Inflation Persistence and Flexible Prices

Authors	Robert D. Dittmar, William T. Gavin, and Finn E. Kydland
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ABSTRACT

If the central bank follows an interest rate rule, then inflation is likely to be persistence, even when prices are fully flexible. Any shock, whether persistent or not, will cause inflation persistence if it causes a persistent change in the spread between the real interest rate and the central bank's target. Inflation persistence in U.S. data can be characterized by a vector autocorrelation function relating inflation and deviations of output from trend. This paper shows that a flexible-price general equilibrium business cycle model with money and a central bank using an interest rate target can account for such inflation persistence.

Keywords: Inflation Persistence, Flexible Prices, Taylor Rule

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Robert Dittmar
Mathematician
Research Department
Federal Reserve Bank
of St. Louis
P.O. Box 442
St. Louis, MO 63166
(314) 444-8592
dittmar@stls.frb.org

William T. Gavin
Vice President
Research Department
Federal Reserve Bank
of St. Louis
P.O. Box 442
St. Louis, MO 63166
(314) 444-8578
gavin@stls.frb.org

Finn E. Kydland
Professor of Economics
Graduate School of
Industrial Administration
Carnegie Mellon
University
Pittsburgh, PA 15213
(412) 268-3691
kydland@cmu.edu

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Introduction

Fuhrer and Moore (1995) characterize inflation persistence in U.S. data using a vector autocorrelation function relating inflation and deviations of output from trend. In the vector autocorrelation function, both inflation and output are highly persistent and there are significant positive cross-correlations between inflation and output. Of course, vector autocorrelation functions, themselves, do not provide evidence about a particular economic structure, but these time series regularities are often invoked to justify the assumption that systematic monetary policy actions have real effects. The identification problem is difficult and there is no widely accepted solution.

This paper shows that a flexible-price, general-equilibrium business cycle model in which monetary policy shocks have almost no real effects can account for the inflation persistence if the central bank follows an interest rate rule. If it does, inflation dynamics are determined by the dynamics of spread between the real interest rate and the central bank's interest rate target. Any shock, whether persistent or not, will cause inflation persistence if it causes a persistent change in the spread between the real interest rate and the central bank's nominal interest rate target. Thus, inflation persistence is expected to be pervasive in any economy where the central bank is using an interest rate rule. The presence of inflation persistence, by itself, has nothing to say about whether prices are sticky or flexible, or whether the real effects of monetary policy are large or small.

Based on Gavin and Kydland (1999), our real business cycle model has a shopping time specification for money. There are no sticky prices and there is no limited participation in financial markets. Agents' decisions in a period are taken only after all shocks are observed. In this model, inflation persistence is sensitive to the degree of interest rate smoothing and the central bank's reaction to output. The only exogenous source of persistence is the technology shock. Note, however, that inflation persistence can occur even if there no persistence in the shocks because the real rate responds persistently to uncorrelated technology shocks.

In the next section we summarize evidence about inflation persistence, focusing on the period since 1980. We then briefly describe the structure of our model. In the following sections, we use the model to show that inflation persistence can be caused by central banks using an interest rate rule, even in the absence of price rigidities.

Inflation Persistence

Our approach is to analyze both U.S. data and the artificial data generated by our model via the methodology of Fuhrer and Moore (1995). In Figure 1, we reproduce the output and inflation components of a vector autocorrelation function similar to the one used by Fuhrer and Moore to illustrate some basic characteristics of U.S. data. These autocorrelation functions are derived from a three-variable autoregression including four lags each of output (the deviation of real GDP from a Hodrick-Prescott trend), inflation (the change in the logarithm of the GDP deflator), and the interest rate (the rate on 3-month U.S. Treasury securities). Our time period is different (1980:Q2 to 2001:Q4), but the shapes are similar to theirs. The persistence of inflation and the cross-correlations are dampened relative to those calculated using pre-1980 data.[1] We also present one-standard-deviation bands around the estimated vector autocorrelation functions; the bands are constructed using the bootstrap technique described by Runkle (1987). The standard deviations are calculated from a distribution created with 10,003 draws from the randomized residuals. Three draws were discarded because they resulted in a VAR with unstable roots.

Starting in the upper left-hand corner of Figure 1 and moving right, we see that inflation is persistent and at least one standard deviation above zero out to the ninth lagged quarter. The cross-correlations between inflation and the lagged output gap are positive and at least one standard deviation above zero for six lags. In the bottom left-hand panel, the cross-correlation between output and the lagged inflation rate is positive in the contemporaneous period, but becomes negative at 2 years, and then returns to zero by the third year. Finally, the autocorrelation function for output shows that it is also persistent. The autocorrelation is high at one lag but decays quickly, reaching zero by the fifth quarter.

The Economic Environment

We investigate the effects of alternative monetary policy rules embedded in a neoclassical growth model with shocks to production technology, shopping time technology, and the monetary policy rule. We include a stochastic shopping time technology so that we will have three independent sources of error in the data sets generated by our model. These data sets will be used to generate vector autocorrelation functions from a three-variable VAR.

The economic structure. Many identical households inhabit the model economy. Each household maximizes

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[1] Gavin and Kydland (1999, 2000) show that the covariance structure of nominal and real time series are not stable across the October 1979 policy change. Levin and Piger (2003) show that ignoring such breakpoints leads to upward bias in the measurement of inflation persistence.

$$E\sum_{t=0}^{\infty}\beta^t u(c_t, l_t), \tag{1}$$

where $0 < \beta < 1$ is a discount factor, c_t is consumption expenditure, and l_t is leisure time. The functional form of the current-period utility function is

$$u(c_t, l_t) = \frac{1}{1-\gamma}\left[c_t^{\mu} l_t^{1-\mu}\right]^{1-\gamma}, \tag{2}$$

where $0 < \mu < 1$ and $\gamma > 0$ but different from 1. This CES function, with unitary substitution elasticity between consumption and leisure, was chosen because it is consistent with postwar U.S. data in which long-run hours worked per person changed little despite the large increase in real hourly compensation.

The household's stock of capital, k, is governed by the law of motion,

$$k_{t+1} = (1-\delta)k_t + x_t, \tag{3}$$

where $0 < \delta < 1$, δ is the depreciation rate, and x_t is investment.

