The Price Puzzle and Indeterminacy*

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Abstract

This paper re-examines the empirical evidence on the price puzzle and proposes a new theoretical interpretation. Using structural VARs and two different identification strategies based on zero restrictions and sign restrictions, we find that the positive response of price to a monetary policy shock is historically limited to the sub-samples associated with a *weak* central bank response to inflation. These sub-samples correspond to the pre-Volcker period for the US and the pre-inflation targeting regime for the UK. Using a micro-founded DSGE sticky price model of the US economy, we then show that the structural VARs are capable of reproducing the price puzzle on artificial data *only* when monetary policy is *passive* and hence multiple equilibria arise. In contrast, the DSGE model never generates on impact a positive inflation response to a policy shock. The omission in the VARs of a variable capturing the high persistence of *expected inflation* under indeterminacy is found to account for the price puzzle observed on actual data.

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1 Introduction

Structural vector autoregressions (SVARs) are widely used to measure and understand the effects of monetary policy innovations on the aggregate economy. The empirical validity of these assessments relies on the selection of a plausible identification scheme, which requires to imposing an appropriate number of restrictions on the relationships among the variables of the empirical model. The contemporaneous zero restrictions used by Sims (1992) and popularized by Christiano, Eichenbaum and Evans (1999) is, for instance, a typical identification strategy to isolate the effects of a policy shock. This identification hinges upon the assumption that the policy instrument reacts contemporaneously to inflation and output, while inflation and output respond to the policy instrument with some lags only.

While most results in the VAR literature are consistent with economic intuition and macroeconomic theory, the typically found positive reaction *on impact* of the price level to a monetary policy shock is a fact that most monetary models have difficulty explaining. This anomaly, first noted by Sims (1992) and labelled 'the price puzzle' by Eichenbaum (1992), seems to cast serious doubt on the ability of correctly identifying a monetary policy shock. If the central bank monitors and responds to a larger information set relative to the one of the VAR, what is referred to as a policy shock is actually a combination of a genuine policy shock and some endogenous policy reactions.

Sims (1992) argues that the central bank may have more information about future inflation than a simple VAR could adequately capture. The result of this omission is that a policy tightening in anticipation of future inflation would be wrongly interpreted by the econometrician as a policy shock. As long as the monetary policy response only partially offsets the inflationary pressure, the VAR would therefore deliver a spurious correlation between a tightening of policy and a rise of inflation, namely the price puzzle. Sims (1992) observes that the inclusion of a commodity price index in the VAR seems to capture enough additional information about future inflation as to possibly solve the puzzle.

In a recent speech as Fed Governor, Bernanke (2004) offered a new interpretation of the hypothesis of mis-identification of the structural shocks conjecturing that:

> "*[...] changes in inflation expectations, which are ultimately the product of the monetary policy regime, can also be confused with truly exogenous shocks in conventional econometric analysis. Marvin Goodfriend (1993) has suggested, for example, that insufficiently anchored inflation expectations have led to periodic 'inflation scares', in which inflation expectations have risen in an apparently autonomous manner. Increases in inflation expectations have the flavor of adverse aggregate supply shocks in that they tend to increase the volatility of both inflation and output, in a combination that depends on how strongly the monetary policy makers act to offset these changes in expectations.*"[1]

This paper offers a theoretically and empirically consistent explanation for the price puzzle using a micro-founded DSGE model and structural VARs. A major contribution is to show that the price puzzle has been historically a distinctive feature of specific monetary policy regimes. These regimes are the period prior to the appointment of Paul Volcker as Fed

[1] It should be noted that Bernanke (2004) refers to Goodfriend's argument of '*insufficiently anchored inflation expectations*' in the context of the 'Great Moderation' defined as the sizable decline of output and inflation variability observed moving from the 1970s and very early 1980s to the rest of the 1980s and the 1990s. In the original paper however Goodfriend (1993) refers to the very end of the 1970s and very early 1980s only.

Chairman in August 1979 for the US and the period prior to the introduction of the inflation targeting regime in 1992 for the UK. This result is robust to using two different identification strategies based on recursive zero restrictions and sign restrictions as well as to augmenting the VARs with unit labor costs, a commodity price index and M2. Moreover, the sub-sample evidence on the price puzzle is found to be independent from using real GDP, detrended output, the output gap or output growth as a measure of real activity.

A wide number of contributions to the empirical literature on monetary policy rules finds that a shift in the conduct of monetary policy occurred at the end of 1979 in the US (Clarida, Galí, and Gertler, 2000, Boivin and Giannoni, 2003, Lubik and Schorfheide, 2004, Cogley and Sargent, 2005, among others) and at the end of 1992 in the UK (Nelson, 2003). We therefore investigate the correlation between the empirical result of this literature about monetary policy and the empirical finding of this paper about the price puzzle.

Using a DSGE sticky price model of the US economy as data generating process, we show that structural VARs on artificial data, based on either zero restrictions or *model consistent sign restrictions*, are capable of reproducing the price puzzle *only* when the central bank does not raise the interest rate sufficiently in response to inflation and thus multiple equilibria arise. In contrast, the DSGE model is not capable of generating on impact a positive response of the price level to a monetary policy shock even when monetary policy is passive.[2] Another main contribution of the paper is to show that the price puzzle is actually a spurious correlation induced by the omission in the VAR of a variable capturing the persistence of expected inflation, which is remarkably higher under indeterminacy. And, the *indeterminacy induced omitted variable bias* is found to account quantitatively for the apparently puzzling response of inflation to a policy shock observed on actual data. Interestingly, our results show that the arguments in Sims (1992) and Bernanke (2004) are supported in the context of a structural model only when monetary policy is passive and thus multiple equilibria arise.

It is worth noticing that since the seminal paper by Sims (1992) and the comment by Eichenbaum (1992), several important recent contributions including Hanson (2004), Giordani (2004) and Leeper and Roush (2003) have advanced our knowledge on the timing and characteristics of the price puzzle. These contributions however are mainly empirical and, to the best of our knowledge, this paper is the first attempt to rationalize the price puzzle using a structural model.[3]

The paper is organized as follows. Section 2 presents a re-examination of the empirical evidence using, among other (augmented) specifications, estimated SVARs in output, inflation and nominal interest rate. The following part describes the DSGE sticky price model used for the theoretical investigation. In Section 4, the dynamic responses of the theoretical model to a monetary policy shock are compared to the impulse responses of the structural VARs estimated on artificial data. The latter are shown to be severely biased relative to the former, and to reproduce the sign and magnitude of the price puzzle observed over the pre-1979 sub-

[2] Following the literature, monetary policy is defined as 'active' ('passive') when the nominal interest rate is moved more (less) than proportionally in response to movements in inflation.

[3] It should be noted that in principle the cost channel and the interaction of active fiscal policy and passive monetary policy could also contribute to the sub-sample evidence on the price puzzle. At the empirical level however, Rabanal (2004) estimates on US aggegate data a DSGE sticky price model augmented with a cost channel and shows that the estimated model is not capable of generating a price puzzle. Lubik (2005) tests for indeterminacy in a DSGE sticky price model that explicitely incorporates fiscal policy and cannot reject the hypothesis that the interaction of monetary and fiscal policy in the US prior to 1979 resulted in an indeterminate equilibrium.

sample only when the model is simulated under indeterminacy. The results from a hybrid version of the DSGE model are also presented. Section 5 offers a new interpretation of the price puzzle and shows that augmenting the SVAR on actual data with the Federal Reserve's inflation forecasts reduces significantly the omitted variable bias that would otherwise emerge. Conclusions are presented in the last section. The source of the data and the construction of the variables are detailed in the Data Appendix while the last Appendix outlines the method in Sims (2001) and the identification strategy proposed in Lubik and Schorfheide (2003 and 2004) to solve the model under indeterminacy.

2 A Re-examination of the Empirical Evidence

This section reconsiders the empirical evidence from the VAR literature and shows that the price-puzzle is a *sub-sample phenomenon*. In particular, a positive response of inflation to an interest rate structural innovation is an outstanding feature of the periods that, in the empirical literature on monetary policy rules, are typically associated with a weak central bank reaction to inflation. This result appears robust to several modifications in the VAR, and is independent of using real GDP or the output gap as a measure of real activity.[4]

2.1 Identification through zero restrictions

The n-variables VAR has the following structural representation

$$AY_t = B(L)Y_{t-1} + u_t \tag{1}$$

where Y_t is the vector of endogenous variables and A is the matrix of the contemporaneous relationships. $B(L)$ represents the lag-structure (from lag 1 to lag p), and u_t is the vector of structural shocks, which has variance-covariance matrix $E\left(u_t u_t'\right) = I$.

The structural VAR can be written in reduced form as

$$Y_t = C(L)Y_{t-1} + v_t$$

where the elements of the matrices C are convolutions of the elements in the matrix A and the elements in the matrices B. The reduced-form residuals are stacked in the vector $v_t = A^{-1}u_t$ and have variance covariance matrix $E\left(v_t v_t'\right) = \sum$.

To identify the monetary policy shock, we adopt the recursive scheme put forward by Christiano, Eichenbaum and Evans (1999) and impose $n\left(n-1\right)/2$ zero restrictions on the matrix of contemporaneous relationships A. This corresponds to employing a Cholesky factorization of the variance covariance matrix estimated from the unrestricted VAR such that $\widehat{A^{-1}}\widehat{A^{-1}}' = \widehat{\sum}$.

With a lower-triangular structure, the ordering $Y_t = [y_t, \pi_t, R_t]'$ implies that the measure of real activity, y_t, is the most exogenous variable, the measure of inflation, π_t, can respond contemporaneously to real activity *only*, whereas the instrument of monetary policy, R_t, can respond contemporaneously to *both* inflation and real activity. The last equation in the structural VAR is interpreted as a contemporaneous policy rule. The model is just-identified.

[4] As the output gap can be measured according to several statistical criteria, it is important to check the robustness of our findings to different empirical definitions. Our results are robust to using a fairly broad range of output gap measures which have been proposed in the literature.

2.2 Full-sample IRFs

We consider US quarterly data for the period 1966Q1-2002Q4.[5] The beginning of the sample corresponds to the date when the Federal funds rate was first traded consistently above the discount rate. The results below are robust to let the first sub-sample begin in the first quarter of 1960 and the second sub-sample begin in the fourth quarter of 1982, which corresponds to the end of Volcker's experiment on non-borrowed reserves targeting. The first set of impulse responses use real GDP as a measure of activity. The baseline measure of inflation is the change in the GDP deflator while the policy instrument is the federal funds rate.

Figure 1 plots the impulse response functions of the three variables to a monetary policy tightening obtained from the estimates of the recursive VAR outlined in the previous section.[6]

[**Figure 1 about here**]

The middle panel shows the price puzzle. After a monetary policy shock, the price level moves upward such as to imply a positive and prolonged increase in inflation. In contrast, the responses of the federal funds rate and the output level appear in line with the predictions of the theory. The zeros on impact are imposed in the identification.

The 95% confidence bands of the inflation reaction do include the zero. The analysis below will show, however, that the price puzzle is indeed very significant over the sub-sample associated with a weak central bank response to inflation. For the time being, it is worth emphasizing not only that the qualitative pattern of inflation in Figure 1 is counter-intuitive but also that many macroeconomic models have serious difficulties in explaining it. This paper reconciles theory and empirics using a DSGE monetary model. As the theory suggests that the output gap rather than the level of output should be used as a measure of real activity, the analysis below will also focus on VARs that include the output gap.

2.3 The Sub-sample Stylized Fact

This section recasts the discussion on the price puzzle in terms of monetary policy shifts and asks whether the change in the conduct of US monetary policy that Clarida, Galí and Gertler (2000), Boivin and Giannoni (2003), Lubik and Schorfheide (2004), and Cogley and Sargent (2005), among others, date to the end of the 1970s, is correlated with the evidence on the price puzzle. To investigate this possibility, we follow earlier contributions and split the sample in the third quarter of 1979 when Paul Volcker was appointed Chairman of the FOMC and fighting inflation became a clear policy objective. We use the same variables and identification scheme of the previous section and compute the IRFs from the restricted VAR over the two sub-samples.

[**Figure 2 about here**]

Figure 2 shows that the price puzzle is significant and sizable during the pre-Volcker period only. The reactions of all variables to the policy shock appear far larger than in the full-sample analysis. In particular, the inflation rate peaks at 57 basis point, while in Figure 1 the peak does not go further than 16 basis point. After seven quarters the inflation rate becomes

[5] A detailed description of the data can be found in the Data Appendix.

[6] The number of lags in the VARs is chosen throughout the paper according to standard lag length criteria. The results are robust to keeping the number of lags fixed across sub-samples.

negative implying that the price level reverses its path. Turning to the post-Volcker regime 1979Q4-2002Q4 in the bottom panel, we do not find any evidence of a price puzzle in that the inflation reaction to a policy shock is negative on impact and then fades away fairly quickly, far from being statistically relevant.[7]

Figures 1 and 2 are based on tri-variate SVARs embedding the real GDP. As Giordani (2004) emphasizes however, the macroeconomic theory predicts that the output gap rather than the level of output should enter a VAR designed for monetary policy analysis. We take this point seriously and estimate a tri-variate VAR in the output gap, inflation and nominal interest rate using the recursive identification scheme outlined above. The output gap x_t is defined as the percentage deviation of output y_t from its potential level y_t^*. In turn, we consider three different measures of potential output that correspond to: i) the estimates of the Congressional Budget Office (CBO), ii) the HP-filter trend, and iii) a quadratic trend.[8] Figure 3 depicts the impulse responses of inflation to a monetary policy shock. The other IRFs, omitted for brevity and available upon request, show patterns consistent with the theory.

