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MONETARY POLICY, INFLATION EXPECTATIONS AND THE PRICE PUZZLE

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Abstract

This paper re-examines the VAR evidence on the price puzzle and proposes a new theoretical interpretation. Using actual data and two identification strategies based on zero restrictions and *model-consistent* sign restrictions, we find that the positive response of prices to a monetary policy shock is historically limited to the sub-samples that are typically associated with a *weak* interest rate response to inflation. Using pseudo data generated by a *sticky price model* of the U.S. economy, we then show that the structural VARs are capable of reproducing the price puzzle *only* when monetary policy is *passive*. The omission in the VARs of a variable capturing *expected inflation* is found to account for the price puzzle observed in simulated and actual data.

JEL classification: E30, E52.

Keywords: SVARs, price puzzle, sticky price model, Taylor principle, passive policy.

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1 Introduction

Structural vector autoregressions (SVARs) are widely used for measuring and understanding the effects of monetary policy innovations on the aggregate economy. While most results in the VAR literature are consistent with economic intuition and macroeconomic theory, the typically found *positive* and *significant* reaction of the price level *on impact* 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), casts serious doubts on the ability of correctly identifying a monetary policy shock. If the central bank monitors and responds to a larger information set than that 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 incorrectly interpreted by the econometrician as a policy shock. As long as monetary policy only partially offsets inflationary pressures, the VAR would deliver a spurious correlation between a tightening of policy and a rise in inflation, namely the price puzzle. Sims (1992) observes that the inclusion of a commodity price index in the VAR appears to capture enough additional information about future inflation as to possibly solve the puzzle.

This paper offers a theoretically consistent explanation for the price puzzle using a small scale DSGE model and structural VARs. Earlier contributions have shown, using zero restrictions, that the price puzzle has been a distinctive feature of US data mainly before the appointment of Paul Volcker as Fed Chairman in 1979 (see Hanson, 2004). In this paper, we show that the price puzzle emerges in the pre-1979 period also when the monetary policy shock is identified using the sign restrictions implied by a standard sticky price model.

A number of contributions to the empirical literature on monetary policy have shown that a shift in the conduct of US monetary policy occurred in 1979 (Judd and Rudebusch, 1998, Clarida, Galí, and Gertler, 2000, Boivin and Giannoni, 2006, Lubik and Schorfheide, 2004, Cogley and Sargent, 2005, among others).[1] We therefore investigate the correlation between the empirical result of this literature about monetary policy and the empirical finding about the price puzzle. Using a sticky price model of the U.S. 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.[2] The DSGE model,

[1] A similar finding is reported also by Sims and Zha (2006), who however dispute the notion that a shift in monetary policy has been the main driver of the Great Moderation.

[2] The cost channel and the interaction of active fiscal policy and passive monetary policy could also, in principle, contribute to the sub-sample evidence on the price puzzle. At the empirical level, however, Rabanal

in contrast, does not generate, on impact, a positive response of the price level to a monetary policy shock, not even when monetary policy is passive.[3] A contribution of the paper is to show that the price puzzle can actually be a spurious correlation induced by the omission in the VAR of a variable capturing the persistence of expected inflation, which is remarkably higher under the passive regime. The *omitted variable problem* is found to account quantitatively for the puzzling response of inflation to a policy shock observed on actual data. Interestingly, our results show that the arguments in Sims (1992) are supported in the context of a structural model only when monetary policy is passive and thus multiple equilibria arise.

The paper is organized as follows. Section 2 presents a re-examination of the empirical evidence using estimated SVARs in output, inflation and the nominal interest rate. The following part describes the 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 *systematically above* the former under indeterminacy only, and to reproduce the sign and magnitude of the price puzzle observed in the pre-1979 period. Section 5 offers a new interpretation of the price puzzle and shows that augmenting the SVAR on actual data with the inflation forecasts from the Survey of Professional Forecasters reduces significantly the omitted variable problem that would emerge otherwise.

2 A re-examination of the VAR evidence

This section reconsiders the empirical evidence from the VAR literature and corroborates the notion that the price-puzzle is limited to a specific historical period. This period corresponds to the monetary regime that in the empirical literature on policy rules is associated with a weak central bank reaction to inflation.