The typical agent spends available time, T, in three basic activities: input in market production, leisure, and transaction-related activities such as trips to the bank, shopping, and so on. Larger money balances make the shopping activity less time consuming. By holding more money, households have more time for work and/or leisure. Household time spent on transactions-related activities in period t is given by

$$\omega_0 - \omega_{1,t}\left(\frac{m_t}{P_t c_t}\right)^{\omega_2}, \tag{4}$$

where

$$\omega_{1,t} = \overline{\omega}_1 + \varepsilon_t^d, \tag{5}$$

m_t is the nominal stock of money at the beginning of period t, and P_t is the price of physical goods relative to that of money. The parameter $\omega_{1,t}$ of the shopping time technology is equal to its steady state level plus an innovation, ε_t^d, that is independent and identically distributed with a zero mean and variance, σ_d^2. By restricting $\omega_{1,t}$ and ω_2 to have the same sign and $\omega_2 < 1$, the amount of time saved increases as a function of real money holdings in relation to consumption expenditures, but at a decreasing rate. Note that in the timing of the model, only money that is brought in from the previous period is available to reduce shopping time.[2]

Leisure in period t is

$$l_t = T - n_t - \omega_0 + \omega_{1,t}\left(\frac{m_t}{P_t c_t}\right)^{\omega_2}, \tag{6}$$

where T is the total time available and n_t is time spent in market production.

The nominal budget constraint for the typical individual is

$$P_t c_t + P_t x_t + m_{t+1} + b_{t+1} = P_t w_t n_t + P_t r_t k_t + (1+R_t) b_t + m_t + v_t, \tag{7}$$

where w_t is the real wage rate, r_t is the rental rate of capital, and v_t is a nominal lump-sum transfer from the government. R_t is the nominal interest rate earned on bonds, which are in zero net supply in equilibrium. The government transfers money balances directly to households according to its policy rule. It produces money and conducts policy at zero cost.

Aggregate output, Y_t, is produced using labor and capital inputs:

$$Y_t = C_t + X_t = z_t N_t^{\theta} K_t^{1-\theta}, \tag{8}$$

[2] Note that this timing convention is used in Kydland (1989).

where X_t is the total of investment expenditures and z_t is the level of technology, which is subject to transitory shocks. The technology changes over time according to

$$z_{t+1} = \rho z_t + \lambda_{t+1}, \tag{9}$$

where $0 < \rho < 1$ and the innovation, λ_{t+1}, is distributed with a positive mean and with variance σ_{λ}^2.

A law of motion analogous to that for individual capital describes the aggregate quantity of capital. The distinction between individual and aggregate variables is represented here by lowercase and uppercase letters, respectively. This distinction plays a role when computing the equilibrium of a model with government policy in which the equilibrium is not simply the solution to a stand-in planner's problem. Competitive factor markets imply that in equilibrium each factor receives its marginal product.

Monetary Policy. Since the early 1960s, the Federal Reserve has used an indicator of reserve market pressures to guide open market operations. For most of the time since the 1970s, that indicator has been the interest rate on bank reserves, the federal funds rate. By setting a short-term target for the federal funds rate, the Fed automatically supplies reserves to meet unexpected shocks to money demand. We assume that the central bank uses this control over the monetary transfer to implement an interest rate rule of the type suggested by Taylor (1993):

$$R_t^* = \bar{r} + \bar{\pi} + \nu_y \left(\ln Y_{t-1} - \ln \bar{Y} \right) + \nu_\pi \left(\pi_{t-1} - \bar{\pi} \right), \tag{10}$$

where R_t^* is the period t nominal interest rate target chosen by the central bank at the beginning of period t; $\pi_t = \ln P_t - \ln P_{t-1}$ is the inflation rate; and the bar over a symbol refers to the steady-state value. Taylor's original specification did not include the lagged interest rate. We also allow for the possibility that the central bank smoothes interest rates. We add the following partial adjustment mechanism:

$$R_t = \rho_R R_{t-1} + \left(1 - \rho_R\right) R_t^* + \varepsilon_t^s, \tag{11}$$

where we have also included a policy shock, ε_t^s, that is independent and identically distributed with a zero mean and variance, $\sigma_{\varepsilon^s}^2$. This shock is a control error that occurs at the beginning of period *t*.

Competitive Equilibrium. A competitive equilibrium is achieved when the households and firms solve their optimization problems and all markets clear. Due to constraints, the agent's choice of any four variables – say leisure, consumption, investment, and nominal borrowing/lending – will determine the others via individual budget and time constraints. Therefore, there are only four unique first-order conditions that can be derived from the agent's optimizing behavior. Roughly, the first can be considered as arising from the intratemporal choice between leisure and consumption:

$$\frac{\partial u}{\partial l}(c_t, l_t)\left(1 + w_t \omega_{1,t} \omega_2 \left(\frac{m_t}{P_t c_t}\right)^{\omega_2} \frac{1}{c_t}\right) = w_t \frac{\partial u}{\partial c}(c_t, l_t). \tag{12}$$

This expression is complicated by the fact that the agent's time spent at leisure is dependent on his time spent shopping, which in turn depends on consumption. If we define $\kappa_t = 1 + w_t \omega_{1,t} \omega_2 \left(\frac{m_t}{P_t c_t}\right)^{\omega_2} \frac{1}{c_t}$, then, in the absence of shopping time, $\kappa_t = 1$ for all *t* and this condition is the standard condition equating the ratio of marginal utilities of leisure and consumption to the real wage rate.

In this model there are three ways of substituting consumption across time. One is through investment in capital, one is through holding money, and one is by holding government bonds. The first of these intertemporal substitution conditions is

$$\frac{\partial u}{\partial c}(c_t, l_t) = \beta E_t\left[\frac{\kappa_t}{\kappa_{t+1}}\frac{\partial u}{\partial c}(c_{t+1}, l_{t+1})(r_{t+1} + 1 - \delta)\right]. \tag{13}$$

Again, note that in the absence of shopping time, this first-order condition becomes the familiar expression equating the ratio of expected marginal utilities to the gross real interest rate.

Next we have the first-order condition associated with the choice of money balances. It can be written as

$$\frac{\partial u}{\partial c}(c_t, l_t) = \beta E_t\left[\frac{\kappa_t}{\kappa_{t+1}}\frac{P_t}{P_{t+1}}\left(1 + \frac{P_{t+1}c_{t+1}}{m_{t+1}}(\kappa_{t+1} - 1)\right)\frac{\partial u}{\partial c}(c_{t+1}, l_{t+1})\right]. \tag{14}$$

Written in this way, we can see that if there are no shopping time costs, then the ratio of expected marginal utilities is equal to the expected real return on that asset. In the case of money, the return is the inverse of the gross inflation rate, or P_t / P_{t+1}.

Finally, the first-order condition associated with buying or selling government bonds is given by

$$\frac{\partial u}{\partial c}(c_t, l_t) = \beta E_t\left[(1 + R_{t+1})\frac{\kappa_t}{\kappa_{t+1}}\frac{P_t}{P_{t+1}}\frac{\partial u}{\partial c}(c_{t+1}, l_{t+1})\right]. \tag{15}$$

Once again we note that in the absence of shopping time costs this first-order condition reduces to the familiar one where the ratio of marginal utilities has been set equal to the real return to holding bonds.