[**Figure 3 about here**]

Immediately, we see that the presence of the output gap does not affect the sub-sample evidence. The reaction of the inflation rate is quite similar across different output gap definitions, and it is also very similar to the impulse response shown in Figure 2. The evidence in favor of the price puzzle is statistically relevant only before 1979 in spite of the fact that the measure of real activity is now the output gap. The response of inflation peaks after a few periods and it is now larger than in the full-sample analysis reported in Figure 1. In contrast, the price puzzle disappears after 1979. Using the growth rate of real GDP as measure of real activity or using the Consumer Price Index (CPI) as measure of inflation gives results, not reported but available upon request, which are fairly similar.

2.4 Robustness Analysis

This section investigates the robustness of our results to using a four-variate and a five-variate SVAR. The expanded vector of endogenous variable is given by $\widetilde{Y}_t = [z_t, y_t, \pi_t, R_t]'$ where z_t contains the additional variable(s). Figure 4 presents the inflation response to a monetary policy shock under four different specifications of the vector $\widetilde{Y}_t$. The first column augments the tri-variate VAR in federal funds rate, inflation and real activity with a measure of real unit labor costs as suggested by the theory and by the empirical analysis in Sbordone (2002). The second column uses the changes in the Production Price Index (PPI: Industrial Commodities) as fourth variable of the VAR in the spirit of Sims (1992), while the third column assesses the ability of $M2$ growth to lead future inflation in the context of the non-recursive identification strategy proposed by Leeper and Roush (2003).[9] The last column presents the results from

[7] Similar results are obtained by Christiano, Eichenbaum and Evans (1999) using a recursive identification and monthly data, and by Boivin and Giannoni (2003) using a recursive factor-augmented VAR and quarterly data. The focus of these papers however is on measuring the monetary policy shocks and on assessing whether monetary policy has become more effective rather than on interpreting the price puzzle.

[8] The HP filter is two-sided and so produces a smoothed series of output that may lead to inconsistent estimates. Other studies however employ this cyclical measure and for the sake of comparison we also report the IRFs using the deviations of output from an HP and a quadratic trend.

[9] Very similar findings are obtained replacing $M2_t$ growth with the level of $M2_t$ or with a measure of real balances, $M2_t/P_t$ where P_t is the GDP deflator at time t. The price puzzle becomes even larger over the

a specification advocated by Christiano, Eichenbaum and Evans (1999) which consists of a five-variate VAR in PPI inflation, real GDP, inflation, federal funds rate and $M2$ growth.

[**Figure 4 about here**]

All impulse response functions in Figure 5 reveal that the data still favor the hypothesis that the price puzzle is limited to the pre-1979 sub-sample. As in the previous figures, the puzzle is quantitatively important and statistically relevant for all specifications, though the estimates for the four-variate VAR with $M2$ growth are somewhat less precise. It is worth emphasizing that the standard practice of including the Production Price Index to solve the price puzzle, as shown in the second and last columns, does not overturn the sub-sample evidence.[10]

2.5 An alternative identification strategy based on sign restrictions

In this section, we discuss the robustness of the results based on *contemporaneous zero* restrictions to using an alternative identification scheme based on *sign* restrictions. The technical implementation of this alternative strategy is already offered in several papers in the literature and will not be repeated here (see Peersman, 2005 and the references therein).

In line with the theoretical model used below, a monetary policy shock has a non-negative impact on the interest rate and a non-positive effect on the output gap. It is worth emphasizing that unlike previous contributions, which rule out the price puzzle by assuming a *non-positive* inflation response to a monetary policy shock, we deliberately leave the inflation response *unconstrained* in an effort to investigate and document the sub-sample regularity associated with the price puzzle.

The effects of supply and demand shocks are consistent with a typical aggregate demand and aggregate supply diagram: a supply (demand) disturbance has a non-negative (non-negative) effect on interest rate and inflation, and a non-positive (non-negative) effect on the output gap. Following Peersman (2005), the restrictions on the interest rate are imposed over the contemporaneous reaction whereas the restrictions on the responses of inflation and output are imposed for, but not limited to, the first four periods.

The choice of identifying also supply and demand shocks as opposed to identifying the monetary policy shock only, while not crucial for the results, is twofold. First, we want to make sure that following other types of shocks the matrix of contemporaneous parameters, which also identifies the policy shock, does not produce responses of inflation, output and interest rate inconsistent with economic intuition and theory. Second, we wish to impose most of the sign restrictions implied by a typical DSGE sticky price model because this is the vehicle used in the section 4 to show that the price puzzle is the artifice of an omitted variable bias. The qualitative results are not affected by varying these numbers.

[**Figure 5 about here**]

pre-1979 sub-sample using two alternative recursive identifications in which money is the most exogenous and then the most endogenous variable in the VAR.

[10] Our results are robust also to using the log of PPI, the Oil Price Index of the Wall Street Journal, the PPI: Crude Fuel, and the PPI: Crude Materials. Similar findings are reported in Fuhrer (2000) and extensively commented in Hanson (2004).

Figure 5 presents the impulse responses of the output gap, inflation and the interest rate to a monetary policy shock. The price puzzle confirms itself as an empirical regularity associated with the pre-1979 sub-sample. Relaxing the contemporaneous zero restrictions actually amplifies the puzzle in that the inflation response becomes now positive and highly significant also on impact. Furthermore, following a policy shock inflation declines on impact over the post-1979 sub-sample with monetary policy having a significant effect on all variables.

2.6 Evidence for the UK

The link between a monetary policy regime and the evidence on the price puzzle does not seem limited to the US. While an international investigation is beyond the scope of this paper, we employ a tri-variate recursive VAR using data for the UK economy before and after the introduction of the inflation targeting regime in the fourth quarter of 1992. The sample starts in 1979Q2 when the Thatcher government was first elected and moved towards a more explicitly counter-inflationary monetary policy. Additionally, the data on the UK labor market, including unit labor costs, began to be systematically collected and published only in 1979 with the establishment of the Labour Force Survey.

[**Figure 6 about here**]

Figure 6 compares the impulse responses of inflation to a monetary policy shock using real GDP, HP-filtered and quadratically detrended output as measure of real activity, and the change in GDP deflator and CPI as measures of inflation, respectively. The policy instrument is the Bank of England Repo rate.[11] The top panel shows that only the pre-1992 estimates are associated with a large and robust price puzzle, although this is not statistically significant. In contrast, the inflation targeting regime is characterized by a few dynamics and the price puzzle is not present anymore. The positive inflation response, which emerges now only for a few quarters, is quite small relative to the IRFs in the top panel.[12]

The hypothesis of a correlation between the price puzzle and the monetary policy regime is consistent with the evidence in Nelson (2003) who finds that the pre- and post-1992 periods are characterized by a marked difference in the monetary policy stance: the nominal interest rate has been raised more than proportionally in response to inflation *only* since 1992.[13]

In summary, Figures 1 to 6 identify a new stylized fact. The VAR evidence of a positive reaction of inflation on impact to a monetary policy shock is limited to specific historical periods. These are the pre-Volcker sample for the US and the pre-inflation targeting regime for the UK. The dating of this stylized fact calls for a new explanation of the price puzzle. Our hypothesis is that most of the apparent price puzzle comes from the (mis)identification of the monetary policy shock during the regimes associated with a *weak* response of interest rate to inflation. The rest of the paper investigates this hypothesis using a standard DSGE sticky price model.

[11] Similar results are obtained using the 3-month Treasury bill rate, which has historically moved quite closely with the different policy instruments used by the UK monetary authorities since 1979. The correlation between the Repo rate and the 3-month Treasury bill rate is 0.97.

[12] Similar results are obtained by Benati and Mumtaz (2005) using sign restrictions.

[13] As the paper focuses on monetary policy, we abstract from fiscal policy considerations which may have also contributed to the inflation outcome of the 1980s in the UK.

3 A Framework for Monetary Policy Analysis

This section describes a log-linearized, microfounded New-Keynesian sticky price model of the business cycle of the kind popularized by Clarida, Galí and Gertler (1999), King (2000) and Woodford (2003) among others. This model consists of the following three aggregate relationships:

$$x_t = E_t x_{t+1} - \tau(R_t - E_t \pi_{t+1}) + g_t \tag{2}$$

$$\pi_t = \beta E_t \pi_{t+1} + \kappa (x_t - z_t) \tag{3}$$

$$R_t = \rho_R R_{t-1} + (1 - \rho_R)(\psi_\pi \pi_t + \psi_x [x_t - z_t]) + \varepsilon_{R,t} \tag{4}$$

$$[g_t, u_t, \varepsilon_{R,t}]' \sim N \left(0_{3x1}, diag \left[\sigma_g^2, \sigma_u^2, \sigma_R^2\right]\right) \tag{5}$$

where x_t is defined as the deviation of output from a long-run trend, π_t represents inflation, and R_t is the nominal interest rate. Inflation and the interest rate are expressed in percentage deviations from their steady state values.

Equation (2) is a log-linearized IS curve stemming from the household's intertemporal problem in which consumption and bond holdings are the control variables and τ represents the intertemporal elasticity of substitution. There is no physical capital in this economy and therefore consumption is proportional to total resources up to an exogenous process g_t. The latter is typically interpreted as a government spending shock or a preferences shock.[14]

Equation (3) captures the staggered feature of a Calvo-type world in which each firm adjusts its price with a constant probability in any given period, and independently from the time elapsed from the last adjustment. The discrete nature of price setting creates an incentive to adjust prices more the higher is the future inflation expected at time t. The parameter $0 < \beta < 1$ is the agents' discount factor while k_t, which is the inverse of the sacrifice ratio, relates the difference between the output deviation from a long-run trend, x_t, and the stochastic marginal cost of production, z_t, to the contemporaneous rate of inflation π_t.

Equation (4) characterizes the behavior of the monetary authorities. This is an interest rate rule according to which the central bank adjusts the policy rate in response to inflation and the output gap, $(x_t - z_t)$. These adjustments are implemented smoothly, with ρ_R measuring the degree of interest rate smoothing. The random variable ε_R stands for the monetary policy shock, which can be interpreted either as unexpected deviations from the policy rule or as policy mistake.

There is no correlation between innovations and their variance-covariance matrix is described in equation (5). Furthermore, all shocks hitting the economy are white noise. The last assumption has been deliberately designed to make transparent the effect of indeterminacy on the persistence of inflation and inflation expectations. Allowing for an autoregressive process for z_t does not alter our conclusions.

4 Impulse Response Functions Analysis

In this section, we investigate whether the small-scale DSGE monetary model detailed above is capable of reproducing the price puzzle. The model is parameterized using the estimates in

[14] Notice that the IS curve can be easily reinterpreted as a schedule explaining the behavior of the 'output gap' defined as the difference between the stochastic components of output and the flexible price level of output (see Clarida, Galí, and Gertler, 1999). In this case, the shock g_t is also a function of potential output variations.

Lubik and Schorfheide (2004). We employ the same structural VAR on two data sets generated under indeterminacy and determinacy. The procedure in the simulations is as follows:

1. Solve the model under both indeterminacy and determinacy, and generate two data sets of 55 and 93 observations including output gap, inflation and interest rate.[15]
2. For each solution, estimate a reduced-form tri-variate VAR on the artificial data and impose the same identification strategies adopted in the empirical analysis
3. Compute the responses of the variables to a structural innovations in the interest rate equation.
4. Repeat steps (i) to (iii) $10,000$ times and for each parameterization select the median structural IRFs.[16]

To the extent that indeterminacy can explain the price puzzle, the SVARs using the data simulated under indeterminacy should reproduce, at least qualitatively, the stylized fact, and possibly generate structural IRFs which are within the empirical 95% confidence bands shown in Section 2. On the other hand, the SVARs using the data simulated under determinacy should not produce any puzzling response.

4.1 Parameterization

In order to implement Step 1 and check the robustness of our results to different parameterizations, we use two sets of estimates for the New-Keynesian model presented in Section 3. These values are reported in Lubik and Schorfheide (2004) for the US economy over some pre- and post-Volcker samples. The only difference relative to their model is that our specification deliberately lacks any endogenous or exogenous persistence in the inflation and output process. This choice reflects the attempt to evaluate the ability of a quite forward-looking model to generate persistence under indeterminacy.

To focus on the importance of a change in monetary policy, we keep all structural parameters of the model fixed across simulations with the exception of the coefficients in the interest rate equation. The first (second) artificial data set corresponds to the pre-1979 (post-1979) estimates of the reaction function. In doing so, any difference in the structural IRFs estimated on the artificial data sets can only be due to the variation in the Taylor rule. Table 1 reports the values of the parameters of the model.[17]

[Table 1 about here]

It is worth noting that the interest rate response to inflation in the second and third columns does not guarantee a unique RE equilibrium because both $\psi_\pi = 0.77$ and $\psi_\pi = 0.89$ violates the Taylor principle. Hence, the parameters in these columns generate indeterminacy while the parameters in the last column do not.

