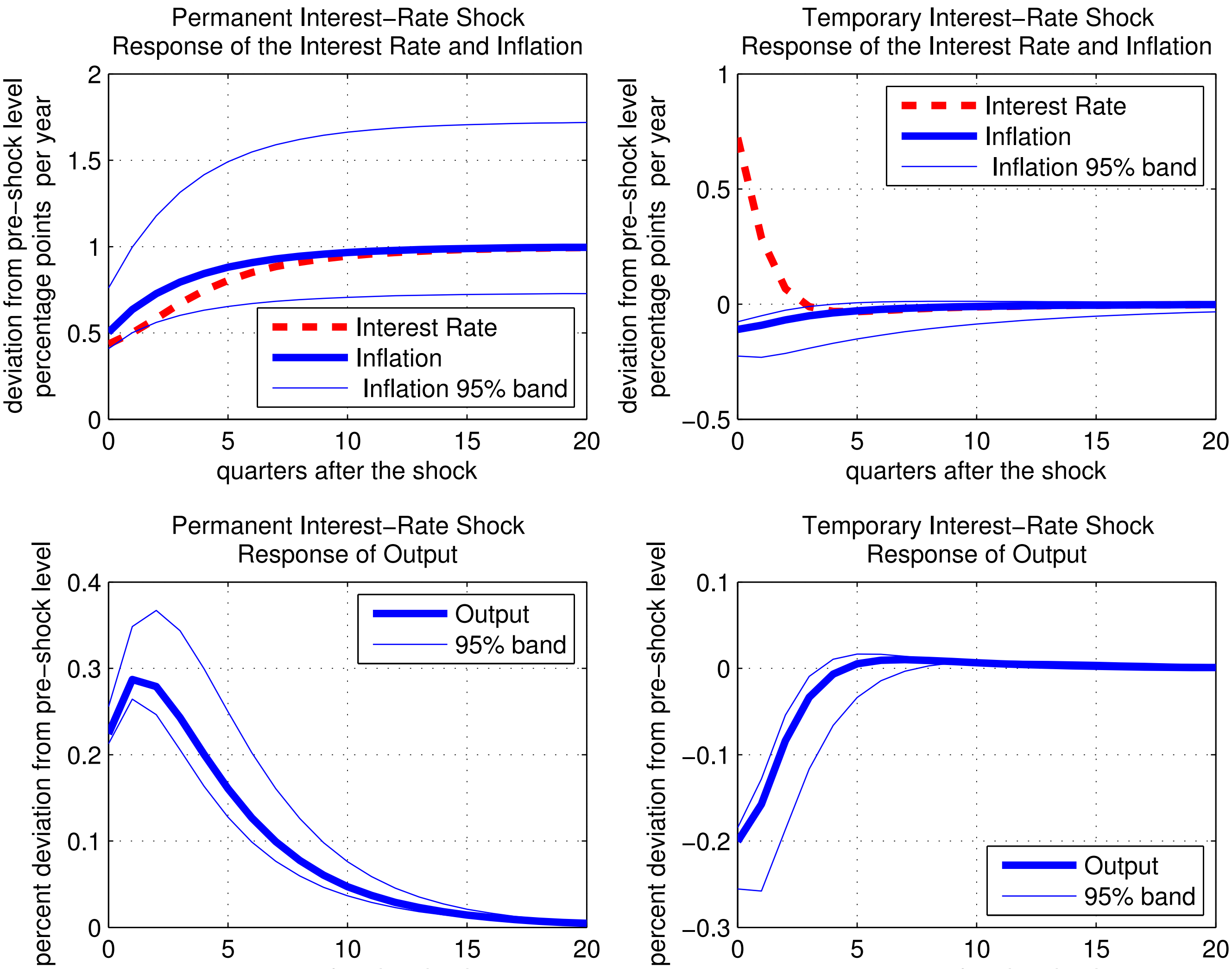
Note. Posterior means. The variables Δy_t, $\Delta \pi_t$, and Δi_t denote output growth, the change in inflation, and the change in the nominal interest rate, respectively.