To analyze the quantitative implications of our model, we use the computational method described by King and Watson (1998). The transition equation for the nominal interest rate is given by the bank's interest rate rule. In equilibrium, aggregate output and the money stock must be consistent with individual choices. The price level is determined in equilibrium by forcing bonds to be in zero net supply. Linearizing first-order conditions, transition equations, and equilibrium conditions around steady-state values results in the approximation that represents our model in the experiments below.

MONETARY POLICY EXPERIMENTS

Table 1 summarizes the baseline calibration used in the experiments. Information about deviations from this baseline case is given in the text and figures when appropriate. The calibration is based on empirical estimates of steady-state relations among the model's variables. Most of the estimates come from long-run or average values. Measurements from panel data also are used.

The parameter θ in the production function is the model's steady-state labor share of output and is set equal to 0.65. This is in line with estimates obtained for the United States if approximately half of proprietors' income is considered to be labor income. We use a quarterly depreciation rate of 0.025. Persistence in the technology shock is assumed to be 0.95 and the standard deviation of the technology shock is set equal to 0.0075—values in line with those estimated by Prescott (1986).

Turning to the household sector, the annual real interest rate is 4 percent, yielding a quarterly discount factor, β, of approximately 0.99. The risk-aversion parameter, γ, is set equal to 2, which means more curvature on the utility function than that corresponding to logarithmic utility. This value is in the range of results reported by Hansen and Singleton (1983) and Neely, Roy, and Whiteman (2001).

We calibrate the money-time tradeoff by setting ω_2, the curvature parameter, equal to -1. This implies a long-run money demand function with interest elasticity equal to -0.5, consistent with the empirical evidence in Hoffman and Rasche (1991), Lucas (1994), and Mulligan and Sala-i-Martin (1997). With the steady-state output and money stock normalized to unity, the steady-state price level is determined by setting the annual income velocity of money at 6.7—equal to the average of M1 velocity between 1980 and 2001.[3] We assume zero real economic growth and zero money supply growth in the steady state, so the steady-state inflation rate is also zero.[4] Given the price level, we derive $\overline{\omega}_1$ from the household's first-order condition for the choice of money holding. The implied steady-state value of $\overline{\omega}_1$ is -0.0022. The magnitudes of $\overline{\omega}_1$ and ω_2 can be understood through a marginal evaluation around the average. If the real money stock is increased by 1 percent relative to its steady state, then a household's resulting weekly time saving is less than a minute. The standard deviation of the payments technology shock is set so that, when it is scaled by the level of payments technology, it is equal to 0.0025.

Without loss of generality, we normalize steady-state shopping time to zero and choose time units so that $n + l = 1$. In line with the panel-data estimates of Ghez and Becker (1975), we set $n = 0.3$. The remaining parameter μ, the share of consumption in the utility function, usually is determined from the condition $MU_\ell / MU_c = w$ and usually turns out to be close to n in magnitude. In this case, because of the dependence of time (and therefore l) on m/Pc, the corresponding condition can be written as

[3] M1 is adjusted for the introduction of sweep accounts after 1994. See Anderson and Rasche (2001) for a discussion of these accounts and the need for adjusting M1.

[4] Adding trends would not change the qualitative nature of our results, but would complicate the measurement of inflation persistence in our experiments.

$$\frac{MU_c}{MU_\ell} = \frac{1}{w} + \frac{\bar{\omega}_1 \omega_2}{c}\left(\frac{m}{Pc}\right)^{\omega_2}. \tag{16}$$

The implied value for μ is 0.33. Because the scale of $\bar{\omega}_1$—and the second term in equation (16)—is small relative to $1/w$, the addition of the shopping time feature has only a tiny effect on the calibration of μ.

The parameters of the Taylor rule are not precisely estimated in the literature. We used Taylor's value for the weight on inflation (1.5). The covariance structure of output and inflation are not very sensitive to alternative values of this parameter. However, the covariance structure is sensitive to the weight on output. Kozicki (1999) uses a wide variety of measures of inflation and output for the United States during the period from 1983 to 1987 to estimate alternative weights in Taylor-type rules. She reports a range of values for the output weight between -0.025 and 0.1.[5] Using a model similar to ours Dressler (2003) estimates the weight on output to be negative, but small and not statistically significant. Using both sticky- and flexible-price models, Ireland (2002) estimates values for the weight on output that are negative, close to the bottom of the range found by Kozicki. We found that a zero weight results in the positive correlation between output and inflation that we observe in the data.

If we do not apply some interest rate smoothing then inflation is much more persistent than estimated in post-1980 data. Clarida, Gali, and Gertler (2000) and Sack and Weiland (2000) estimate the interest rate smoothing parameter to be in the range of 0.7 to 0.8. Rudebusch (2002) argues that it should be much lower. We chose a degree of interest rate smoothing (0.5) that, in conjunction with a zero weight on output and our assumed shock variances, led to a first order autocorrelation of inflation that was about 0.5. The standard deviation of the monetary policy shock is assumed to be 0.125, or 50 basis points per quarter at annual rates.

Baseline case. In Figure 2 we report the vector autocovariance function of output and inflation using the baseline policy rule. As discussed above, the policy rule was calibrated so that the first order autocorrelation for inflation is about 0.5. Both the cross correlation of inflation with lagged output and the cross correlation of output with lagged inflation are positive at short horizons. The autocorrelation in output also looks much like U.S. data because the technology shock process was calibrated to match time series properties of real GDP. Contrary to the U.S. data, patterns of the cross-correlations between inflation and output appear to be backwards; that is, the model cross-correlations of inflation with lagged output becomes negative after about a year, whereas in data they remain positive for about two years. The model cross-correlations of output with lagged inflation remain positive for about two years, whereas in the data they become negative at about one year. This occurs because the trough in the price level leads the peak in the output cycle in the data, but lags in our model. But, as Cooley and Hansen (1995) showed, that is also true in sticky price models.

Stabilizing inflation. Inflation persistence is not sensitive to ν_π, the weight on inflation, as long as the weight is large enough to avoid indeterminacy. Using an analytically tractable model with some features similar to ours and zero weight on output in the policy rule, Carlstrom and Fuerst (2001) show that there are real indeterminacies

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[5] These values are taken from Table 3, page 18, of Kozicki and adjusted for our quarterly scaling of inflation and the interest rate. The estimates are a bit higher in specifications that include interest-rate smoothing.

for values of ν_π less than unity.[6] Numerical analysis confirms that this is the case for our model when there is no weight on output. When the $\nu_y = 0.125$, indeterminacy exists when ν_π falls below 1.061. The region of indeterminacy lies below a curve that is approximately linear from $(\nu_\pi, \nu_y) = (1,0)$ to $(\nu_\pi, \nu_y) = (1.061, 0.125)$.