[15] The number of observations has been chosen to match the quarterly data points available from 1966Q1 to 1979Q3 and from 1979Q4 to 2002Q4, respectively. In each simulated sample, 100 extra-observations are produced to provide us with a stochastic vector of initial conditions, and then are discarded.

[16] Similar results are obtained employing the mean.

[17] Notice that we impose the values obtained by Lubik and Schorfheide (2004) for the matrix $\widetilde{M}$. The same exercise performed with the $\widetilde{M}$ matrix computed as suggested by the least-square criterion presented in the appendix does not lead to any qualitative change.

4.2 The DSGE Model-consistent IRFs and the SVARs

This section compares two *different* sets of IRFs following a monetary policy shock of the same magnitude. The first set represents the DSGE model-consistent reactions, which are the impulse responses computed by solving the system (2) to (5). The second group of impulse responses are generated using Steps 1 to 4 of the algorithm above, and therefore correspond to the estimates of the structural SVARs on the artificial series of the output gap, inflation and nominal interest rate generated by the model under indeterminacy and under determinacy. The magnitude of the policy shock is, in both sets of IRFs, a one-standard-deviation of the structural shock estimated using the SVAR on the artificial data.

[**Figure 7 about here**]

The results under indeterminacy using the parameterization labelled 'Prior 1' in Table 1 are shown in the first row of Figure 7. Solid lines represent the model-consistent IRFs while dotted lines stand for the IRFs of the SVAR on artificial data. Several interesting results arise. First, the model consistent inflation reaction to the policy shock is negative on impact. After a few quarters, this reaction becomes positive and reaches a peak at 24 basis point before converging smoothly to the initial level. Not surprisingly, we obtain an inflation response which is very similar to the response estimated by Lubik and Schorfheide (2004).

The DSGE model is not able of producing a price puzzle, though it is able to account under indeterminacy for the inertia of inflation following a monetary policy shock. This suggests that the results in Estrella and Fuhrer (2002), who find that purely forward-looking models are not capable of reproducing the persistent and hump-shaped responses to a monetary policy shock observed in empirical VARs, may be attributed, at least for inflation, to limiting implicitly the solution of the model to the determinacy region.

The inflation reaction from the recursive VAR on artificial data begins at zero by construction, depicts a quite steep curve that reaches its peak at about 50 basis points after a few quarters and then starts to converge towards the steady state. After 15 quarters only, the behavior of the two responses is virtually indistinguishable. The VAR evidence is therefore qualitatively in line with the predictions of the model-consistent IRFs but it shows a sizable, though gradually declining, upward bias.

The reaction of the federal funds rate to a policy shock is reported in the third column. The estimated interest rate response from the SVAR on simulated data is shifted outward relative to the response implied by the DSGE model. This is likely to reflect the fact that, because of the inflation IRF bias, the systematic component of monetary policy responds to a higher level of inflation in the recursive VAR on simulated data. In contrast, the response of the output gap is fairly in line with the structural model with the only exception, by construction, of the zero contemporaneous restriction imposed in the SVAR. Indeterminacy in this model thus mostly influences the persistence of inflation and the interest rate, whereas it does not seem to influence much the persistence of the output gap response (see also Lubik and Schorfheide, 2003).

The solution of the model under determinacy returns two sets of IRFs that are virtually indistinguishable. The New Keynesian model suggests that following a policy rate shock the price level initially decreases 70 basis points. After a few periods below zero, however, inflation returns to its steady state value reflecting the lack of endogenous inflation persistence in the model. The response of output gap and inflation in the estimated VAR are different, by construction, in the contemporaneous period only while the response of the policy rate effectively tracks the model-consistent IRF at all periods.

[**Figure 8 about here**]

Figure 8 presents the results using the parameterization labelled 'Prior 2' in Table 1. In general, the responses of all variables to a monetary policy shock bear out *qualitatively* the responses in Figure 7. The inflation reaction under indeterminacy displayed in the middle panel of the first row shows however an important *quantitative* difference. The gap between the model-consistent prediction and the response from the recursive VAR is far larger than the gap obtained using the previous parameterization. In particular, the maximum inflation differential is about 40 basis points as opposed to the 16 basis points under Prior 1. Furthermore, the gap begins to shrink after a few quarters but it does not disappear, even after 20 periods. A similar result emerges about the policy rate response shown in the last column. The distance between the two lines is clearly larger under Prior 2. In contrast, the output gap reacts similarly under the two parameterizations.

When monetary policy is active and therefore the solution of the LRE model is unique, the responses in the second row of Figure 8 are virtually identical to the responses in the second row of Figure 7. This suggests that two alternative parameterizations, as those used in this paper, do not return any notable distinction as long as the expectations of inflation and output gap are well anchored by an active monetary policy. In contrast, different values of the structural parameters may play a quantitatively important role when monetary policy does not raise the nominal interest rate sufficiently in response to a rise in inflation and hence induces indeterminacy.

[**Figure 9 about here**]

The first and second row of Figure 9 are obtained using the sign restrictions described above and the data simulated by the sticky price model under indeterminacy and determinacy. In line with the results from the recursive identification, the price puzzle emerges in Panel A only when monetary policy is passive. Furthermore, the inflation response in the first row reveals that relaxing the contemporaneous zero restrictions actually amplifies the 'price puzzle' with respect to Figure 8. This evidence corroborates the view that the bias of the structural VARs, relative to the model, is not due to the identification strategy. Under determinacy, which corresponds to a case where the VAR is correctly specified and thus the policy shock is correctly identified, the IRFs of the VAR based on sign restrictions track quite closely those of the DSGE model and the price puzzle does not materialize.

The result that using structural VARs when the data are drawn from the indeterminacy region introduces a bias *on impact* in the inflation response to a policy shock is, to the best of our knowledge, new in the literature. This finding suggests that under indeterminacy a structural VAR in output, inflation and interest rate is insufficient to capture the dynamics of the underlying economy. In particular, the estimated positive reaction on impact appears spurious and possibly due to a specification error of the kind Bernanke (2004) conjectured in the passage of his speech reported in the Introduction. We postpone the discussion of the *indeterminacy induced omitted variable bias* to Section 6.

4.3 Replicating the Price Puzzle

The DSGE model is never capable of generating a price puzzle. In contrast, the recursive VAR on the simulated series is, under both parameterizations, capable of generating a sizable positive response of inflation on impact.

[Figure 10 about here]

The middle panel of Figure 10 brings together the inflation responses to a monetary policy shock estimated on actual and simulated data. All estimates are based on a recursive tri-variate VAR in output gap, inflation and interest rate. Dotted lines represent 95% confidence interval of the VAR estimated on actual data in Figure 3 and they are reported here for expositional convenience. Stars (circles) represent the prediction of the SVAR on data simulated under Prior 1 (Prior 2). The two impulse responses computed on the simulated data effectively track the response estimated on actual data and furthermore they fall within the 95% bands at all periods. Moreover, the IRFs obtained using artificial data reproduce the peak in the third quarter observed in the estimates on actual data. The simulations deliver a more persistent path for the inflation response, albeit the difference is not implausible, especially taking sampling uncertainty into account.

A similar picture emerges from the policy rate reactions in the right panel. The SVARs using data generated from the DSGE model (2)-(5) produce responses that for magnitude and persistence are consistent with the results on actual data. The left panel shows however that the model is less successful in reproducing the persistence of the output response. Next section explores whether habit formation can explain this difference.[18]

4.4 Habit Formation

This section performs an important robustness check by introducing habit formation in the specification of the aggregate demand. This modification serves two purposes. The first purpose is to explore whether the results in the previous section may be overturned when an additional source of persistence is added to the model. The second goal is to investigate whether a richer specification can improve upon the model (2)-(5) in terms of the persistence of the output response to a policy shock.

Several recent contributions suggest that the aggregate demand relation may be better described as a convex combination of future realizations and past observations of the output gap. Söderlind, Söderström, and Vredin (2005) find that to fit the US facts, the New-Keynesian model needs a large forward-looking component in the determination of output. In contrast, the results in Estrella and Fuhrer (2002) and Rudebusch and Fuhrer (2004) suggest the backward-looking term is dominant. Further evidence is provided in Lubik and Schorfheide (2004) and Ireland (2005) who estimate a New Keynesian model with habit formation and

[18] A comparison of the second row of Figure 7 and 8 with the second row of Figure 3 reveals that over the first three quarters the baseline model solved under determinacy is less successful in replicating the empirical IRF of output gap, inflation and interest rate estimated over the post-1979 sample. Interestingly, we notice that the SVAR on data simulated under determinacy produces IRFs that always fall in the empirical 95% confidence intervals *only* when the data generating process is characterized by persistent shocks to the IS equation. This observation calls for a deeper investigation of the relative contribution of endogenous and exogenous persistence to the aggregate fluctuations in the post-1979 US economy. We leave this topic for future research.

price indexation and find a significant role for the former but none for the latter. In order to capture the suggestions from these contributions, we modify the IS curve as follows:

$$x_t = \omega_x E_t x_{t+1} + (1-\omega_x)x_{t-1} - \tau(R_t - E_t\pi_{t+1}) + g_t \tag{6}$$

and repeat the algorithm in Section 5 using the parameters in Table 2 and the model (3)-(5),(6).

[Table 2 about here]

The parameter ω_x is set to 0.50, which broadly falls in the range of estimates reported in the contributions quoted above. The results are presented in Figure 11.

[Figure 11 about here]

The output gap response now shows a higher persistence relative to the IRF in Figure 11. In particular, it returns to its equilibrium value after 10 quarters, as opposed to 3 quarters in the purely forward-looking specification. Habit formation does not seem to improve significantly the statistical fit of the impulse response on output from the simulated VAR, and most importantly does not overturn the results on the inflation and interest rate responses. Furthermore, the latter IRFs easily fall within the empirical 95% confidence bands for most quarters.

5 Interpreting the Sub-Sample Stylized Fact

This section explores the source of the bias in the SVARs and assesses the extent to which misspecification can account for the price puzzle observed during the passive monetary policy regimes. Given that our simulations produce very similar results setting sunspot fluctuations to zero at all times, the hypothesis that this type of shock be responsible for the price puzzle is discarded from the set of candidate explanations.

5.1 The Role of the Omitted Variable in the SVAR

In the simpler case where the central bank does not smooth the nominal interest rate ($\rho_R = 0$), the three equation New-Keynesian model can be solved analytically. Under determinacy the dynamics of the economy only depend on fundamentals and it is possible to re-write the output gap, inflation and interest rate equations as a function of the structural shocks *only*. Under indeterminacy, in contrast, the transmission of structural shocks is altered and the system is augmented with a latent variable which is *not present* in the unique rational expectations equilibrium. In particular, Lubik and Schorfheide (2004) show that when monetary policy is passive the evolution of the endogenous variables can be described as follows:

$$\begin{bmatrix} x_t \\ \pi_t \\ R_t \end{bmatrix} = \underset{3x4}{\Phi}^{IND} \begin{bmatrix} \varepsilon_t \\ \zeta_t \end{bmatrix} + \underset{3x1}{\Upsilon} w_{1,t-1} \tag{7}$$

where $w_{1,t-1}$ is a latent variable that follows the AR(1) process:

$$w_{1,t} = \lambda_1 w_{1,t-1} + q_t$$

The parameter λ_1 is the stable eigenvalue of Γ_1^* of the system (2)-(5), the innovation q_t is a combination of structural and sunspot shocks while Φ^{IND} and Υ are matrices of convolutions of the structural parameters of the model.

This simple example discloses two important insights. First, a tri-variate VAR in output gap, inflation and nominal interest rate is misspecified when the data are generated according to a New-Keynesian model and the monetary policy rule violates the Taylor Principle. Second, the source of mis-specification is the omission of a latent variable. While it is not possible to derive an explicit mapping between the series of $w_{1,t-1}$ and each variable in the system, we notice that under indeterminacy expected inflation is highly persistent and appears to capture a sizable part of the additional dynamics generated by the passive monetary policy.[19] This observation suggests that a structural VAR that properly accounts for expected inflation could reduce, at least in principle, the price puzzle bias.

[Figure 12 about here]

Figure 12 plots the response of the output gap, inflation and interest rate from the *augmented* four-variate recursive VAR where expected inflation is ordered first in the vector of series $\tilde{Y}_t = [E_t\pi_{t+1}, y_t, \pi_t, R_t]'$ generated from the baseline New-Keynesian model. The IRFs are shown for the indeterminacy solution as the latent variable is present in this case only. The results, albeit robust to both parameterizations, are reported using Prior 2 where the bias is quantitatively larger and therefore the scope for an omitted variable explanation is more challenging. For the sake of comparison, the corresponding impulse response functions from the tri-variate VAR in Figure 8 are reproduced as dotted lines. The IRFs using the augmented four-variate VAR are displayed as pentagrams. The pentagrams track the IRFs of the structural model (solid lines) remarkably well and the *price puzzle bias* appears simply to vanish. Furthermore, a comparison with the dotted lines from the tri-variate VAR reveals that controlling for expected inflation accounts for virtually all the omitted latent variable bias that is behind the price puzzle detected by the structural VARs.[20]

This finding qualifies and extends Sims' conjecture about the mis-identification of the policy shock in a mis-specified VAR. In particular, expected inflation matters not only for their ability to predict future inflation but also, more importantly, for their ability to mimic the latent variable that arises under indeterminacy only. Our results therefore also provide a rationale for the finding in Bernanke, Boivin and Eliasz (2005) that the inclusion of a latent factor (ordered first) in an otherwise standard three-variate recursive VAR can sensibly reduce the price puzzle over the full postwar sample. A similar result can be found in Kozicki and Tinsley (2003) using a time-varying model.