6.1 Robustness

This section tests the robustness of he result that most of the variance of changes in inflation explained by monetary shocks is accounted for by shocks that produce neo-Fisherian short-run comovement in interest rates and inflation. It does so by shutting off the stationary disturbance to the inflation target, z_t^{m2}, reestimating the model, and checking how the data chooses to reallocate its contribution to the variance of inflation changes. Specifically, the question this exercise addresses is whether the room left by z_t^{m2} is absorbed primarily by the permanent component of the inflation target, X_t^m, which produces neo-Fisherian dynamics, by the temporary monetary shock, z_t^m, or by one or more real shocks. From a technical point of view, the stochastic structure in this specification is more comparable with that of the empirical model of section 3, as it allows for only two monetary disturbances, a nonstationary one and a stationary one.

Table 7 shows that the role played by z_t^{m2} in the baseline new-Keynesian model is taken up by the nonstationary monetary shock, X_t^m. The fraction of the variance of the inflation change, $\Delta \pi_t$, explained by X_t^m increases from 30 to 51 percent. The difference, 21 percent, equals the share explained by z_t^{m2} in the baseline specification. By contrast, the transitory monetary shock, z_t^m, continues to play a small role (1.2 percent in the baseline model versus 1.8 in the present formulation).

Figure 13: Estimated Impulse Responses to Permanent and Temporary Monetary Shocks in the New-Keynesian Model Without a Stationary Inflation-Target Shock



Notes. Impulse responses are posterior mean estimates. Asymmetric error bands are computed using the Sims-Zha (1999) method.

Figure 13 displays the impulse responses of inflation, the policy rate, and output to permanent and transitory monetary shocks (X_t^m and z_t^m) implied by the reestimated New-Keynesian model without a stationary inflation-target shock, z_t^{m2}. The main message conveyed by the figure is that qualitatively the responses implied by this version of the new-Keynesian model concur with those implied by its baseline counterpart. In particular, a permanent increase in the inflation target (left panels of the figure), is implemented with an increase in the nominal interest rate and causes an increase in inflation and output in the short term. And a transitory increase in the nominal interest rate (right panels of the figure) causes a fall in inflation and a contraction in aggregate activity.

7 Conclusion

Discussions of how monetary policy can lift an economy out of chronic below-target inflation are almost always based on the logic of how transitory interest-rate shocks affect real and nominal variables. Nowadays, there is little theoretical or empirical controversy around how this type of monetary shock transmits to the rest of the economy: An increase in the nominal interest rate causes an increase in the real interest rate, which puts downward pressure on both aggregate activity and price growth. Within this logic, a central bank trying to reflate a low-inflation economy will tend to set interest rates as low as possible. This policy is effective as long as the cut in interest rates is expected to be transitory.

The question is what happens when the low-interest-rate policy is in place for a decade or more (as in the eurozone or Japan), and agents come to expect that it will continue to be maintained over the indefinite future. The available evidence shows that at some point these economies find themselves with zero or negative nominal rates and with the low-inflation problem not going away. One interpretation of what happens at this point is that the classic Fisher effect kicks in, and the situation perpetuates: The monetary authority keeps the interest rate low because inflation is still below target (the temporary-interest-rate-shock logic) and inflation is low because the interest rate has been low for a long period of time (the Fisher effect).

In this paper I provide empirical evidence drawn from an empirical and an optimizing model in favor of the hypothesis that a gradual and permanent increase in the nominal interest rate leads to a monotonic adjustment of inflation to a permanently higher level, low real interest rates, and no output loss. An alternative interpretation of this result is that implementing a lasting increase in the de-facto inflation target requires gradually rising rates in the short run, and causes a rising path of inflation. These findings are consistent with the neo-Fisherian prediction that a credible announcement of a gradual return of the nominal interest rate to normal levels can achieve a swift reflation of the economy with sustained levels of economic activity.

Appendix

This appendix contains detailed expositions of the empirical and optimizing models.