In our experiments with the baseline model but with alternative weights on inflation, we found that both the first-order autocorrelation (ϕ_1) for inflation and the cross-correlation between inflation and output were relatively insensitive to values of ν_π between 1.2 and 3. In all our experiments, a draw was discarded if it resulted in an estimated VAR with unstable roots. This occurs more often as we get closer to the region of indeterminacy.

Output stabilization. The inflation autocorrelations are more sensitive to the weight on output than they are to the weight on inflation. Figure 3 reports the results of experiments in which we set the weight on inflation at 1.5 and vary the weight on output between plus and minus 0.125. With $\nu_y = -0.125$, ϕ_1 is 0.80. It declines to a minimum value of 0.54 as ν_y is raised toward zero. Then it rises quickly to a plateau at 0.90 as ν_y is raised further. Given the other baseline parameters, variance of the inflation rate is minimized for values of ν_y near .025. The VARs appear to be most stable when there is no weight on output.

The positive correlation between inflation and output in U.S. data has been broadly interpreted as evidence that monetary policy has large real effects. Figure 4 shows how the cross-correlation is influenced by the weight on output in the policy rule.

[6] Their case that is closest to ours is the cash-in-advance specification for money demand with a backward-looking rule. There are still important differences in the utility function and the timing of the household's

The correlation is positive, about one half, if there is no weight on output or if the weight is negative. For positive values of v_y the correlation eventually becomes negative.

Interest-rate smoothing. In preparing for this study, we thought that interest-rate smoothing would be important. Dotsey (1999) uses a model with sticky prices to show that the output effects of a monetary policy shock are greatly amplified with interest-rate smoothing. He also found that inflation persistence may disappear if the central bank smoothes interest rates. In this flexible price model, the main effect of adding interest-rate smoothing is to reduce inflation persistence.

Figure 5 reports the results of experiments in which we vary the weight on the lagged interest rate, ρ_R, between 0 and 1. With the baseline calibration for other parameters, raising ρ_R from 0 to 1 reduces the first-order autorcorrelation from above 0.9 to 0. Even if there is no persistence in technology shock, the first-order autocorrelation will be above 0.9 if there is no interest rate smoothing. Inflation persistence drops more quickly the more interest rates are smoothed if there is no persistence in the technology shock. Interest-rate smoothing tends to make VARs from the experimental data unstable as ρ_R approaches unity. The model is undetermined at $\rho_R = 1$.[7]

IMPULSE RESPONSES

In this section we report impulse responses to a one-percent shock to the level of technology. We do not show the response of output because it is insensitive to changes

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access to the bond market that affect the pricing of the nominal interest rate and the conditions for real determinacy.

[7] There is a region of indeterminacy in our model for the baseline model with interest-rate smoothing for values of ρ_R between 1 and 5.18.

in the policy rule.[8] This approximate neutrality results because a realistic calibration of the shopping time function does not make money holdings large enough to matter for output fluctuations. The response of output follows a pattern familiar in RBC models. A positive technology shock raises output by more than the size of the shock because hours worked also increases. High persistence in the technology shock causes output to remain well above the steady state for many years. The path for output is largely independent of the policy regime. The response of the price level, however, is not. This is important for understanding the effects of putting weight on output in the policy rule. Therefore, we focus on two policy rules in this section. One is our baseline case. The other is the baseline case except that we set the coefficient on output to 0.125, the value implied for our quarterly model by Taylor's original specification that used annual rates for the interest rate and inflation.

Figure 6 shows the impulse responses of the price level to a positive technology shock. In the baseline case, the price level rises, but only slightly. In the case with a large weight on output, the price level declines smoothly. The inflation dynamics can be seen more clearly in Figure 7 which shows the interest and inflation rate responses to technology shocks under these two cases. Except for the one-period delay in the policy reaction, the interest rate and inflation responses are very similar. It is interesting to note that putting more weight on output does not mean that interest rates rise in response to a technology shock. In this model the opposite occurs because of the dynamic interactions between output and inflation.

[8] However, monetary policy can be important for the real economy if the central bank chooses a policy rule that leads to real indeterminacy.

At first glance, it may appear unusual that putting more weight on output causes the response of the nominal interest rate to a technology shock to become negative. The dynamic response can be understood by thinking about what happens with a fixed money stock. In a model like ours but with a fixed money stock, a 1 percent shock to technology leads to about a 0.3 percent decline in the price level. The one-time decline in the price level is unexpected and, by itself, does not affect nominal interest rates. The price level then very gradually rises back to the steady state (inflation is slightly above the steady state rate). Since output and the price level move in opposite directions, putting a large weight on output has the effect of muting the effect of interest rate policy on stabilizing inflation. Under the Taylor rule, on impact, the price level response to a technology shock looks more like it would under a fixed money rule. When there is no weight on output, the public knows that interest rate policy is aimed at stabilizing inflation. In effect, the interest rate rule is a promise to provide money growth in a manner that prevents the need for price jumping. Consequently, the price level does not have to fall in the period of the shock.

Figure 8 shows how the money stock responds to a positive technology shock. When the central bank is following the Taylor rule with a large coefficient on output, a technology shock is associated with a simultaneous reduction in the inflation rate. In the next period, the central bank responds by lowering the interest rate about 20 to 25 basis points. This is associated with a large jump in the money stock. This is consistent with the central bank's need to deliver a long period of inflation slightly below the steady state rate. The real interest rate will remain above its steady state, while the nominal rate remains below the steady state. When there is no weight on output, the result is opposite, but muted. The money supply falls slightly in the period when the central bank raises the interest rate. In this case the nominal rate stays slightly above the real interest rate for an extended period so that the equilibrium requires a long period of inflation slightly above the steady state. In this model, setting the weight on output equal to 0.025 essentially eliminates any effect of a technology shock on inflation or the market interest rate.

CONCLUSION

Inflation persistence has been considered evidence against flexible price general equilibrium models because it is nearly impossible to generate inflation persistence in these models if the central bank is following an exogenous money supply rule. Most of the quantitative work on the cyclical effects of monetary policy in these models was done using such money supply rules. We show that it is quite easy to generate inflation persistence in flexible price models if the central bank is following an interest rate rule. The key to understanding inflation dynamics under interest rate targeting rules is to understand how the central bank is managing the short-term nominal interest rate relative to the real interest rate. Any policy that induces a persistent difference between the nominal and real interest rates will also induce inflation persistence. There is also a substantially lower variance of inflation in models with interest rate rules than in models with a fixed money stock or exogenous money supply rules. In the case of the fixed money stock, the fluctuations in the price level are driven mainly by fluctuations in real output. In the case of interest rate rules, they are driven by fluctuations in the spread between nominal and real interest rates.