[19] The solution of a linear rational expectations model requires that all unstable roots of the system be suppressed. The New-Keynesian model used in this paper is characterized by two roots. When monetary policy conforms to the Taylor Principle the two roots are unstable, i.e. the system is determinate, and the solution generates no 'extra' persistence relative to the specification of the model. In contrast, indeterminacy is characterized by only one *unstable* root, thereby implying that the solution now generates additional dynamics through the *stable* root.

[20] The residual discrepancy between the IRFs of the four-variate SVAR and the IRFs of the DSGE model in Figure 13, while negligible relative to the case without inflation expectations (dotted line), is likely due to other factors we do not control for. These factors include the contemporaneous zero restrictions and the omission of the output gap expectations in the SVAR. The result in Figure 13 however suggests that these alternative explanations are likely to play only a minor role.

5.2 Assessing the Impact of the Federal Reserve's Inflation Forecasts

The previous results pose an important empirical question: 'what macroeconomic series can approximate *in practice* the latent variable induced by a passive monetary policy?'. The New-Keynesian model used in this paper suggests that the latent variable is indeed a *product* of the passive monetary policy regime. Equation (7) reveals that whenever the latent variable is omitted from the VAR, the identification of the structural shocks is invalid in that, for instance, the innovations to the interest rate equation are not anymore truly exogenous; rather they are a convolution of the monetary policy shock and a specification error.

And, by neglecting this misspecification, the incorrectly identified policy shock has indeed, in Bernanke's words, the *flavor* of an adverse supply shock in that, as shown in Figures 7 and 8, it moves inflation and output in opposite directions. Under determinacy, in contrast, the monetary policy shock is correctly identified and, in line with the theory, it causes inflation and output to move in the same direction. Furthermore, the inclusion of expected inflation in the model-based SVAR in Figure 12 appears to account for most of the omitted variable bias in the responses of inflation and interest rate.

This evidence suggests a simple empirical test on the ability of expected inflation to approximate the theoretical latent variable. This test consists in using the Federal Reserve's information on future inflation in the SVAR on actual data. This information is contained in the 'Greenbook', an extensive and detailed analysis of the US and world economy prepared by the Fed staff before each meeting of the Federal Open Market Committee. The forecasts from the Greenbook are published with a five years lag. Were the Federal Reserve's expectations on future inflation quantitatively important, we should observe a significant reduction of the price puzzle on actual data.

To explore this hypothesis, we then run two four-variate structural VARs on actual data using the two identification strategies based on the contemporaneous zero restrictions and the sign restrictions employed in the empirical section. For the recursive (lower-triangular) identification, the vector of endogenous variables is ordered as follows: $\tilde{Y}_t = \left[E_t \pi^G_{t+1}, y_t, \pi_t, R_t\right]'$, where $E_t \pi^G_{t+1}$ represents the one-quarter ahead inflation forecasts from the Greenbook.[21] We focus on this time series because one-quarter ahead is the relevant horizon to forecast inflation in the New-Keynesian model used in this paper.[22]

It is worth emphasizing that we are interested in isolating the effect of a monetary policy shock, and thus using the inflation predictions from the Board of Governors is likely to improve the identification of the systematic component of monetary policy. The Greenbook forecasts presumably include information from a wide range of sources including the policy makers' judgement. To the extent that the forecasts produced by commercial agencies are less broad

[21] In estimating the SVAR we are implicitely assuming that the identified policy shock is contemporaneously uncorrelated with the Greenbook forecasts. On the basis of an extensive VAR literature however, we also impose that inflation and real activity respond to changes in policy with some lags only. Moreover, the results from our SVAR are robust to using the current-quarter and the two-quarter ahead Greenbook forecasts. Altogether, this suggest that our estimates should not suffer an endogeneity problem. Lastly, we obtain very similar results imposing the additional restriction that the interest rate responds contemporaneously to either the Greenbook forecasts or to current inflation.

[22] Sample-availability is another reason for focusing on the one-quarter ahead inflation forecasts. In fact, this series begins in 1968Q3, and it is among the longest available predictions. Our results are robust to using both the two-quarter ahead inflation forecasts, which begin in 1968Q4, and the current-quarter forecasts, which begin in 1967Q4. By contrast, the series of the one-year ahead inflation expectations is available since 1974Q2, which limits considerably the case for a reliable sub-sample investigation.

in scope and sources, using alternative forecasts could lead us to mis-measuring the monetary policy shock in the structural VAR.[23]

[Figure 13 about here]

Figure 13 plots the results over the sub-sample 1968Q3-1979Q3. The left panel refers to the estimates based on zero restrictions while the right panel corresponds to the sign restrictions identification strategy. The solid lines with squares represent the estimated inflation response from the SVARs *augmented* with the Greenbook expected inflation. The dash-dotted lines represent the $5th$ and $95th$ percentiles of the relative distributions. We are interested in comparing the performance of the augmented SVAR relative to the solid line, which represents the IRF from the tri-variate SVAR on actual data using output gap, inflation and interest rate *only*.

Two results stand out. First, as suggested by the indeterminacy induced omitted variable bias hypothesis, the 'incorrectly identified' policy shock from the tri-variate SVAR produces an inflation response (solid line) that over the first nine quarters is significantly above the IRF from the 'correctly identified' four-variate augmented SVARs (solid line with squares). Second, while the zero is inside the lower and upper percentiles over the very first periods, the identification based on sign restrictions, which does not impose any zero on impact, delivers now a *negative* point estimate for the contemporaneous response of inflation as opposed to the *positive* 1.2 response estimated under the tri-variate SVAR in Figure 5. This suggests that expected inflation are indeed empirically important in this sub-sample, and that such result is robust to two different identification strategies.

Interestingly, adding expected inflation to the SVAR estimated over the sub-sample 1979Q4-1999Q4 produces IRFs, not reported and available upon request, that are virtually identical to the IRFs from the estimated tri-variate SVAR in output gap, inflation and federal funds rate only. We thus conclude that *only* when monetary policy is passive and therefore expectations are not well-anchored, inflation expectations are very informative about the dynamics of the economy. In particular, expected inflation are helpful to correctly identify a monetary policy shock.

6 Conclusions

The contribution of this paper is twofold. At the empirical level, it shows that the price puzzle is a sub-sample regularity of the periods that, in the empirical literature on monetary policy rules, are typically associated with a weak central bank response to inflation. These are the years prior to the appointment of Paul Volcker as Fed Chairman in August 1979 for the US and the period prior to the introduction of the inflation targeting regime in October 1992 for the UK. The finding is robust to augmenting the VAR with unit labor costs, commodity price index and M2. The VAR evidence presented in this paper is new because it is obtained using two different identification strategies based on zero restrictions and sign restrictions, and because it is shown to hold independently from the measure of real activity and the measure of inflation used.

[23] Romer and Romer (2000) argue convincingly that the Greenbook forecasts do have a superior historical performance in forecasting inflation relative to the private sector forecasts.

At the theoretical level, this paper employs a popular DSGE sticky price model of the US economy to investigate whether indeterminacy, as induced by a passive monetary policy, can account quantitatively for the price puzzle observed during the pre-1979 period. Although previous research has proposed a number of helpful strategies to control for this price anomaly in the data, this paper is, to the best of our knowledge, the first theoretically and empirically consistent attempt to rationalize the price puzzle using a structural model.

On the basis of montecarlo simulations, we argue that the price puzzle in the SVARs is spurious because neither under determinacy nor under indeterminacy the theoretical model produces on impact a positive inflation response to a monetary policy shock. Furthermore, we show that the price puzzle is due to the omission of a latent variable capturing the 'extra' dynamics that characterize the DSGE model under indeterminacy *only*. Expected inflation are found to approximate this omitted latent variable reasonably well, both in the theory and in the data. Our results thus formally support Bernanke (2004) conjecture that in specific historical periods changes in inflation expectations are essential for identifying truly structural shocks.

The DSGE New-Keynesian model used in this paper, while widely employed for monetary policy analysis, is highly stylized. Indeed, the link between the degree of activism in the policy rule and multiple equilibria may be far more complex than a simple three equation system could capture. An interesting avenue for future research would be to investigate the empirical relevance of equilibrium indeterminacy using larger models of the business cycle where monetary aggregates and the exchange rate are also fully specified. It may well be the case that the explanation proposed in this paper could also account for other long-standing puzzles in macroeconomics.

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Data appendix

The data for the US have been collected in March 2004 from the website of the Federal Reserve Bank of St. Louis. The data for the UK have been collected in November 2004 from the Bank of England. The inflation rate, π_t, is the quarter-to-quarter annualized growth rate of the price index. The output gap, x_t is computed as either the difference between Potential output and RGDP or as a filtered RGDP. The two filter used are the filter proposed by Hodrick and Prescott and a quadratic trend. Monthly series are transformed in quarterly series by taking end-of-quarter observations. Log levels of all variables (except the policy rates, the output gap measures, and the inflation rates) are used in the estimations.

US data

GDP Deflator: Gross Domestic Product: Implicit Price Deflator. Seasonally adjusted. Index 2000=100. Source: Bureau of Economic Analysis.

CPI: Consumer Price Index For All Urban Consumers: All Items. Seasonally adjusted. Index 1996=100. Source: Bureau of Labor Statistics.

PPI: Production Price Index: Industrial Commodities. Index 2000=100. Seasonally adjusted. Source: Bureau of Labor Statistics.

PPI: Production Price Index: Crude Fuel. Index 1982=100. Seasonally adjusted. Source: Bureau of Labor Statistics.

PPI: Production Price Index: Crude Materials. Index 1982=1000. Seasonally adjusted. Source: Bureau of Labor Statistics.

OILPRICE: Spot Oil Price: West Texas Intermediate. Seasonally adjusted. Source: Wall Street Journal / Haver Analytics.

Greenbook Expected Inflation: Greenbook forecasts (1 and 2 quarters ahead) for the GNP/GDP price level, quarter-by-quarter growth rate, annualized. Source: Federal Reserve Board of Governors.

ULC: Nonfarm Business sector unit labor costs. Seasonally adjusted. Index 1992=100. Source: Bureau of Labor Statistics.

Potential Output: Congressional Budget Office estimate. Chained 2000 \$. Source: CBO.

RGDP: Real Gross Domestic Products, 3 Decimal. Chained 2000 \$. Source: Bureau of Economic Analysis.

FFR: Effective Federal Funds Rate. Source: Board of Governors of the Federal Reserve System H.15

M2: M2 Money Stock. Source: Board of Governors of the Federal Reserve System H.3

UK data

GDP Deflator: Gross Domestic Product: Implicit Price Deflator. Seasonally adjusted. Index 2001=100. Source: Office for National Statistics.

CPI: Consumer Price Index: All Items. Seasonally adjusted. Index 1996=100. Source: Office for National Statistics.

ULC: Business sector unit labor costs. Computed as whole economy unit labor costs excluding government sector and including government procurements from the private sector. Seasonally adjusted. Index 2001=100. Source: Bank of England calculations on ONS series.

RGDP: Real Gross Domestic Products. Chained 2001 £. Source: Office for National Statistics.

Policy rate: Bank's Repo Rate. Source: Bank of England.

Appendix: Solution of the Canonical LRE Model

The linear rational expectations model described by equations (2) to (5) can be cast in the following canonical form:

$$\Gamma_0(\theta)s_t = \Gamma_1(\theta)s_{t-1} + \Psi(\theta)\varepsilon_t + \Pi(\theta)\eta_t \tag{8}$$

where the vector $s_t = [x_t, \pi_t, R_t, E_t x_{t+1}, E_t \pi_{t+1}]'$ collects the n variables of the system, $\varepsilon_t = [\varepsilon_{R,t}, g_t, u_t]'$ is the vector of l fundamental shocks, $\eta_t = [(x_t - E_{t-1}x_t), (\pi_t - E_{t-1}\pi_t)]'$ collects the k rational expectations forecast errors, and $\theta = [\psi_\pi, \psi_x, \rho_R, \beta, , \kappa, \tau, \sigma_R, \sigma_g, \sigma_u]$ is the vector of the parameters of the model outlined in the previous section.