Consistent with the empirical literature on monetary policy shifts, we divide the postwar period around the third quarter of 1979, when Paul Volcker was appointed Chairman of the Fed and fighting inflation became a clear policy objective. The two periods are therefore 1966Q1-1979Q3 and 1979Q4-2006Q4. The beginning of the first subsample corresponds to the date when the Federal funds rate was first traded consistently above the discount rate. The choice of the break date is also supported by standard statistical tests. A Chow-test run on the reduced form federal funds rate equation in a VAR(4) rejects the null of stability with

(2007) estimates a DSGE sticky price model augmented with a cost channel on U.S. aggegate data and shows that the estimated model is not capable of generating a price puzzle.

[3] 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. The inability of the structural model to produce a positive response of price to a policy shock is conditional to the estimates in Lubik and Schorfheide (2004), which will be used below to generate the artificial data. For an estimated sticky-price model capable of generating a price puzzle under a passive policy regime, see Belaygorod and Dueker (2007).

a p-value equal to 0.006.[4]

2.1 Zero restrictions

A possible way to identify the monetary policy shock is to adopt the recursive scheme put forward by Christiano, Eichenbaum and Evans (1999) and employ a Cholesky factorization of the variance covariance matrix estimated from the unrestricted VAR. 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.

As for our variables, Giordani (2004) emphasizes that the inclusion of a measure of output gap reduces the biases that could otherwise arise when comparing predictions from a structural macro model and a VAR. Our measure of real activity is the CBO output gap, constructed as percentage log-deviation of real GDP with respect to the Congressional Budget Office potential output. The measure of inflation is the annualized quarter-on-quarter GDP deflator inflation rate, while the policy instrument is the federal funds rate (average of monthly realizations). The data were collected from the website of the Federal Reserve Bank of St. Louis.

Figure 1 displays the impulse response functions estimated for the two subsamples with VARs displaying a constant, no trend, and 2 (4) lags as for the first (second) subsample.[5] The reaction of inflation to a unitary monetary policy tightening suggests a significant difference when moving from the first to the second subsample. The price puzzle is present during the pre-1979 regime only. Following the monetary policy tightening, the inflation rate *significantly increases* in the short-run, and maintains a value statistically larger than zero for a few quarters while reverting to its steady-state value. The responses of interest rate and output have the expected signs. Turning to the post-Volcker era in the bottom panel, we do not find any evidence of a price puzzle in that the inflation reaction to a policy shock is not positive. In fact, it is negative on impact and then fades away fairly quickly. Importantly, such a response is far from being statistically relevant.

The estimated responses of the output gap and inflation are hardly significant in the second subsample, consistent with evidence obtained, among others, by Boivin and Giannoni (2006). The literature has put forward a couple of interpretations for this. The first interpretation regards the reduced influence exerted by monetary policy shocks on the economy, reduction

[4] Our results are robust to beginning the first sub-sample 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.

[5] The number of lags in the VARs is chosen throughout the paper according to the Schwarz information criterion. The results are robust to keeping the number of lags fixed across sub-samples. One standard error bands are computed via Montecarlo simulations to control for small-sample biases.

possibly due to technological and financial innovations that might have enabled firms and consumers to better tackle the impact of interest rate fluctuations. An alternative explanation refers to the improvement of systematic monetary policy. Given a monetary policy shock, inflation and output deviations with respect to their targets might have been more effectively contrasted by a tighter systematic reaction in the post-Volcker experiment era. If this is the case, the modest reactions of output and inflation to a monetary policy shock would be a direct consequence of better monetary policy management (see Boivin and Giannoni, 2006, for empirical evidence supporting this interpretation).

In summary, Figure 1 shows that the price puzzle is statistically relevant in the pre-1979 subsample only. Barth and Ramey (2001) and Hanson (2004) point out that these results may be obtained also with VARs estimated with monthly data. Our evidence lines up also with the results in Boivin and Giannoni (2002 and 2006), and Barakchian and Crowe (2009). Furthermore, the finding of a price puzzle in the 1970s appears independent from using real GDP or the output gap as a measure of real activity (see Castelnuovo and Surico, 2006, for a battery of alternative specifications confirming this finding). While being possibly sensitive to the VAR specification, we can safely state that the price puzzle evidence, if present, is much weaker in the second subsample.