References

Anderson, R.G., and R.H. Rasche, "Retail Sweep Programs and Bank Reserves: 1994-1999," Federal Reserve Bank of St. Louis *Review* 83 (January/February 2001), 51-72.

Carlstrom, C.T., and T.S. Fuerst, "Real Indeterminacy in Monetary Models with Nominal Interest Rate Distortions," *Review of Economic Dynamics* 4 (2001), 767-789.

Clarida, R., J. Gali, and M. Gertler, "Monetary Policy Rules and Macroeconomic Stability: Evidence and Some Theory," *Quarterly Journal of Economics* 115 (February 2000), pp.147-180.

Cooley, T.F., and G.D. Hansen, "Money and the Business Cycle," in T.F. Cooley, ed., *Frontiers of Business Cycle Research* (Princeton University Press, 1995), 175-216.

Dotsey, M., "The Importance of Systematic Policy for Economic Activity," Federal Reserve Bank of Richmond *Economic Quarterly* 85 (Summer 1999), 41-59.

Dressler, S. "Monetary Policy Regimes and Causality," mimeo, University of Texas, October 2003.

Fuhrer, J.C., and G.R. Moore, "Inflation Persistence," *Quarterly Journal of Economics* 110 (February 1995),127-159.

Gavin, W.T., and F.E. Kydland, "Nominal Facts and the October 1979 Policy Change," Federal Reserve Bank of St. Louis *Review* (November/December 2000), 39-61.

________, and ________, "Endogenous Money Supply and the Business Cycle," *Review of Economic Dynamics* 2 (1999), 347-369

Ghez, G.R. and G.S. Becker, *The Allocation of Time and Goods over the Life Cycle*. New York: Columbia University Press, 1975.

Hansen, L., and K.J. Singleton, "Stochastic Consumption, Risk Aversion, and the Temporal Behavior of Asset Returns," *Journal of Political Economy* 91 (April 1983), 249-265.

Hoffman, D.L., and R.H. Rasche, "Long-Run Income and Interest Elasticities of Money Demand in the United States," *Review of Economics and Statistics* 73 (1991), 665-674.

Ireland, P.N. "Endogenous Money or Sticky Prices?" NBER Working Paper 9390, December 2002.

King, R.G., and M.W. Watson, "The Solution of Singular Linear Difference Systems Under Rational Expectations," *International Economic Review* 39 (November 1998), 1015-1026.

Kozicki, S., "How Useful Are Taylor Rules?" *Economic Review,* Federal Reserve Bank of Kansas City, Second Quarter 1999, 5-33.

Kydland, F.E., "Monetary Policy in Models with Capital," in van der Ploeg, F. and A. J. de Zeeuw eds., *Dynamic Policy Games* (Elsevier Science Publishers B. V., North-Holland), 1989.

Levin A.T., and J.M. Piger, "Is Inflation Persistence Intrinsic in Industrial Economies?" Federal Reserve Bank of St. Louis Working Paper 2002-023C, Revised May 2003.

Lucas, R.E. Jr., "Inflation and Welfare," *Econometrica* 68 (March 2000), 247-74.

Mulligan, C.B., and X.X. Sali-i-Martin, "The Optimum Quantity of Money: Theory and Evidence." *Journal of Money, Credit, and Banking*, 29 (November 1997, Part 2), 687-715.

Neely, C.J., A. Roy, and C. Whiteman, "Identification Failure in the Intertemporal Consumption CAPM," *Journal of Business and Economic Statistics* 19 (October 2001), 395-403.

Prescott, E.C., "Theory Ahead of Business Cycle Measurement," Federal Reserve Bank of Minneapolis *Quarterly Review,* Fall 1986, 9-22.

Rudebusch, G.D., "Term Structure Evidence on Interest Rate Smoothing and Monetary Policy Inertia," *Journal of Monetary Economics* 49 (September 2002), 1161-1187.

Runkle, D.E., "Vector Autoregressions and Reality," *Journal of Business and Economic Statistics* 5 (October 1987), 437-442.

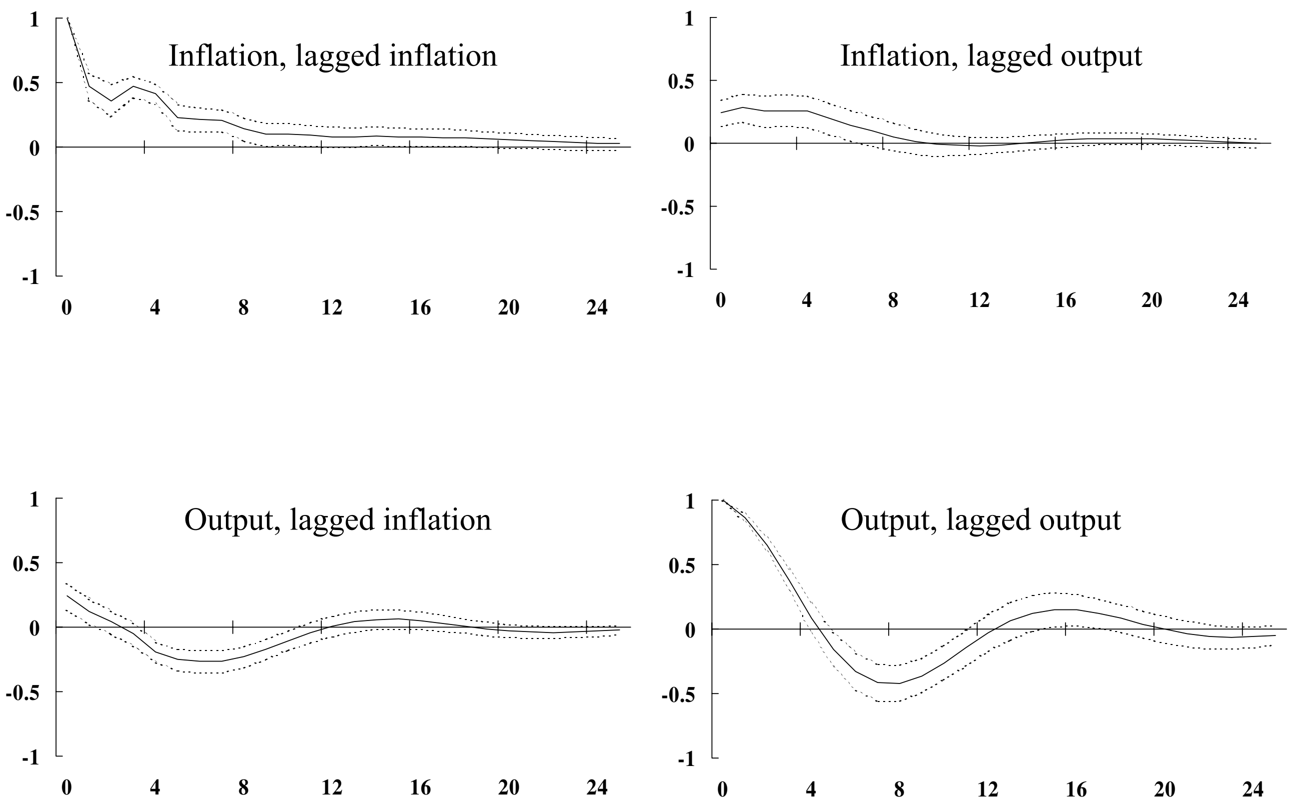
Sack, B.P., and V. Wieland, "Interest-Rate Smoothing and Optimal Monetary Policy: A Review of Recent Empirical Evidence, " *Journal of Economics and Business* 52 (January 2000), 205-228.