In order to transform the canonical form and solve the model, we follow Sims (2001) and exploit the generalized complex Schur decomposition (QZ) of the matrices Γ_0 and Γ_1. This corresponds to computing the matrices Q, Z, Λ and Δ such that $QQ' = ZZ' = I_n$, Λ and Δ are upper triangular, $\Gamma_0 = Q'\Lambda Z$ and $\Gamma_1 = Q'\Delta Z$. Defining $w_t = Z's_t$ and pre-multiplying (8) by Q, we obtain:

$$\begin{bmatrix} \Lambda_{11} & \Lambda_{12} \\ 0 & \Lambda_{22} \end{bmatrix} \begin{bmatrix} w_{1,t} \\ w_{2,t} \end{bmatrix} = \begin{bmatrix} \Delta_{11} & \Delta_{12} \\ 0 & \Delta_{22} \end{bmatrix} \begin{bmatrix} w_{1,t-1} \\ w_{2,t-1} \end{bmatrix} + \begin{bmatrix} Q_{1.} \\ Q_{2.} \end{bmatrix} (\Psi\varepsilon_t + \Pi\eta_t) \tag{9}$$

where, without loss of generality, the vector of generalized eigenvalues λ, which is the vector of the ratios between the diagonal elements of Δ and Λ, has been partitioned such that the lower block collects all the explosive eigenvalues. The matrices Δ, Λ and Q have been partitioned accordingly, and therefore $Q_{j.}$ collects the blocks of rows that correspond to the stable ($j = 1$) and unstable ($j = 2$) eigenvalues respectively.

The explosive block of (9) can be rewritten as:[24]

$$w_{2,t} = \Lambda_{22}^{-1}\Delta_{22}w_{2,t-1} + \Lambda_{22}^{-1}Q_{2.}(\Psi\varepsilon_t + \Pi\eta_t) \tag{10}$$

Given the set of m equations (10), a non-explosive solution of the linear rational expectations model (8) for s_t requires $w_{2,t} = 0 \; \forall t \geq 0$. This can be obtained by setting $w_{2,0} = 0$ and choosing for every vector ε_t the endogenous forecast error η_t that satisfies the following condition

$$Q_{2.}(\Psi\varepsilon_t + \Pi\eta_t) = 0 \tag{11}$$

A general stable solution for the endogenous forecast error can be computed through a singular value decomposition of $\underbrace{Q_{2.}\Pi}_{mxk} = \underbrace{U}_{mxm}\underbrace{D}_{mxk}\underbrace{V'}_{kxk} = \underbrace{U_{.1}}_{mxr}\underbrace{D_{11}}_{rxr}\underbrace{V'_{.1}}_{rxk}$, where D_{11} is a diagonal matrix and D and U are orthonormal matrices. Using this decomposition, Lubik and Schorfheide (2003) show that in equilibrium the vector of endogenous forecast errors reads as follows:

$$\eta_t = (-V'_{.1}D_{11}^{-1}U_{.1}Q_{2.}\Psi + V_{.2}\widetilde{M})\varepsilon_t + V_{.2}\zeta_t \tag{12}$$

where $\widetilde{M}$ is the $(k-r)xl$ matrix governing the influence of the sunspot shock on the model dynamics.

[24] It is possible to have some zero-elements on the main diagonal of Λ_{22}. In this case, the latter matrix is not invertible. The 'solving-forward' solution proposed by Sims (2001) and extended by Lubik and Schorfheide (2003) overcomes this problem. A Technical Appendix with a more detailed discussion of the solution strategy is available from the authors upon request.

Assuming that Γ_0^{-1} exists, the solution (12) can be combined with (8) to yield the following law of motion for the state vector:

$$s_t = \Gamma_1^* s_{t-1} + \left[\Psi^* - \Pi^* V_{.1} D_{11}^{-1} U_{.1}' Q_{2.} \Psi + \Pi^* V_{.2} \widetilde{M}\right] \varepsilon_t + \Pi^* V_{.2} \zeta_t \tag{13}$$

where a generic $X^* = \Gamma_0^{-1} X$.

In general, we can be confronted with three cases. If the number of endogenous forecast errors k is equal to the number of nonzero singular values r, the system is determined and the stability condition (11) uniquely determines η_t. In such a case, $V_{.2} = 0$, then the last two addends of (13) drop out. This implies that the dynamics of s_t is purely a function of the structural parameters θ.

If the number of endogenous forecast errors k exceeds the number of nonzero singular values r, the system is indeterminate and sunspot fluctuations can arise. Lubik and Schorfheide (2003) show that this can influence the solution along two dimensions. First, sunspot fluctuations ζ_t can affect the equilibrium dynamics. Second, the transmission of fundamental shocks ε_t is no longer uniquely identified as the elements of $\widetilde{M}$ are not pinned down by the structure of the linear rational expectations model.

Alternatively, the number of endogenous forecast errors k can be smaller than the number of nonzero singular values r, and then the system has no solutions. These three conditions generalize the procedure in Blanchard and Kahn (1980) of counting the number of unstable roots and predetermined variables.[25]

In order to compute $\widetilde{M}$ and then the solutions of the model under indeterminacy, it is necessary to impose some additional restrictions on the endogenous forecast errors. Following Lubik and Schorfheide (2004), we choose $\widetilde{M}$ such that the impulse responses $\frac{\partial s_t}{\partial \varepsilon_t'}$ associated with the system (13) are continuous at the boundary between the determinacy and the indeterminacy region. This solution is labelled 'continuity'.[26]

Let Θ^I and Θ^D be the sets of all possible vectors of parameters $\theta's$ in the indeterminacy and determinacy region respectively. For every vector $\theta \in \Theta^I$ we identify a corresponding vector $\widetilde{\theta} \in \Theta^D$ that lies on the boundary of the two regions and choose $\widetilde{M}$ such that the response of s_t to ε_t conditional on θ mimics the response conditional on $\widetilde{\theta}$. This corresponds to requiring that the condition

$$\frac{\partial s_t}{\partial \varepsilon_t'}(\theta) = B_1(\theta) + B_2(\theta) = \Psi^* - \Pi^* V_{.1} D_{11}^{-1} U_{.1}' Q_{2.} \Psi + \Pi^* V_{.2} \widetilde{M} \tag{14}$$

be as close as possible to the condition

$$\frac{\partial s_t}{\partial \varepsilon_t'}(\widetilde{\theta}) = B_1(\widetilde{\theta}) \tag{15}$$

Applying a least-square criterion, we can then compute

$$\widetilde{M} = \left[B_2'(\theta) B_2(\theta)\right]^{-1} B_2'(\theta) \left[B_1(\widetilde{\theta}) - B_1(\theta)\right] \tag{16}$$

[25] The solution method proposed by Sims (2001) has the advantage that it does not require the separation of predetermined variables from 'jump' variables. Rather, it recognizes that in equilibrium models expectational residuals are attached to equations and that the structure of the coefficient matrices in the canonical form implicitly selects the linear combination of variables that needs to be predetermined for a solution to exist.

[26] Alternatively, the solution of the model under indeterminacy can be computed using the assumption that the effects of the sunspot shocks are orthogonal to the effects of the structural shocks. This identification yields results, not reported but available upon request, that are qualitatively similar to the findings for the continuity case.

and use (16) to calculate the solution of the model in (12) and (13).[27]

The new vector $\widetilde{\theta}$ is obtained from θ by replacing ψ_π with the condition that marks the boundary between the determinacy and indeterminacy region in the system (2) to (4). Woodford (2003) shows that this condition corresponds to the following interest rate reaction to inflation

$$\widetilde{\psi_\pi} = 1 - \frac{\psi_x}{\kappa}(1-\beta) \tag{17}$$

[27] Lubik and Schorfheide (2004) notice that this way of computing the vector $\widetilde{M}$ relates to the search for the minimal-state-variable solution advocated by McCallum (1983), i.e. the most meaningful solution from an economic perspective among the n-possible ones under indeterminacy.

Table 1. Model Parameters

Parameters	*Indeterminacy Prior 1*	*Indeterminacy Prior 2*	*Determinacy*
ψ_π	**0.77**	**0.89**	**2.19**
ψ_x	**0.17**	**0.15**	**0.30**
ρ_R	**0.60**	**0.53**	**0.84**
β	0.99	0.99	*0.99*
			Prior 1 / Prior 2
κ	0.77	0.75	*0.77 / 0.75*
τ^{-1}	1.45	2.08	*1.45 / 2.08*
σ_R	0.23	0.24	*0.23 / 0.24*
σ_g	0.27	0.21	*0.27 / 0.21*
σ_u	1.13	1.16	*1.13 / 1.16*
σ_ζ	0.20	0.23	-

Note: The parameterization of the data generating process is borrowed from Lubik and Schorfheide (2004), Table 3. Prior 1 (2) corresponds to the set of estimated values they obtain under their first (second) Prior. The indeterminacy solution uses the estimates of the *M* matrix in Lubik and Schorfheide (2004), i.e. $[M_{R\zeta}\ M_{g\zeta}\ M_{u\zeta}]$ = [-0.68 1.74 –0.69].

Table 2. Model Parameters – habit formation

Parameters	*Indeterminacy*
ψ_π	**0.99**
ψ_x	**0.10**
ρ_R	**0.59**
β	0.99
κ	0.66
τ^{-1}	1.58
ω_x	0.50
σ_R	0.26
σ_g	0.18
σ_u	1.29
σ_ζ	0.20

Note: The parameterization of the data generating process is borrowed from Lubik and Schorfheide (2004). The estimates of the M matrix are as in Lubik and Schorfheide (2004), i.e. [$M_{R\zeta}$ $M_{g\zeta}$ $M_{u\zeta}$] = [-0.68 1.74 –0.69].

Figure 1. IRFs to a Monetary Policy Shock: Full Sample 1966Q1-2002Q4

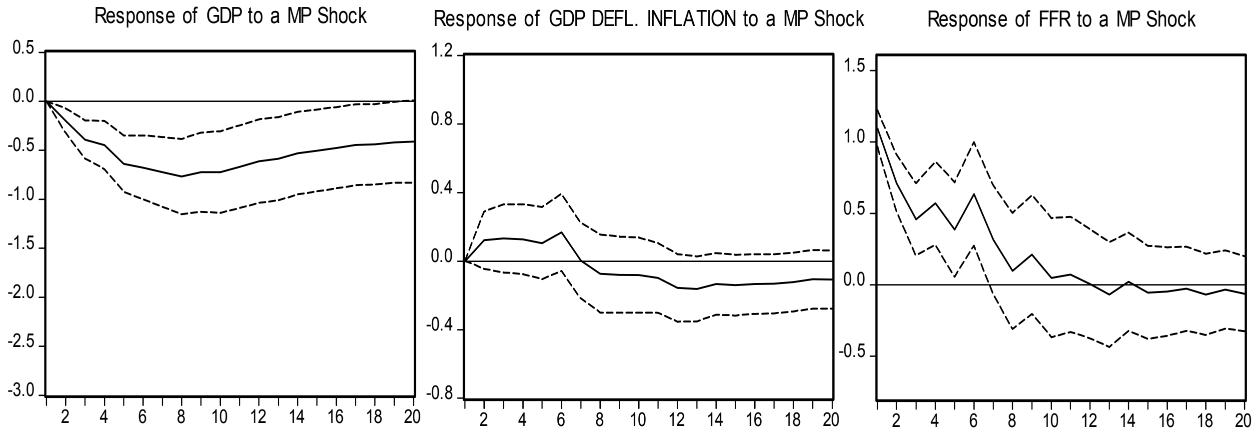
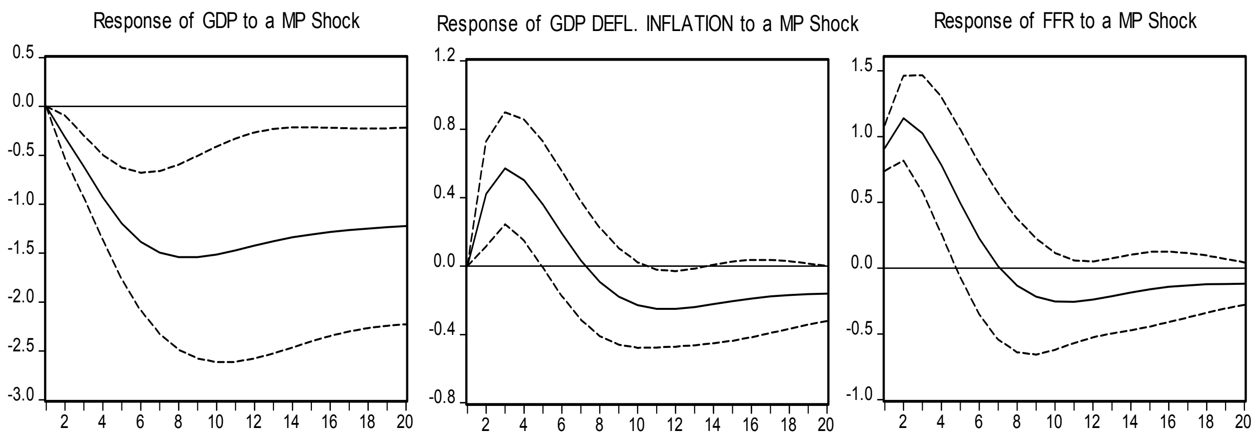
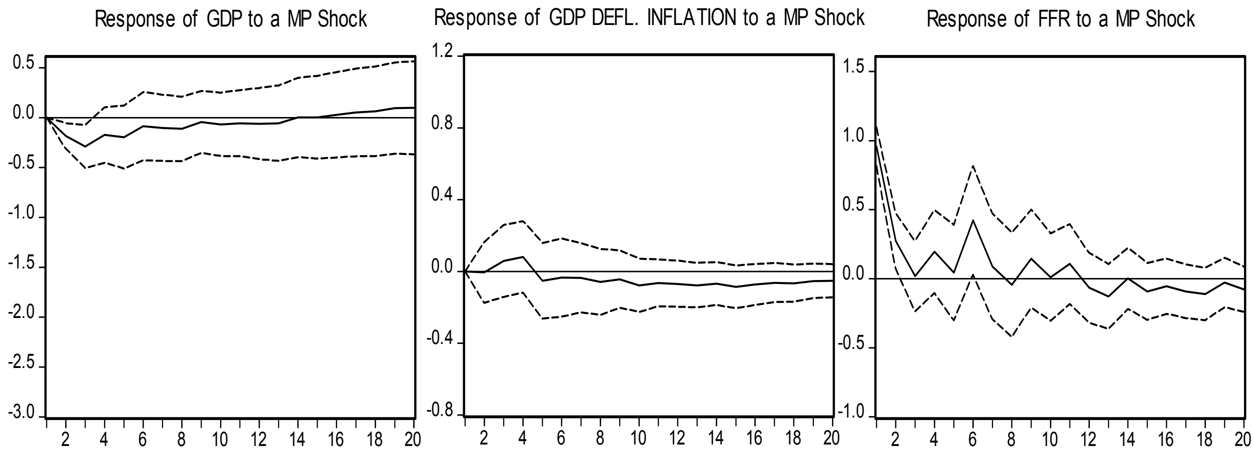