2.2 A model-consistent identification strategy: sign restrictions

The recursive identification assumption is widely employed in the empirical macro literature, and the price puzzle obtained by Sims (1992) stems from a VAR in which the monetary policy shock is identified via a Cholesky scheme. However, the new-Keynesian model does not imply a recursive relationships among output, inflation, and the policy rate. In this section, then, we discuss the robustness of our results to using an alternative identification scheme based on the *sign* restrictions implied by the New-Keynesian model presented in section 3.[6]

We impose the restrictions that 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.

As for the effects of shocks to the Phillips curve and the IS curve, they are consistent with a typical aggregate demand and aggregate supply diagram: a disturbance to the Phillips (IS) curve has a non-negative (non negative) effect on the interest rate and inflation, and a non-positive (non-negative) effect on the output gap. The reason for our choice of identifying other disturbances in addition to the monetary policy shock, while not crucial for the results,

[6] For a description on the technical implementation of this alternative strategy, see Peersman (2005), Uhlig (2005), Rubio-Ramirez et al. (2006), and the references therein.

is twofold. First, we want to make sure that the matrix of contemporaneous parameters, which also identifies the policy shock, does not produce responses of inflation, output and interest rate to other shocks that are 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 Section 4 to show that the price puzzle is the artifact caused by an omitted variable problem.

In Figure 2, we present 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 to the pre-1979 sub-sample. Relaxing the contemporaneous zero restrictions, in fact, amplifies the puzzle in that the inflation response now becomes positive also on impact. By contrast, following a policy shock inflation declines on impact over the post-1979 sub-sample and becomes also significantly less persistent.[7]

3 A framework for monetary policy analysis

This section investigates whether the apparent price puzzle may come from the (mis)identification of the monetary policy shock during the regimes associated with a *weak* response of interest rate to inflation. The vehicle for our analysis is a simple sticky price model of the kind popularized by Clarida, Galí and Gertler (1999), King (2000) and Woodford (2003) among others. This model consists of the following equations:

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

$$\pi_t = \beta E_t \pi_{t+1} + \kappa \left(x_t - z_t\right) \tag{2}$$

$$R_t = \rho_R R_{t-1} + (1 - \rho_R) \left[\psi_\pi E_t \pi_{t+q} + \psi_x \left(x_t - z_t\right)\right] + \varepsilon_{R,t} \tag{3}$$

$$\varepsilon_t \equiv [g_t, z_t, \varepsilon_{R,t}]' \sim N\left(0_{3x1}, \Sigma_{3x3}\right) \quad \text{with } diag\left(\Sigma\right) = \left[\sigma_g^2, \sigma_z^2, \sigma_R^2\right] \quad \text{and} \quad \textit{off-diag} = 0s \tag{4}$$

where x_t is defined as the deviation of output from its trend-path, 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 (1) is a log-linearized IS curve derived from the household's intertemporal problem in which consumption and bond holdings are the control variables and τ represents the intertemporal elasticity of substitution, which in this model is the inverse of the relative risk

[7] The link between a monetary policy regime and the evidence on the price puzzle is not limited to the U.S. economy. While an international investigation is beyond the scope of this paper, Castelnuovo and Surico (2006) and Benati (2008) employ tri-variate structural VARs on U.K. data before and after the introduction of the inflation targeting regime in the fourth quarter of 1992, and find a sizable price puzzle only during the earlier sub-sample. See Nelson (2003) for evidence on the U.K. monetary policy rules before and after 1992.

aversion, i.e. $\tau \equiv \sigma^{-1}$. 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.[8]

Equation (2) 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 κ relates detrended output, x_t, and the stochastic marginal cost of production, z_t, to the rate π_t.

Equation (3) 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. The reaction to inflation may refer to contemporaneous realizations - identified by $q = 0$ - or expected future realizations - captured by $q = 1$. 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 mistakes.