Taylor J.B., "Discretion versus Policy Rules in Practice," *Carnegie-Rochester Conference Series on Public Policy* 39 (December 1993), 195-214.

Table 1: Parameter Calibration for the Baseline Case

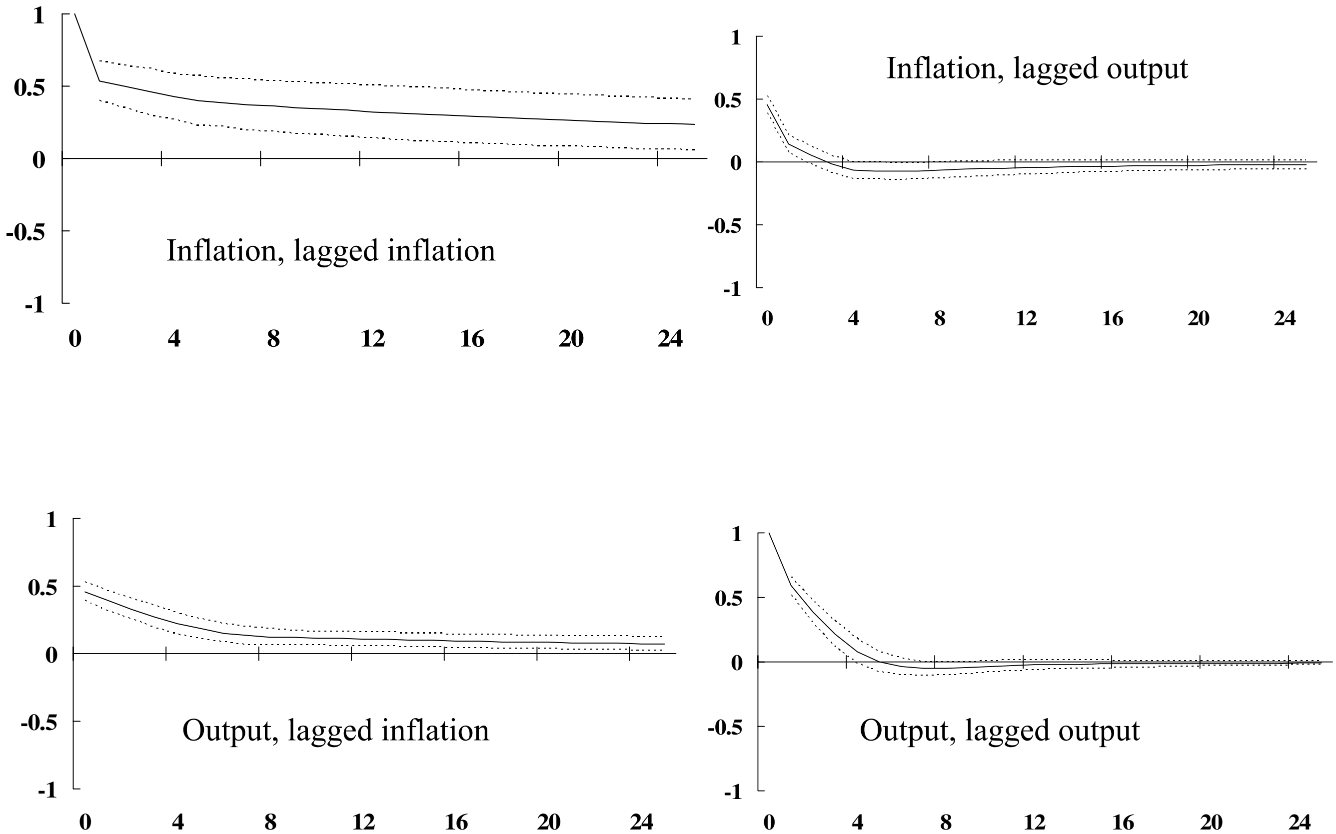
Parameter	**Symbol**	**Value**
Depreciation rate	δ	0.025
Discount factor	β	0.99
Relative risk aversion	γ	2
Consumption share in utility	μ	0.33
Shopping time parameters	$\overline{\varpi}_1$	-0.0022
	ω_2	-1
Labor share in production	θ	0.65
Steady state share of time supplying labor services	n	0.3
Fed's reaction to inflation	ν_π	1.5
Fed's reaction to output gap	ν_y	0
Persistence in the Policy Rule	ρ_z	0.5
Persistence in the Technology shock	ρ_z	0.95
Standard deviation of Shocks		
Production Technology	σ_z	0.0075
Payments technology	$\sigma_{d^*} \lvert \overline{\varpi}_1 \rvert$	0.0025
Monetary policy	σ_s	0.125

Figure 1: U.S. Data 1980:Q2 to 2001:Q4 Vector Autocorrelation Function



One-standard-deviation error bands are calculated using a bootstrap method with 10,000 draws. Three draws were rejected because the roots of the VAR were unstable.

Figure 2: Vector Autocorrelation Function Using Model Data with the Baseline Interest Rate Rule



These are the average vector autocorrelation functions computed from 100 histories. The dashed lines reflect plus and minus one standard deviation. One draw was rejected because the roots of the VAR were unstable.