Figure 2. IRFs to a Monetary Policy Shock: Sub-sample Analysis

Sub-sample 1966Q1-1979Q3



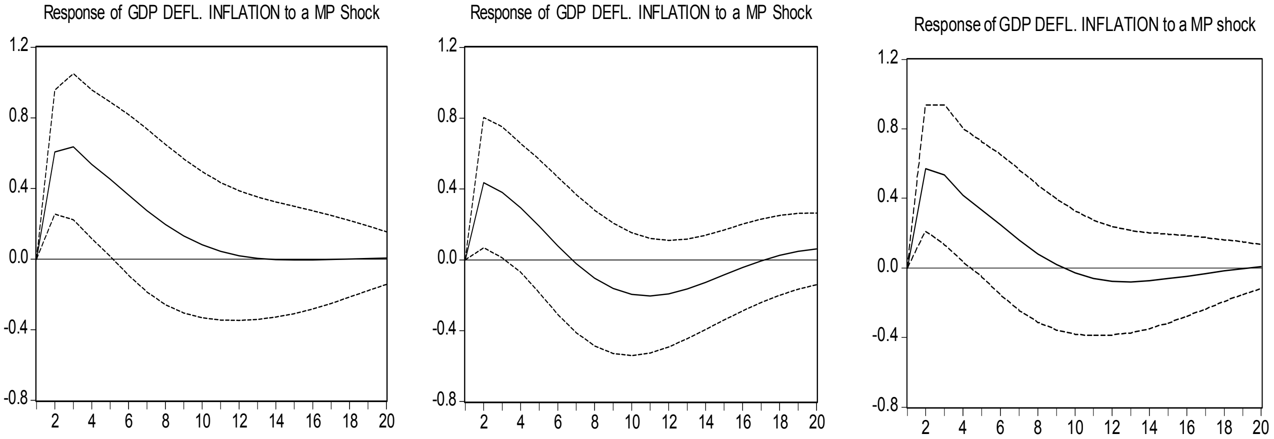
Sub-sample 1979Q4-2002Q4



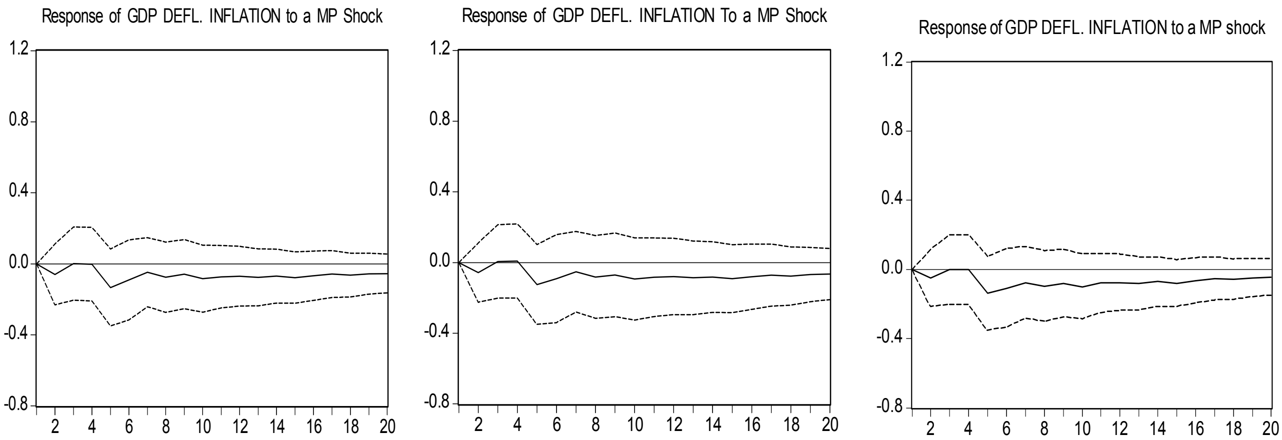
Note: Tri-variate VAR in Real GDP, GDP deflator inflation, and federal funds rate. Identification achieved through a Cholesky (lower triangular) factorization of the variance-covariance matrix. Solid lines are point estimates, dotted lines are 95% confidence bands (analytical). Number of lags selected according to standard statistical lag-length criteria.

Figure 3. GDP Deflator Inflation Reaction to a Monetary Policy Shock: Sub-sample Analysis with Different Business-cycle Measures

Sub-sample 1966Q1-1979Q3

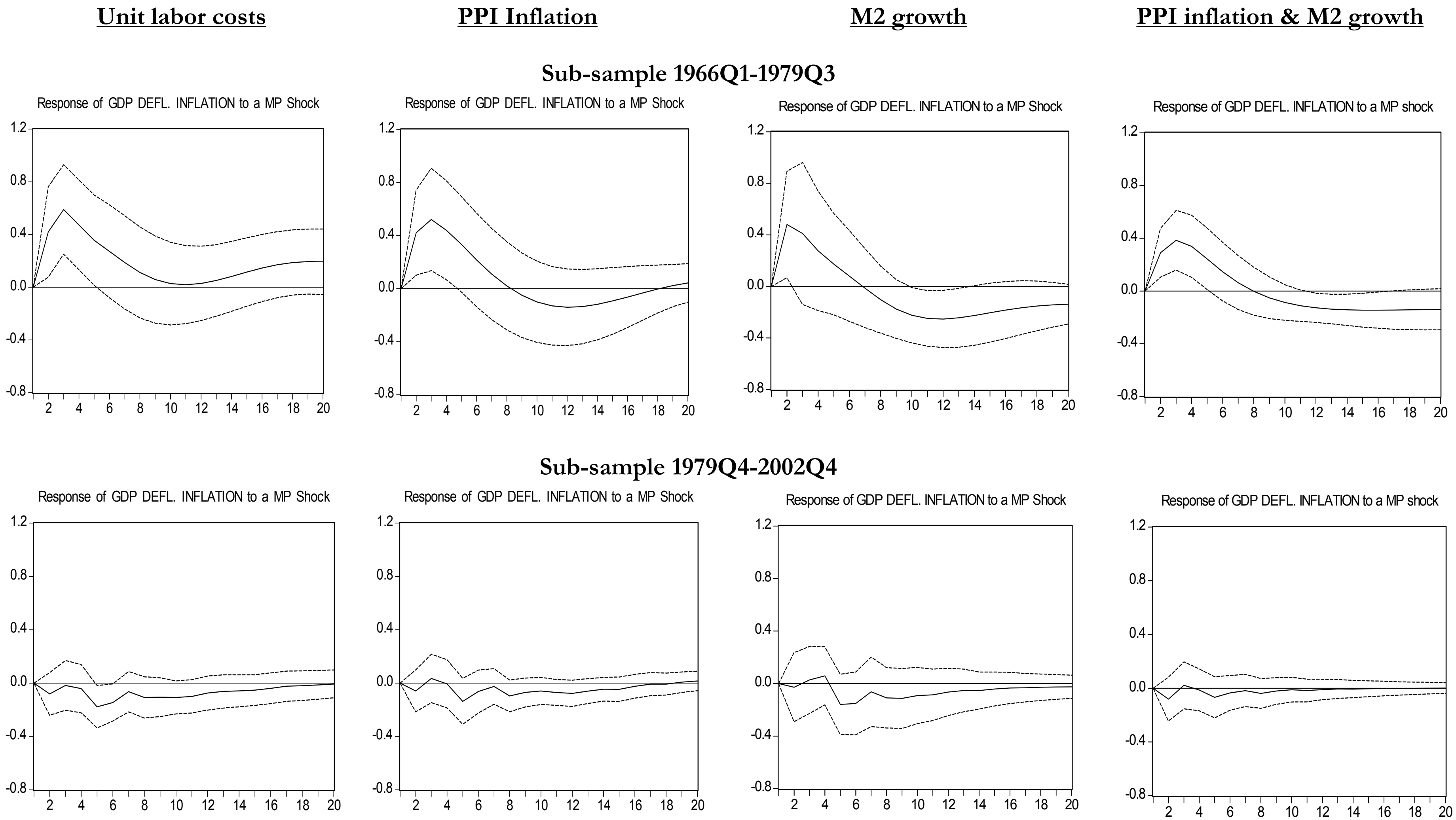


Sub-sample 1979Q4-2002Q4



Note: Tri-variate VAR in a business-cycle measure, GDP deflator inflation, and federal funds rate. The business cycle measures are, left to right: CBO-based output gap, HP-filtered output gap and quadratically detrended output gap. Identification achieved through a Cholesky (lower triangular) factorization of the variance-covariance matrix. Solid lines are point estimates, dotted lines are 95% confidence bands (analytical). Number of lags selected according to standard statistical lag-length criteria.

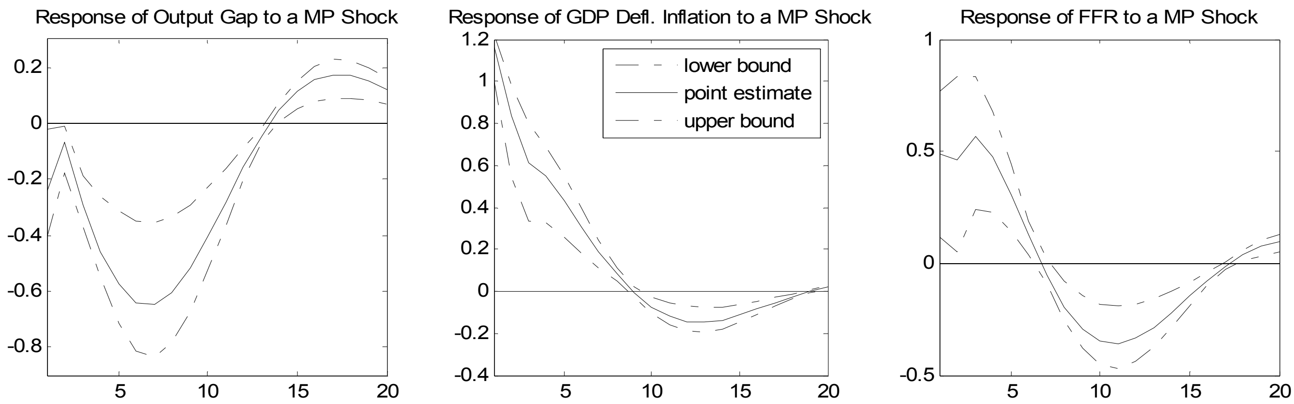
Figure 4. GDP Deflator Inflation Reaction to a Monetary Policy Shock: Robustness Analysis with an Expanded Vector of Endogenous Variables



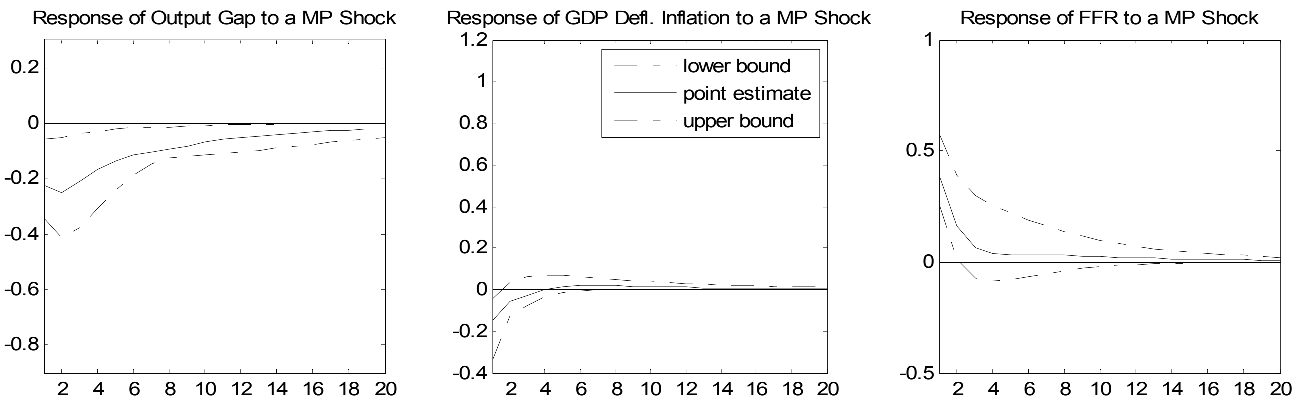
Note: Augmented VARs using 'additional variable/s', CBO-based output gap, GDP deflator inflation, and federal funds rate. The 'additional variable/s' are: real unit labor costs in the first column, PPI in the second column, M2 in the third column, and both M2 and PPI in the fourth column (all in logs, multiplied by 100). The Structural VARs in the first two and last columns use a recursive identification schemes whereas the third column employs the ordering [$\Delta M2_t$ x_t π_t i_t]' with the following zero restrictions on A=[α_{11} α_{12} 0 α_{14}; 0 α_{22} 0 0; 0 α_{32} α_{33} 0; α_{41} α_{42} α_{43} α_{44}]) in v=A^{-1}u. Solid lines are point estimates, dotted lines are 95% confidence bands (analytical). Number of lags selected according to standard statistical lag-length criteria.