A Detailed Exposition of the Empirical Model

Let Y_t be a vector collecting these three variables,

$$Y_t \equiv \begin{bmatrix} y_t \\ \pi_t \\ i_t \end{bmatrix},$$

where y_t denotes the logarithm of real output per capita, π_t denotes the inflation rate expressed in percent per year, and i_t denotes the nominal interest rate expressed in percent per year. Let $\tilde{Y}_t$

$$\tilde{Y}_t \equiv \begin{bmatrix} (y_t - X_t^n) \times 100 \\ \pi_t - X_t^m \\ i_t - X_t^m \end{bmatrix},$$

where X_t^m is a permanent monetary shock, z_t^m is a transitory monetary shock, X_t^n is a nonstationary nonmonetary shock, and z_t^n is a stationary nonmonetary shock. Let $\hat{Y}_t$ denote the deviation of $\tilde{Y}_t$ from its unconditional mean, that is,

$$\hat{Y}_t \equiv \begin{bmatrix} \hat{y}_t \\ \hat{\pi}_t \\ \hat{i}_t \end{bmatrix} \equiv \tilde{Y}_t - E\tilde{Y}_t,$$

where E denotes the unconditional expectations operator.

The law of motion of $\hat{Y}_t$ takes the autoregressive form

$$\hat{Y}_t = \sum_{i=1}^{L} B_i \hat{Y}_{t-i} + C u_t \tag{10}$$

where

$$u_t \equiv \begin{bmatrix} x_t^m \\ z_t^m \\ x_t^n \\ z_t^n \end{bmatrix},$$

$$x_t^m \equiv \Delta X_t^m - \Delta X^m$$

and

$$x_t^n \equiv (\Delta X_t^n - \Delta X^n) \times 100.$$

with Δ denoting the time-difference operator, $\Delta X^m \equiv E\Delta X_t^m$, and $\Delta X^n \equiv E\Delta X_t^n$. The variables x_t^m and x_t^n denote demeaned changes in the nonstationary shocks. The objects B_i, for $i = 1, \ldots, L$, are 3-by-3 matrices of coefficients, C is a 3-by-4 matrix of coefficients, and L is a scalar denoting the lag length of the empirical model. The vector u_t is assumed to follow an AR(1) law of motion of the form

$$u_{t+1} = \rho u_t + \psi \epsilon_{t+1}, \tag{11}$$

where ρ and ψ are 4-by-4 diagonal matrices of coefficients, and ϵ_t is a 4-by-1 i.i.d. disturbance distributed $N(\emptyset, I)$.

The observable variables used in the estimation of the empirical model are output growth expressed in percent per quarter, the change in the nominal interest rate, and the interest-rate-inflation differential, defined as

$$r_t \equiv i_t - \pi_t.$$

The following equations link the observables to variables included in the unobservable system

(10)-(11):

$$
\begin{aligned}
100 \times \Delta y_t &= 100 \times \Delta X^n + \hat{y}_t - \hat{y}_{t-1} + x_t^n \\
r_t &= r + \hat{i}_t - \hat{\pi}_t \\
\Delta i_t &= \Delta X^m + \hat{i}_t - \hat{i}_{t-1} + x_t^m
\end{aligned} \tag{12}
$$

where $r \equiv Er_t$ represents the unconditional mean of the interest-rate-inflation differential. The variables Δy_t, r_t, and Δi_t are assumed to be observed with measurement error. Let o_t be the vector of variables observed in quarter t. Then

$$
o_t = \begin{bmatrix} \Delta y_t \times 100 \\ r_t \\ \Delta i_t \end{bmatrix} + \mu_t \tag{13}
$$

where μ_t is a 3-by-1 vector of measurement errors distributed i.i.d. $N(\emptyset, R)$, and R is a diagonal variance-covariance matrix.