Figure 3: The Effect of v_y on Inflation Persistence

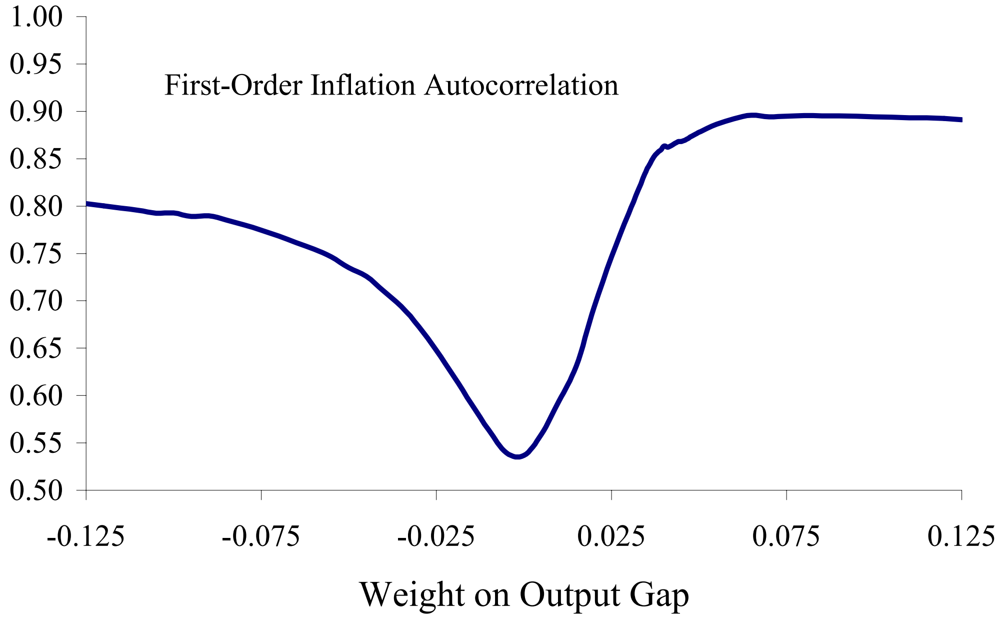


Figure 4: The Effect of v_y on the Output-Inflation Correlation

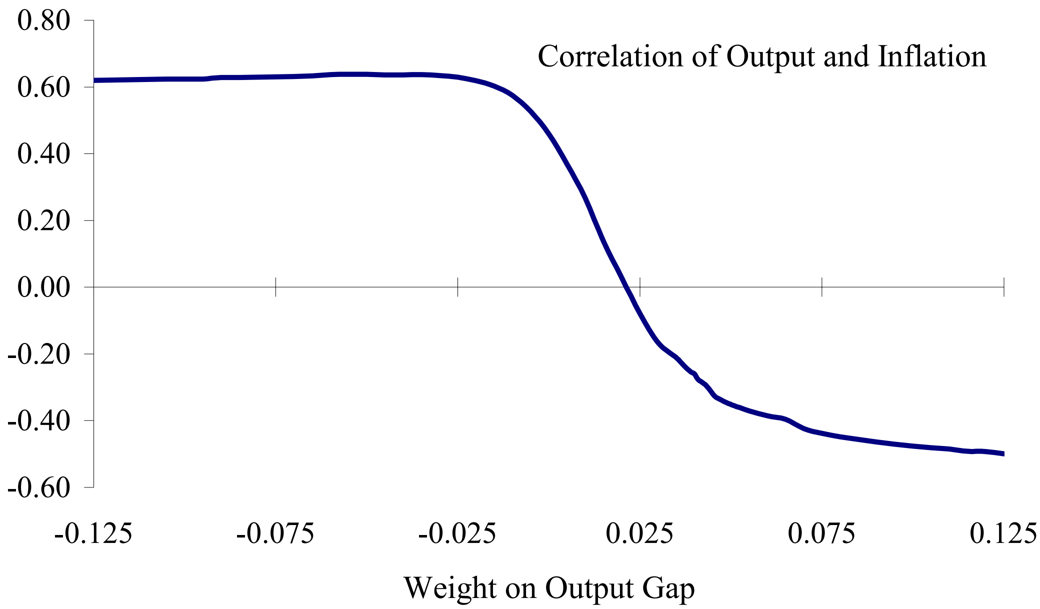


Figure 5: The Effect of ρ_R on Inflation Persistence

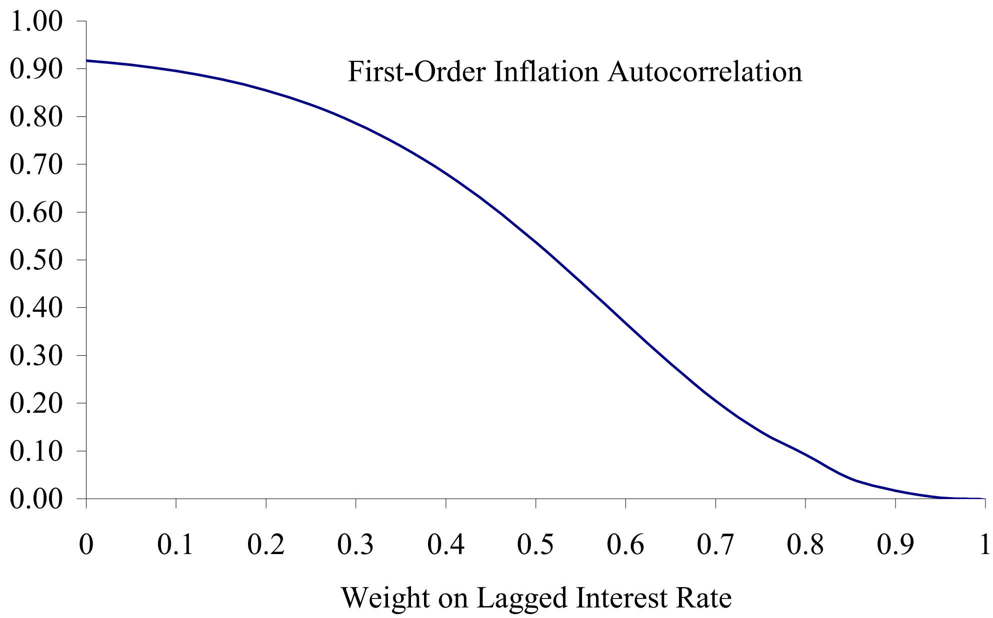
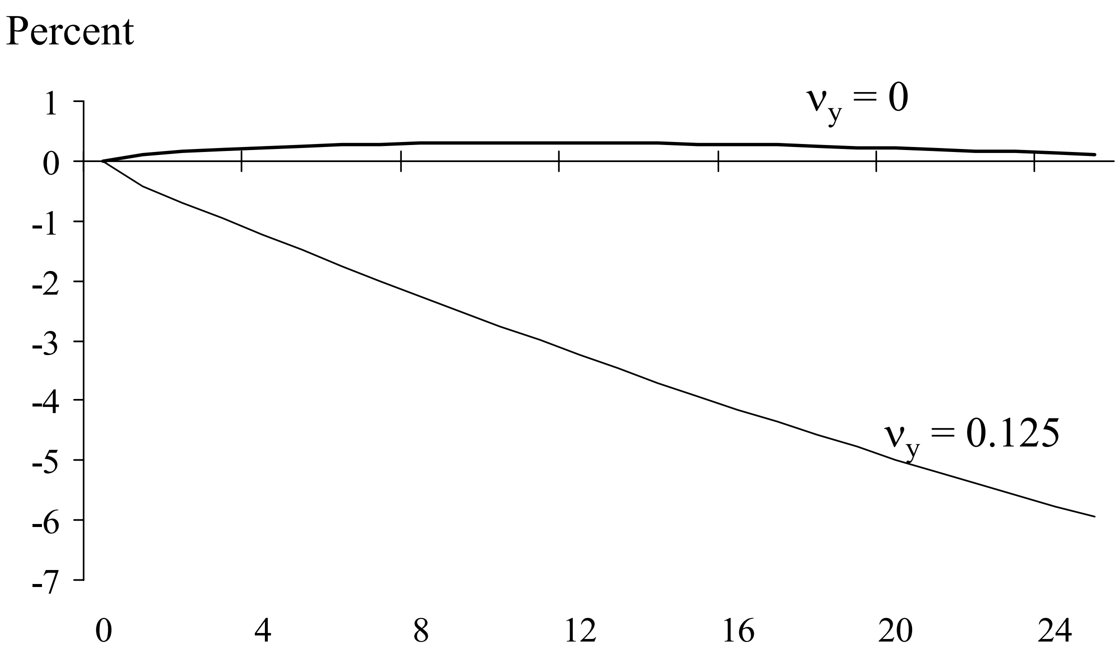
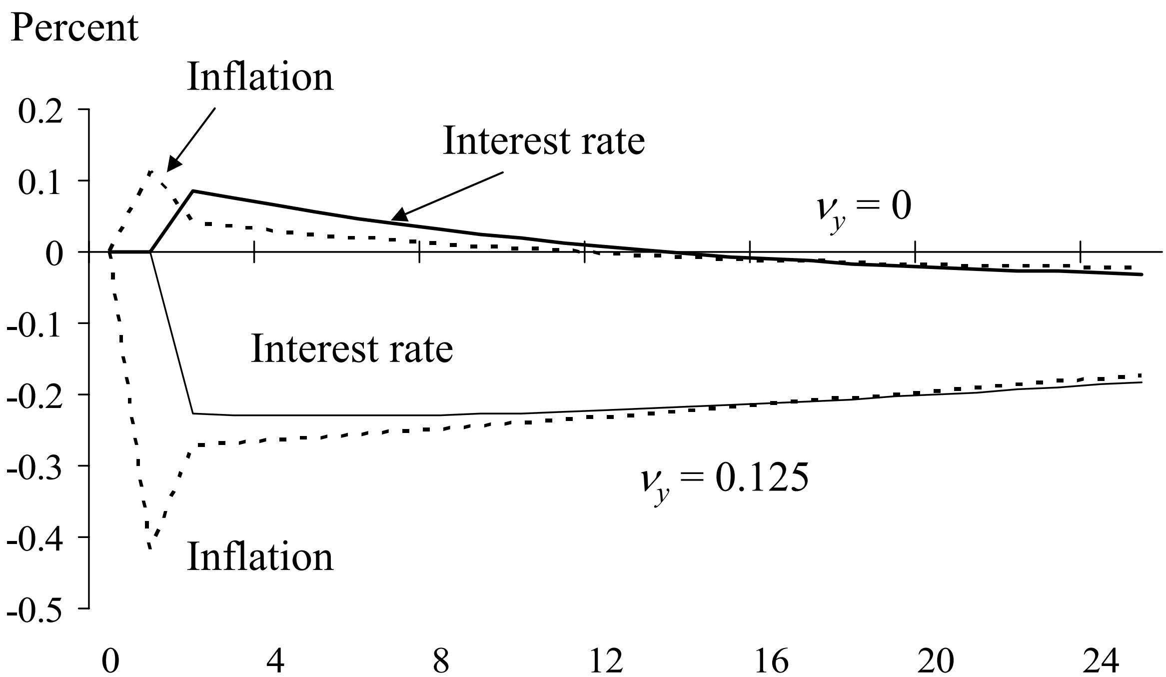


Figure 6: Price Response to a 1% Technology Shock