Figure 5. IRFs to a Monetary Policy Shock: Sub-sample Analysis
- Identification Based on Sign Restrictions -

Sub-sample 1966Q1-1979Q3



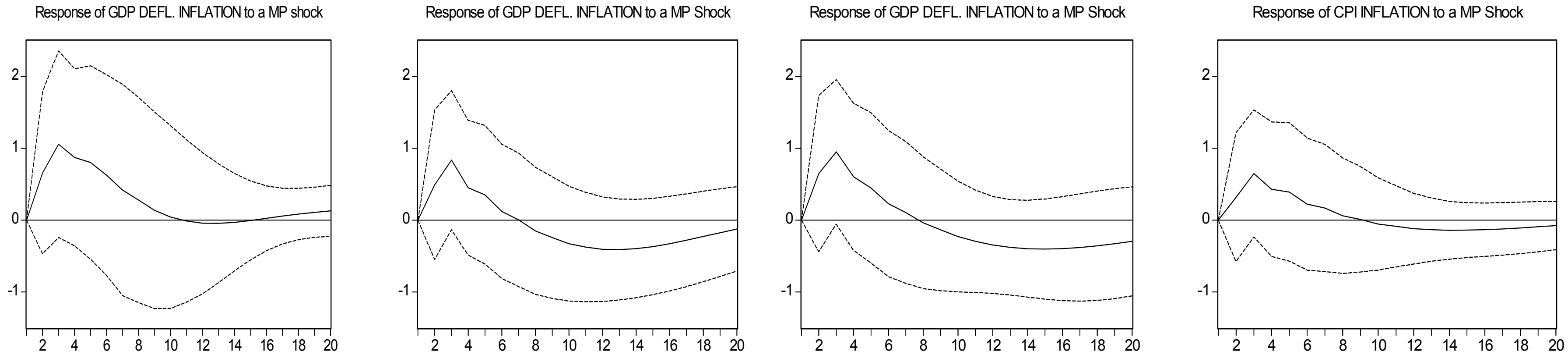
Sub-sample 1979Q4-2002Q4



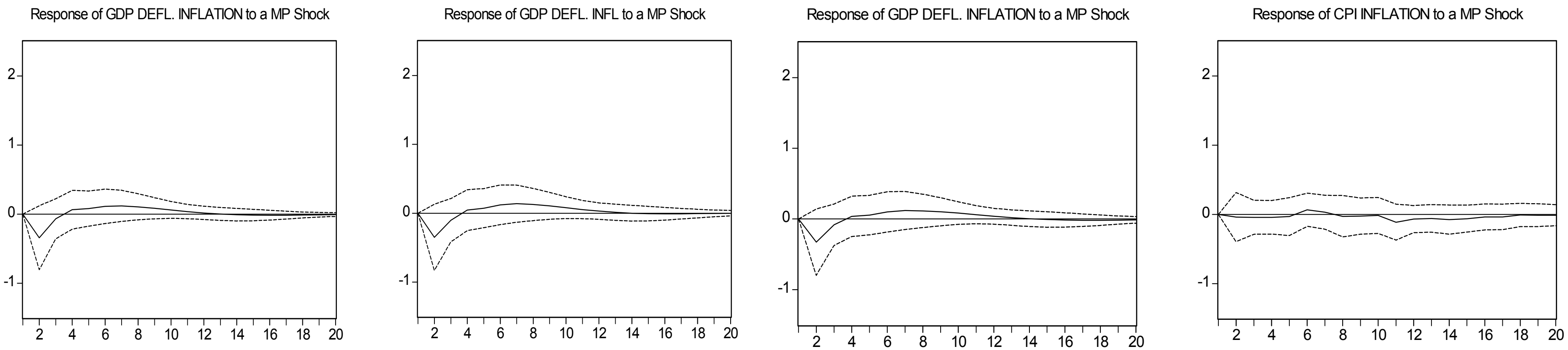
Note: Tri-variate VAR in CBO ouput gap, GDP deflator inflation, and federal funds rate. Identification based on the sign restrictions reported in Table 3. Solid lines are point estimates, dotted lines are 95% confidence bands. Number of lags selected according to standard statistical lag-length criteria.

Figure 6. Inflation Reaction to a Monetary Policy Shock – UK data: Sub-sample Analysis with Different Measures of Inflation and Real Activity

Sub-sample 1979Q2-1992Q4



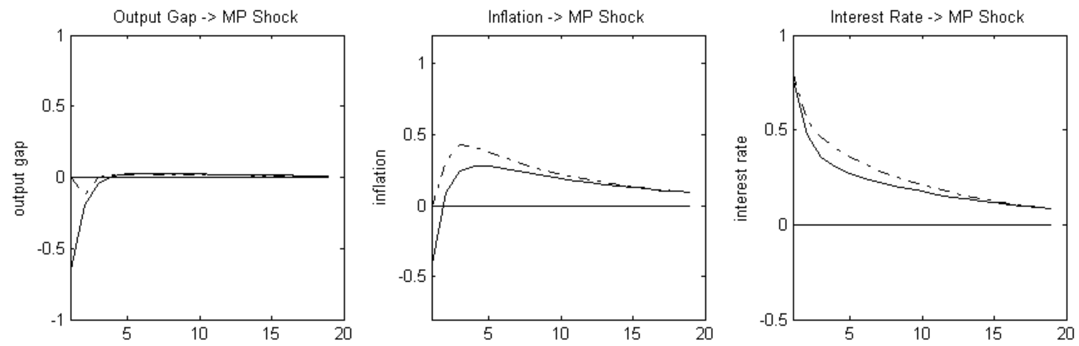
Sub-sample 1993Q1-2002Q4



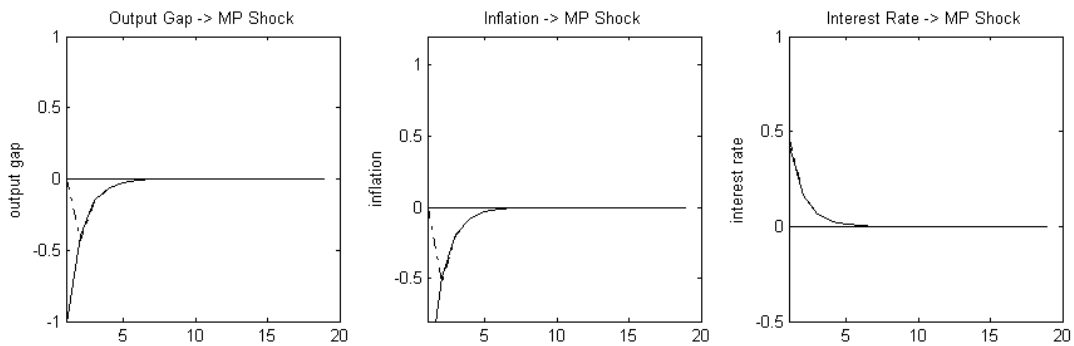
Note: Tri-variate VAR in a measure of real activity, a measure of inflation, and the nominal interest rate. The measures of real activity are, left to right: real GDP, HP-filtered output, quadratically detrended output and HP-filtered output (all in logs, multiplied by 100). The measure of inflation is the GDP deflator for all columns but the last one, which uses the CPI. Identification achieved through a Cholesky (lower triangular) factorization of the variance-covariance matrix. Solid lines are point estimates, dotted lines are 95% confidence bands (analytical). Number of lags selected according to standard statistical lag-length criteria.

Figure 7. Impulse Response Functions to a Monetary Policy Shock: Structural Model vs. Structural VAR on simulated data - PRIOR 1

Panel A: Indeterminacy



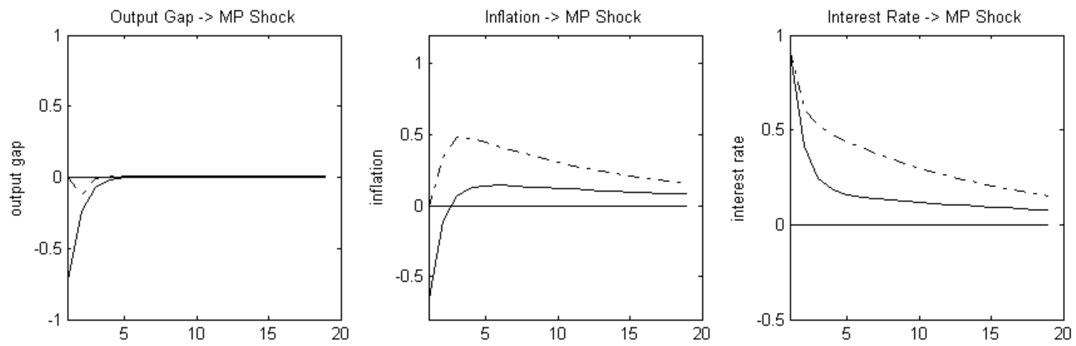
Panel B: Determinacy



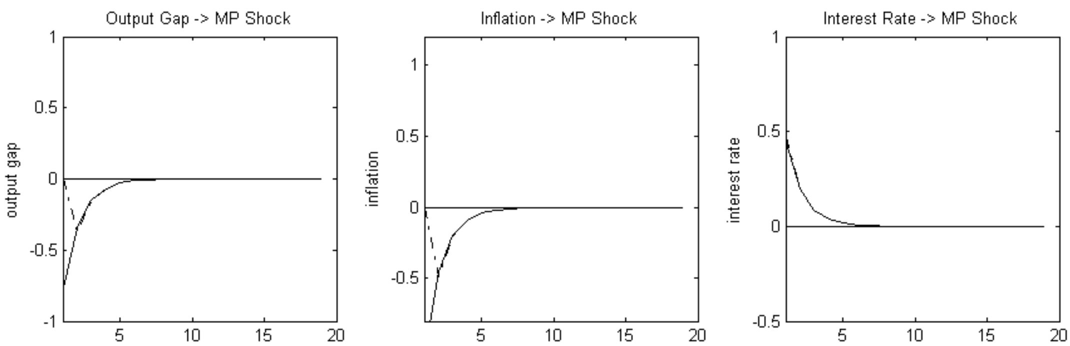
Note: Solid lines represent the *Structural model*. Dotted lines represent the *Structural VAR on simulated data*. The data generating process is the New-Keynesian model in the main text parameterized according to Prior 1 in Table 1. The point estimates of the Structural VAR on simulated data are based upon 10,000 repetitions. In each simulated sample, 100 extra observations are produced, and then discarded, to get a vector of stochastic initial conditions. Identification achieved through a Cholesky (lower triangular) factorization of the variance-covariance matrix using the following ordering: output gap, inflation and nominal interest rate. Number of lags selected according to standard statistical lag length criteria.