The state-space representation of the system composed of equations (10), (11), (12), and (13) can be written as follows:

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

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

where

$$
\xi_t \equiv \begin{bmatrix} \hat{Y}_t \\ \hat{Y}_{t-1} \\ \vdots \\ \hat{Y}_{t-L+1} \\ u_t \end{bmatrix},
$$

The matrices F, P, A, and H are known functions of B_i, $i = 1, \ldots L$, C, ρ, ψ, ΔX^n, ΔX^m, and r. Specifically, let

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

and let I_j denote an identity matrix of order j, $\emptyset_j$ denote a square matrix of order j with all entries equal to zero, and $\emptyset_{i,j}$ denote a matrix of order i by j with all entries equal to zero. Also let L, S, and V denote, respectively, the number of lags, the number of shocks, and the number of endogenous variables included in the empirical model. Then, for $L \geq 2$ we have

$$F = \begin{bmatrix} B & C\rho \\ \left[I_{V(L-1)}\, \emptyset_{V(L-1),V}\right] & \emptyset_{V(L-1),S} \\ \emptyset_{S,VL} & \rho \end{bmatrix}, P = \begin{bmatrix} C\psi \\ \emptyset_{V(L-1),S} \\ \psi \end{bmatrix};$$

$$A' = \begin{bmatrix} 100 \times \Delta X^n \\ r \\ \Delta X^m \end{bmatrix}, \text{ and } H' = \begin{bmatrix} M_\xi & \emptyset_{V,V(L-2)} & M_u \end{bmatrix},$$

where, in the specification considered in the body of the paper ($S = 4$, $V = 3$, and a particular ordering of the endogenous and exogenous variables in the vectors $\hat{Y}_t$ and u_t), the matrices M_ξ and M_u take the form

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

The case $L = 1$ is a special case of $L = 2$ in which $B_2 = \emptyset_V$.

B Detailed Exposition of the Optimizing Model

B.1 The Household's Optimality Conditions

Households choose processes $\{C_t, h_t, B_{t+1}\}_{t=0}^{\infty}$ to maximize the utility function (5) subject to the budget constraint (6) and to some borrowing limit that prevents them from engaging in Ponzi schemes. Letting $\beta^t \Lambda_t / P_t$ denote the Lagrange multiplier associated with the budget constraint, the first-order conditions of the household's optimization problem are

$$e^{\xi_t}(C_t - \delta \widetilde{C}_{t-1})^{-\sigma}(1 - e^{\theta_t} h_t)^{\chi(1-\sigma)} = \Lambda_t$$

$$\frac{\chi e^{\theta_t}(C_t - \delta \widetilde{C}_{t-1})}{1 - e^{\theta_t} h_t} = W_t$$

and

$$\Lambda_t = \beta(1 + I_t) E_t \left[\frac{\Lambda_{t+1}}{1 + \Pi_{t+1}} \right],$$

where $W_t \equiv W_t^n / P_t$ denotes the real wage, and $\Pi_t \equiv P_t / P_{t-1} - 1$ denotes the consumer-price inflation rate.

Given C_t, the household chooses the consumption of varieties C_{it} to minimize total expenditure, $\int_0^1 P_{it} C_{it} di$, subject to the aggregation technology (7), where P_{it} denotes the nominal price of variety i. This problem delivers the following demand for individual varieties:

$$C_{it} = C_t \left(\frac{P_{it}}{P_t} \right)^{-\eta}, \tag{14}$$

where the price level P_t is given by

$$P_t \equiv \left[\int_0^1 P_{it}^{1-\eta} di \right]^{\frac{1}{1-\eta}}, \tag{15}$$

and represents the minimum cost of one unit of the composite consumption good.

B.2 The Firm's Optimality Conditions

The problem of the firm producing variety i is to choose processes $\{P_{it}, C_{it}, Y_{it}, h_{it}\}_{t=0}^{\infty}$ to maximize (9) subject to the demand equation (14), the production technology (8), and the requirement that demand be satisfied at the price set by the firm,[7]

$$Y_{it} \geq C_{it} \tag{16}$$

Letting $q_t P_{it}/(P_t \mu_t)$ be the Lagrange multiplier associated with the demand constraint (16), the first-order conditions associated with the firm's profit maximization problem are