There is no correlation between innovations and their variance-covariance matrix is described in equation (4). 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.[9]

4 Impulse response functions analysis

In this section, we investigate whether the small-scale monetary model detailed above is capable of reproducing the price puzzle. The model is parameterized using the estimates presented in Lubik and Schorfheide (2004). We employ the same identification used for the structural VARs 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 109 observations including output gap, inflation and interest rate.[10]

[8] 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.

[9] Notice that the interest rate smoothing induces persistence of the endogenous variables in the reduced-form representation of the system.

[10] The number of observations has been chosen to match the quarterly data points available from 1966Q1 to 1979Q3 and from 1979Q4 to 2006Q4, respectively. In each simulated sample, 100 extra-observations are produced to generate a stochastic vector of initial conditions, and then are discarded.

2. For each solution, estimate a reduced-form tri-variate VAR on the artificial data and impose the same identification scheme adopted in the empirical analysis in Section 2.

3. Compute the variable responses 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.

To the extent that equilibrium indeterminacy can explain the price puzzle, the SVARs using data generated under this condition should reproduce, at least qualitatively, the stylized fact, and possibly generate structural IRFs that are within the empirical 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, we need to calibrate the structure of the economy and the monetary policy rules to the history of the U.S. economy. As for aggregate demand and supply, we use the estimates of the New-Keynesian model (1)-(4) by Lubik and Schorfheide (2004), which are reported in Panel A of Table 1. The only difference relative to their model is that our specification intentionally 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. The first (second) artificial data set corresponds to the reaction function parameters under the heading Indeterminacy (Determinacy) in Panel B of Table 1. 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 (see Benati and Surico, 2009, for a similar exercise on the Great Moderation). It is worth noting that the interest rate response to inflation in the first row does not guarantee a unique RE equilibrium because $\psi_\pi = 0.89$ violates the Taylor principle.[11] Hence, the parameters of the policy rule in this row generate indeterminacy while the parameters in the second row do not. 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.

4.2 Evidence on changes in U.S. monetary policy: a brief review

A vast empirical literature has documented that an important change in the conduct of U.S. monetary policy occurred at the end of the 1970s in that the nominal interest rate response

[11] We postpone the presentation of the Taylor principle to Section 5. Under the passive policy regime, we follow Lubik and Schorfheide (2003 and 2004) and we solve the model under the assumption that the impulse-response functions do not change discountinously at the boundary between active and passive regimes. This solution is labeled 'countinuity'. We obtain very similar results under the assumption of 'orthogonality' according to which the effects of the structural shocks are orthogonal to the effects of the sunspot shocks.

to inflation became more than one-to-one. The policy reaction to output is typically found only marginally larger in the post-Volcker sample while the estimated degree of interest rate smoothing is higher in the most recent period.

These results are found by Lubik and Schorfheide (2004) when taking the model presented above to U.S. data. In particular, they provide strong evidence in favor of i) indeterminacy in the pre-Volcker sample and ii) a significant shift towards a more anti-inflationary policy stance inducing equilibrium uniqueness when entering the 1980s. Given that we employ their model in our analysis, it is somewhat natural for us to borrow the parameter values from Lubik and Schorfheide's contribution.

It is worth stressing, however, that variations of the postulated policy rule appear to lead to the same qualitative results. While Lubik and Schorfheide (2004) assume a *current*-looking policy rule to perform their full system estimations, Clarida et al (2000) and Judd and Rudebusch (1988) concentrate on single-equation regressions for a large battery of *forward*-looking, *backward*-looking and *current*-looking policy rules.

As for the transmission mechanism, we note that variations of the standard sticky price model do not seem to overturn the evidence of a shift in US monetary policy. Boivin and Giannoni (2006), for instance, employ a VAR similar to the one used in this paper and a DSGE model similar to the one used by Lubik and Schorfheide (2004): their minimum distance estimates support the improved monetary policy explanation of the great moderation. A similar conclusion is reached by Canova (2009).[12]

On the basis of the available evidence, we model a shift from passive to active monetary policy. We assume a contemporaneous policy rule, i.e. we will set $q = 0$ in equation (3), and we will assess the robustness of our findings to employing a forward-looking policy rule, i.e. $q = 1$.