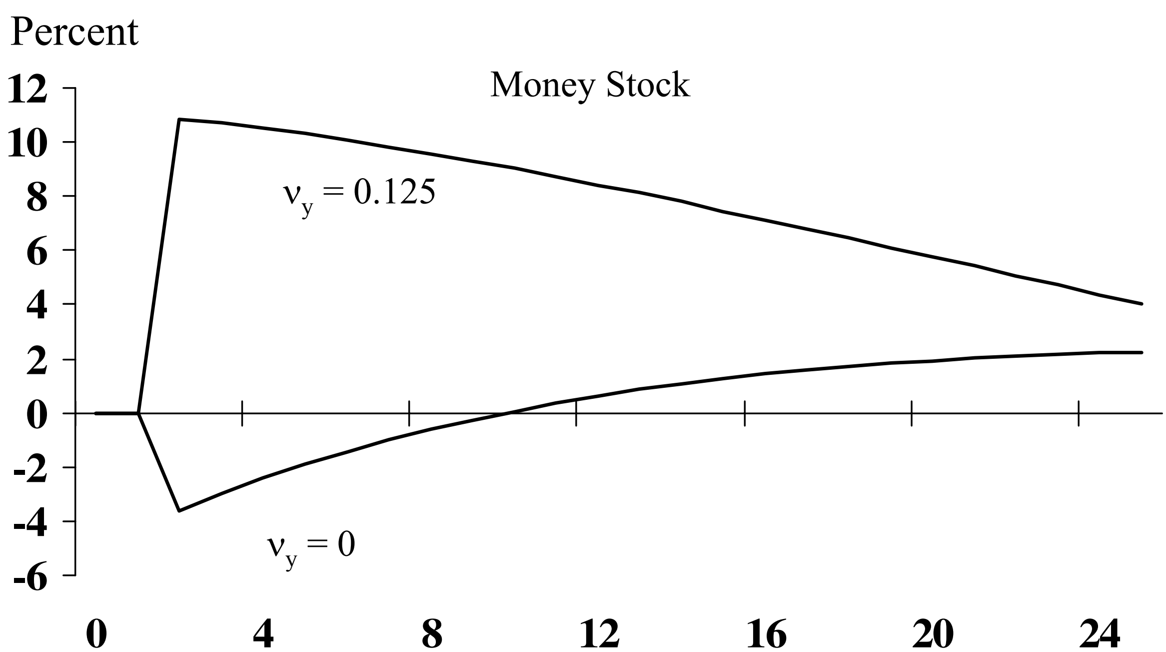
In all these experiments, $\nu_{\pi} = 1.5$ and $\rho_R = 0.5$.

Figure 7: Responses to a 1% Technology Shock



Inflation is shown with a dashed line and the interest rate is shown with a solid line. In all these experiments, $\nu_\pi = 1.5$ and $\rho_R = 0.5$.

Figure 8: Money Stock Response to a 1% Technology shock



In all these experiments, $\nu_\pi = 1.5$ and $\rho_R = 0.5$.