$$\mu_t = \frac{P_{it}/P_t}{W_t/(\alpha e^{z_t} X_t^n h_{it}^{\alpha-1})}$$

$$\eta C_{it}\left(\frac{\eta-1}{\eta} - \frac{1}{\mu_t}\right) = -\phi X_t^n \frac{P_t/P_{it-1}}{1+\widetilde{\Pi}_t}\left(\frac{P_{it}/P_{it-1}}{1+\widetilde{\Pi}_t} - 1\right) + \phi E_t \frac{q_{t+1}}{q_t} X_{t+1}^n \frac{P_{it+1}P_t/P_{it}^2}{1+\widetilde{\Pi}_{t+1}}\left(\frac{P_{it+1}/P_{it}}{1+\widetilde{\Pi}_{t+1}} - 1\right)$$

The first optimality condition says that the multiplier μ_t represents the markup of prices over marginal cost. The second optimality condition says that, all other things equal, if the price markup is above its normal level, $\mu_t > \eta/(\eta-1)$, the firm will increase prices at a rate below normal, $P_{it}/P_{it-1} < 1 + \widetilde{\Pi}_t$.

B.3 Market Clearing and Equilibrium

Clearing of the labor market requires that the demand for labor by firms equal the household's supply of labor, that is,

$$\int_0^1 h_{it} di = h_t. \tag{17}$$

Because all households are identical, so are individual and aggregate consumption per

[7] Strictly speaking, the right-hand side of this constraint must include the demand for goods of variety i by all firms for the purpose of generating the units of composite goods devoted to cover the price adjustment costs, which is given by $\frac{\phi}{2} X_t^n \left(\frac{P_{it}}{P_t}\right)^{-\eta} \int_0^1 \left(\frac{P_{jt}/P_{jt-1}}{1+\widetilde{\Pi}_t} - 1\right)^2 dj$. However, because price adjustment costs are quadratic in $\frac{P_{jt}/P_{jt-1}}{1+\widetilde{\Pi}_t} - 1$, which is zero along the deterministic balanced growth path, this source of demand for good i and all of its derivatives with respect to P_{it} are zero in equilibrium up to first order.

capita,

$$C_t = \widetilde{C}_t.$$

I focus attention on a symmetric equilibrium in which all firms charge the same nominal price and employ the same amount of labor, that is, an equilibrium in which h_{it} and P_{it} are the same for all $i \in [0,1]$. We then have from equations (14), (15), (8), and (17) that $P_{it} = P_t$, $C_{it} = C_t$, $h_{it} = h_t$, and $Y_{it} = e^{z_t} X_t^n h_t^\alpha$, for all i. Output, measured in units of the final good is then given by $Y_t \equiv \left(\int_0^1 P_{it} Y_{it} di \right) / P_t = e^{z_t} X_t^n h_t^\alpha$. As long as the nominal wage is positive, the firm will choose to satisfy the demand constraint (16) with equality. By virtue of this condition, we have that in equilibrium

$$Y_t = C_t.$$

Finally, I express the model in terms of stationary variables by dividing all variables with stochastic trends by their respective permanent components. Thus, I create the variables $c_t \equiv C_t/X_t^n$, $y_t \equiv Y_t/X_t^n$, $w_t \equiv W_t/X_t^n$, $\lambda_t \equiv \Lambda_t/X_t^{n-\sigma}$, $1+\pi_t \equiv (1+\Pi_t)/X_t^m$, $1+i_t \equiv (1+I_t)/X_t^m$, and $1+\widetilde{\pi}_t \equiv (1+\widetilde{\Pi}_t)/X_t^m$.