Figure 8. Impulse Response Functions to a Monetary Policy Shock: Structural Model vs. Structural VAR on simulated data - PRIOR 2

Panel A: Indeterminacy



Panel B: Determinacy

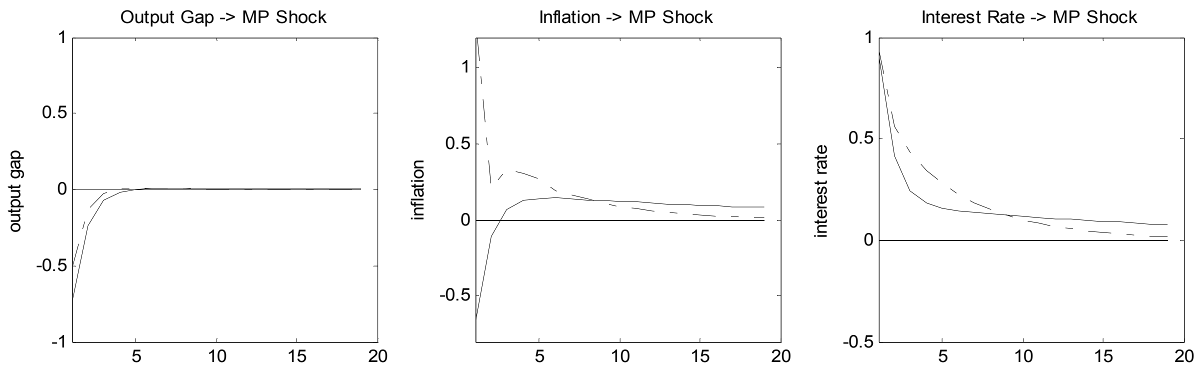


Note: Solid lines represent the *Structural model*. Dotted lines represent the *Structural VAR on simulated data*. The data generating process is the New-Keynesian model in the main text parameterized according to Prior 2 in Table 1. The point estimates of the Structural VAR on simulated data are based upon 10,000 repetitions. In each simulated sample, 100 extra observations are produced, and then discarded, to get a vector of stochastic initial conditions. Identification achieved through a Cholesky (lower triangular) factorization of the variance-covariance matrix using the following ordering: output gap, inflation and nominal interest rate. Number of lags selected according to standard statistical lag length criteria.

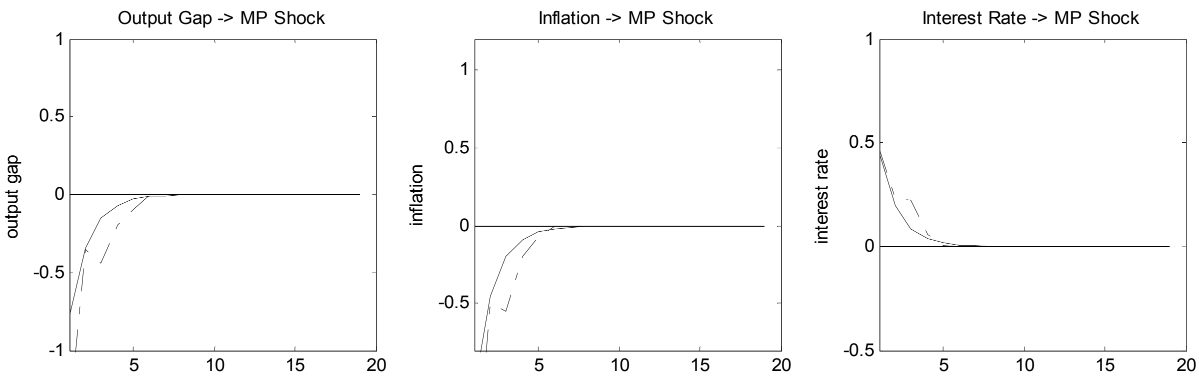
Figure 9. Impulse Response Functions to a Monetary Policy Shock: Structural Model vs. Structural VAR on simulated data - Prior 2

Identification Based on Sign Restrictions

Panel A: Indeterminacy

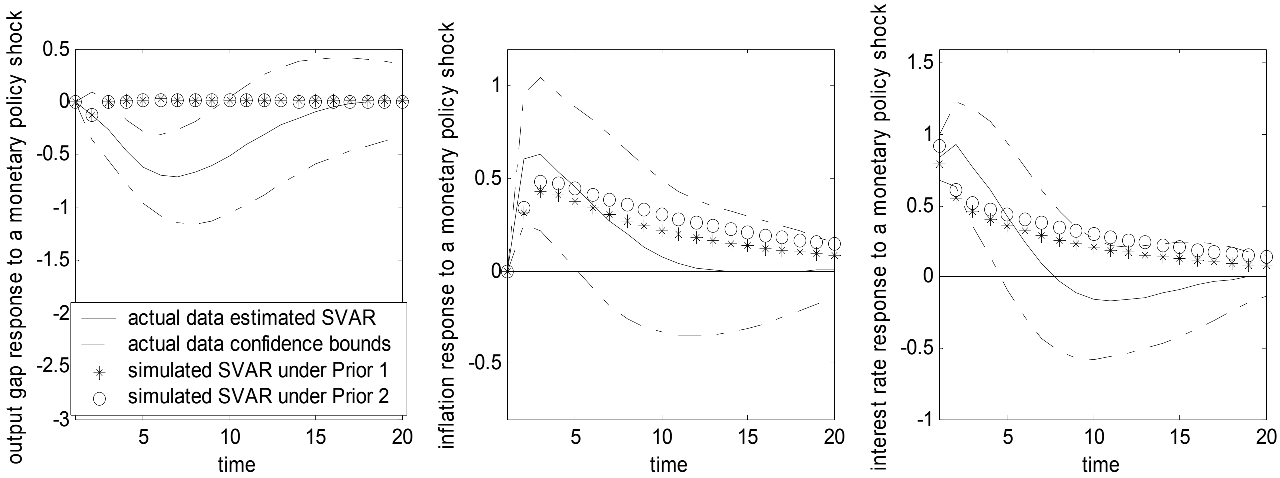


Panel B: Determinacy



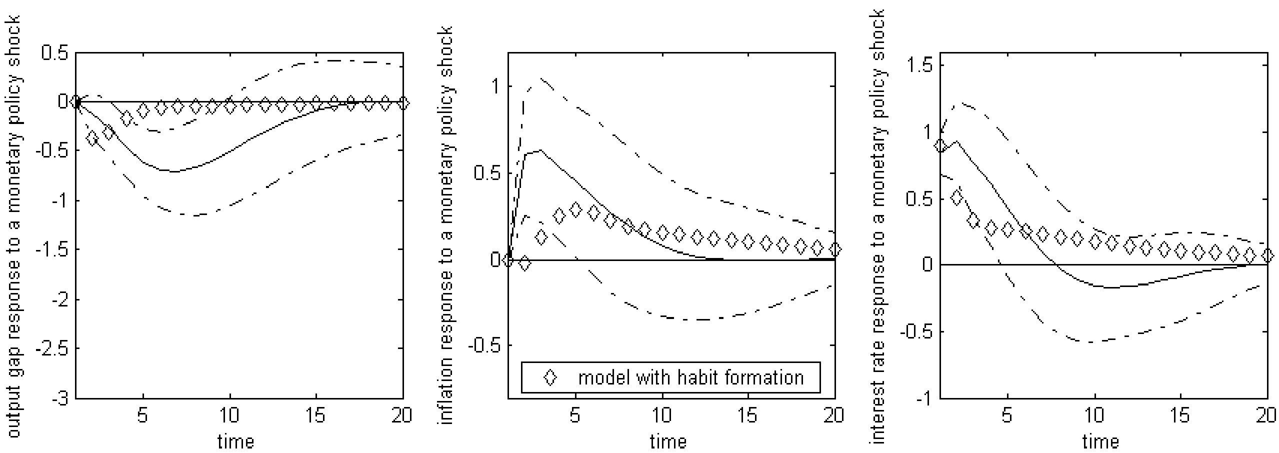
Note: Solid lines represent the *Structural model*. Dotted lines represent the *Structural VAR on simulated data*. The data generating process is the New-Keynesian model in the main text parameterized according to Prior 2 in Table 1. The point estimates of the Structural VAR on simulated data are based upon 10,000 repetitions. In each simulated sample, 100 extra observations are produced, and then discarded, to get a vector of stochastic initial conditions. Identification based on the sign restrictions reported in Table 3. Number of lags selected according to standard statistical lag length criteria.

Figure 10. Comparison of Estimated and Simulated Impulse Response Function to a Monetary Policy Shock: Benchmark Model



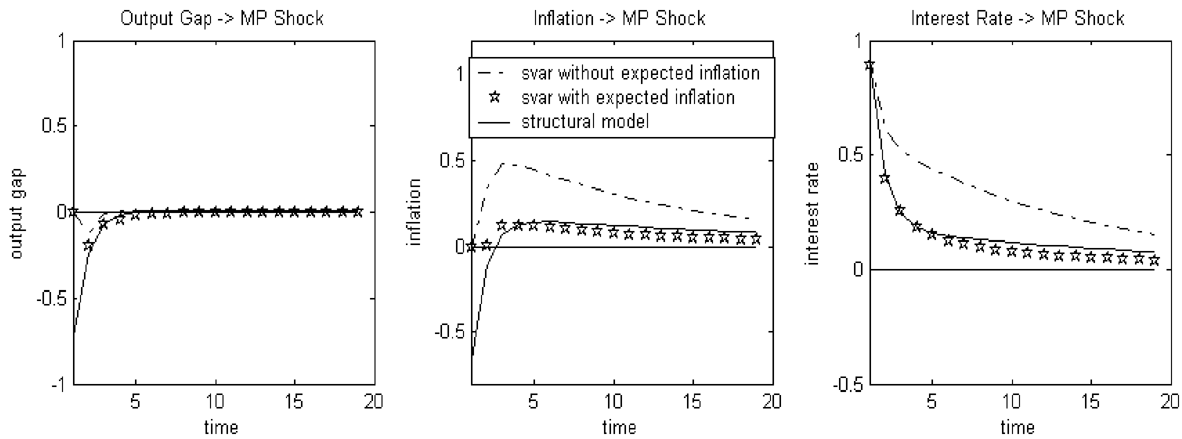
Note: Tri-variate VAR in output gap, inflation rate, and federal funds rate. Solid and dash-dotted lines refer to the structural VAR estimated on actual data (mean and 95% analytical confidence bands). Circles and stars refer to the structural VAR estimated on simulated data. Identification achieved through a Cholesky (lower triangular) factorization of the variance-covariance matrix. Number of lags selected according to standard statistical lag-length criteria.

Figure 11. Comparison of Estimated and Simulated Impulse Response Function to a Monetary Policy Shock: Model with Habit Formation



Note: Tri-variate VAR in output gap, inflation rate, and federal funds rate. Solid and dash-dotted lines refer to the structural VAR estimated on actual data (mean and 95% analytical confidence bands). Diamonds refer to the structural VAR estimated on data simulated from a model with habit formation. Identification achieved through a Cholesky (lower triangular) factorization of the variance-covariance matrix. Number of lags selected according to standard statistical lag-length criteria.

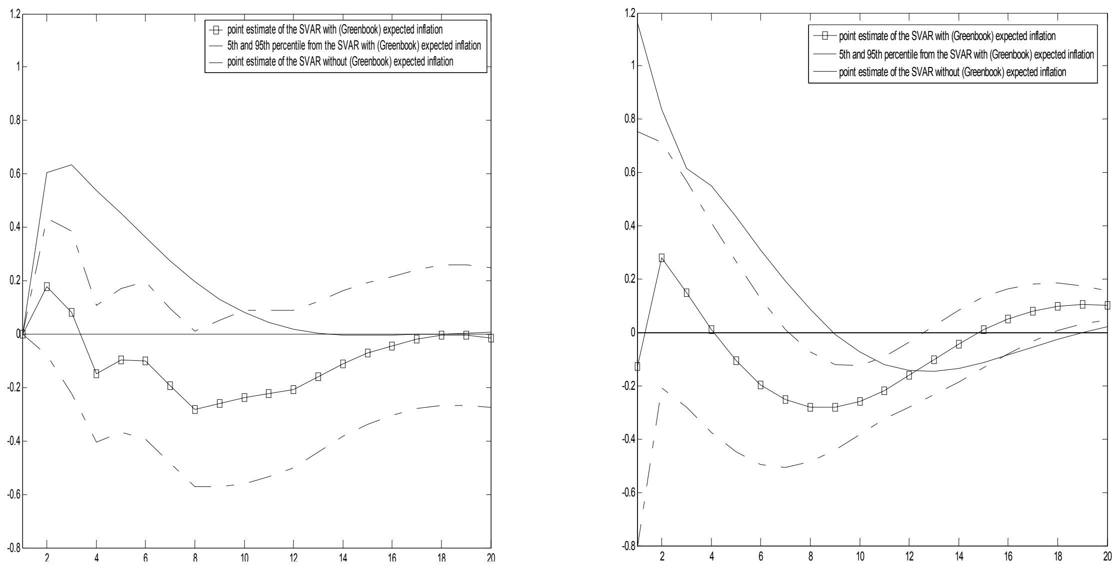
Figure 12. Impulse Response Functions to a Monetary Policy Shock: The Role of the Omitted Variable under Indeterminacy



Note: Solid lines represent the *Structural model*. The point estimates of the Structural VAR on simulated data are based upon 10,000 repetitions. In each simulated sample, 100 extra observations are produced, and then discarded, to get a vector of stochastic initial conditions. Identification achieved through a Cholesky (lower triangular) factorization of the variance-covariance matrix using the following ordering: expected future inflation, output gap, inflation and nominal interest rate. Number of lags selected according to standard statistical lag length criteria.

Figure 13. Comparison of the Inflation Responses to a Monetary Policy Shock from Estimated SVARs *with and without* the Greenbook Expected Inflation: pre-Volcker period

Contemporaneos Zero restrictions *Sign Restrictions*



Note: The solid lines with squares at each data point and the dash-dotted lines refer to the structural four-variate VAR estimated on actual data (mean, 5th and 95th percentile) which also include the one-quarter ahead Greenbook expected inflation. The solid lines refer to the tri-variate structural VARs estimated on actual data withtout including the Greenbook expected inflation.