A competitive equilibrium is then a set of process $\{y_t, h_t, \lambda_t, \pi_t, i_t, w_t, \mathrm{mc}_t, \widetilde{\pi}_t\}$ satisfying

$$e^{\xi_t} \left(y_t - \delta \frac{y_{t-1}}{e^{g_t}} \right)^{-\sigma} \left(1 - e^{\theta_t} h_t\right)^{\chi(1-\sigma)} = \lambda_t$$

$$\frac{\chi e^{\theta_t} \left(y_t - \delta \frac{y_{t-1}}{e^{g_t}} \right)}{1 - e^{\theta_t} h_t} = w_t$$

$$\lambda_t = \beta(1+i_t) E_t \left[\frac{\lambda_{t+1}}{1+\pi_{t+1}} e^{-g_{t+1}^m - \sigma g_{t+1}} \right],$$

$$y_t = e^{z_t} h_t^\alpha$$

$$\mathrm{mc}_t = \frac{w_t}{\alpha e^{z_t} h_t^{\alpha-1}}$$

$$\frac{1+\pi_t}{1+\widetilde{\pi}_t}\left(\frac{1+\pi_t}{1+\widetilde{\pi}_t}-1\right) = \beta E_t e^{(1-\sigma)g_{t+1}}\frac{\lambda_{t+1}}{\lambda_t}\frac{1+\pi_{t+1}}{1+\widetilde{\pi}_{t+1}}\left(\frac{1+\pi_{t+1}}{1+\widetilde{\pi}_{t+1}}-1\right)+\frac{1}{\phi(\mu-1)}\left(\mu \mathrm{mc}_t-1\right)y_t \tag{18}$$

$$1+i_t = \left[A\left(1+\pi_t\right)^{\alpha_\pi} y_t^{\alpha_y}\right]^{1-\gamma_I}\left(\frac{1+i_{t-1}}{e^{g_t^m}}\right)^{\gamma_I} e^{z_t^m},$$

$$1+\widetilde{\pi}_t = e^{-\gamma_m g_t^m}(1+\widetilde{\pi}_{t-1})^{\gamma_m}(1+\pi_t)^{1-\gamma_m}$$

where $\mathrm{mc}_t \equiv 1/\mu_t$ and $\mu \equiv \eta/(\eta-1)$ denote, respectively, the equilibrium real marginal cost and the steady-state product markup. Equation (18) is a Phillips curve and says that all other things equal, current inflation is increasing in the marginal cost.

A first-order approximation of the Phillips curve around $\pi_t = \pi = 0$ yields

$$\widehat{\pi}_t - \widehat{\widetilde{\pi}}_t = \widetilde{\beta} E_t(\widehat{\pi}_{t+1} - \widehat{\widetilde{\pi}}_{t+1}) + \kappa \widehat{\mathrm{mc}}_t, \tag{19}$$

where $\widetilde{\beta} \equiv \beta e^{(1-\sigma)g}$, $\kappa \equiv \frac{(\eta-1)y}{\phi}$, $\widehat{\pi}_t \approx \pi_t - \pi$, $\widehat{\widetilde{\pi}}_t \approx \widetilde{\pi}_t - \pi$, $\widehat{\mathrm{mc}}_t \approx \ln(\mathrm{mc}_t/\mathrm{mc})$, and $\mathrm{mc} = 1/\mu$. This is a familiar expression of a linear Phillips curve, except that it is cast in terms of deviations of the cyclical component of inflation, $\widehat{\pi}_t$ from the cyclical component of a weighted average of past inflations, $\widehat{\widetilde{\pi}}_t$.

References

Aruoba, S. Boragan, and Frank Schorfheide, "Sticky Prices versus Monetary Frictions: An Estimation of Policy Trade-Offs," *American Economic Journal: Macroeconomics 3,* 2011, 60-90.

Christiano, Lawrence J., Martin Eichenbaum, and Charles L. Evans, "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy," *Journal of Political Economy 113,* 2005, 1-45.

Cochrane John H., "The Neo-Fisherian question," 'The Grumpy Economist' blog, 2014.

Cochrane John H., "Michelson-Morley, Fisher, and Occam: The Radical Implications of Stable Quiet Inflation at the Zero Bound," NBER Macroeconomics Annual 2017, volume 32, edited by Martin S. Eichenbaum and Jonathan Parker.

Cogley, Timothy, and Thomas J. Sargent, "Drifts and Volatilities: Monetary Policies and Outcomes in the Post WWII US.," *Review of Economic Dynamics 8,* 2005, 262.302.

De Michelis, Andrea, and Matteo Iacoviello, "Raising an Inflation Target: The Japanese Experience with Abenomics," *European Economic Review 88,* 2016, 67-87.

Fève, Patrick, Julien Matheron, and Jean-Guillaume Sahuc, "Disinflation Shocks in the Eurozone: A DSGE Perspective," *Journal of Money, Credit and Banking 42,* MarchApril 2010, 289-323.

Erceg, Christopher J., and Andrew T.Levin, "Imperfect Credibility and Inflation Persistence?," *Journal of Monetary Economics 50,* May 2003, 915-944.

Galí, Jordi, *Monetary Policy, Inflation, and the Business Cycle: An Introduction to the New Keynesian Framework,* Princeton University Press: Princeton, New Jersey, 2008.

Garín, Julio, Robert Lester, and Eric Sims, "Raise Rates to Raise Inflation? Neo-Fisherianism in the New Keynesian Model," *Journal of Money, Credit and Banking 50,* 2018, 243-259.

Goodfriend, Marvin, and Robert G. King, "The incredible Volcker disinflation," *Journal of Monetary Economics 52,* 2005, 981-1015.

Ireland, Peter N., “Changes in the Federal Reserve’s Inflation Target: Causes and Consequences,” *Journal of Money, Credit and Banking 39,* December 2007, 1851-1882.

Iskrev, Nicolay, “Local Identification in DSGE Models,” *Journal of Monetary Economics 57,* 2010, 189-210.

King, Robert G. and Mark W. Watson, “Inflation and Unit Labor Cost,” *Journal of Money, Credit and Banking 44,* December 2012, 111-149.

Lukmanova, Elizaveta, and Katrin Rabitsch, “New Evidence on Monetary Transmission: Interest Rate Versus InflationTarget Shocks,” manuscript, Vienna University of Economics and Business, July 2019.

Milani, Fabio, “Learning and the Evolution of the Feds Inflation Target,” manuscript, University of California, Irvine, July 2009.

Nicolini, Juan Pablo, “Two Illustrations of the Quantity Theory of Money Reloaded,” manuscript, Federal Reserve Bank of Minneapolis, 2017.

Ritto, João, João Valle e Azevedo, and Pedro Teles, “The Neutrality of Nominal Rates: How Long is the Long Run?,” Working Papers w201911, Banco de Portugal, Economics and Research Department, 2019.

Schmitt-Grohé, Stephanie, and Martín Uribe, “Liquidity Traps: An Interest-Rate-Based Exit Strategy,” NBER Working Paper No. 16514, November 2010.

Schmitt-Grohé, Stephanie, and Martín Uribe, “The Making Of A Great Contraction With A Liquidity Trap and A Jobless Recovery,” NBER Working Paper No. 18544, November 2012.

Schmitt-Grohé, Stephanie, and Martín Uribe, “Liquidity Traps: An Interest-Rate-Based Exit Strategy,” *Manchester School 82, S1,* September 2014, 1-14.

Schmitt-Grohé, Stephanie, and Martín Uribe, “Liquidity Traps And Jobless Recoveries,” *American Economic Journal: Macroeconomics 9,* January 2017, 165-204.

Sims, Christopher, and Tao Zha, “Error Bands for Impulse Responses,” *Econometrica 67,* 1999, 1113-1156.

Sims, Christopher A., and Tao Zha, "Were There Regime Switches in U.S. Monetary Policy?," *American Economic Review 96,* March 2006, 54-81.

Uhlig, Harald, "What Are the Effects of Monetary Policy on Output? Results from an Agnostic Identification Procedure," *Journal of Monetary Economics 52,* 2005, 381-419.

Williamson, Stephen D., "Neo-Fisherism, A Radical Idea, or the Most Obvious Solution to the Low-Inflation Problem," *The Regional Economist,* July 2016, 5-9.

Williamson, Stephen D., "Low Real Interest Rates and the Zero Lower Bound," Working paper, University of Western Ontario, July 2018.