4.3 Impulse response functions: DSGE vs. SVARs

This section compares two *different* sets of IRFs following a monetary policy shock. The first set represents the DSGE model-consistent reactions, which are the impulse responses computed by solving the system (1) to (4). 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 output gap, inflation and the nominal interest rate generated by the model under indeterminacy and under determinacy, following a unitary shock.

The results under indeterminacy are shown in the first row of Figure 3. 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

[12] It should be noted that other studies such as Smets and Wouters (2007) do not find evidence in favor of a shift in monetary policy. The authors, however, constrain their estimates to be in the determinacy region.

shock is negative on impact. After a few quarters, this reaction becomes mildly positive 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 fairly steep curve that reaches its peak at about 50 basis points after a couple of quarters, then starts converging towards the steady state. Indeed, this dynamic response represents evidence for the price puzzle being an artifact that stems from the failure of the estimated SVAR to correctly identify the effects of the monetary policy shock under indeterminacy. Notably, this pattern is within (or close to) the empirical error bands of the inflation response identified using the recursive strategy on actual data.[13]

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 difference of the inflation IRFs, 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 sole 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.

The solution of the model under determinacy returns two sets of IRFs that are virtually indistinguishable. The New Keynesian model suggests an on-impact inflation drop following a policy rate shock. 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 very closely tracks the model-consistent IRF at all periods.[14]

[13] Importantly, the price puzzle arising under indeterminacy is not due to a small-sample bias, but instead to the misspecification of the vector. In fact, we repeated the exercise with very large samples (10,000 observations), and still found clear (and incorrect) evidence pointing towards the price puzzle under indeterminacy. This result, not shown for the sake of brevity, is available upon request.

[14] We verified that this result does not hold true under "near indeterminacy", i.e. when monetary policy is active but very close to become passive. By contrast, the main message from these IRFs is unchanged using the alternative parameterization in Lubik and Schorfheide (2004). Moreover, we show in Castelnuovo and Surico (2006) that the results presented here are not overturned by introducing habit formation into the model.

Forward-looking Taylor rule

The "in-laboratory" exercises conducted so far have relied upon the current-looking Taylor rule estimated by Lubik and Schorfheide (2004). However, Clarida et al. (2000) and Boivin and Giannoni (2006) stress the relevance of the break in the systematic reaction to *expected* inflation. One may then wonder how robust the results presented in Figure 3 may be to using a forward-looking rule. To tackle this issue, we repeat our exercise by assuming $q = 1$ in equation (3). As for the calibration of the parameter ψ_π, we maintain 0.89, a value statistically in line with the one obtained by Clarida et al. (2000, Table II, page 157).

Figure 4 depicts the responses conditional to the forward-looking Taylor rule. One may easily notice that, from a qualitative standpoint, there are little changes relative to what already discussed: under indeterminacy the estimated SVAR performs poorly and signals a price puzzle when, in fact, the unexpected interest rate hike induces firms able to re-optimize to set lower prices. Interestingly, a forward-looking Taylor rule appears to trigger a more severe recession and a more marked deflation. Under determinacy, the SVAR estimates track the dynamic reactions in the data generating process (solid line) remarkably well.

Mapping between data and theory: Sign restrictions

The exercise on pseudo-data is based on zero restrictions. While very popular in the empirical literature, this recursive identification scheme is inconsistent with the structure of the sticky price model of section 3, and therefore it may make it more difficult to isolate the source of the "simulated price puzzle".

To tackle this issue, we re-estimate tri-variate SVARs with pseudo-data by employing an identification scheme consistent with the timing of our DSGE model. In particular, we impose the following sign-restrictions: a supply (demand) disturbance have a non-negative (non negative) effect on the interest rate and inflation, and a non-positive (non-negative) effect on the output gap.

The first and second row of Figure 5 display the outcome of this exercise. In line with the results from the recursive identification, the price puzzle emerges in Panel A only when monetary policy is passive.[15] Consequently, this evidence corroborates the view that the systematically larger response of the structural VARs relative to the model is not due to the mismatch between the timing of the DSGE model and the one imposed by the previously employed Cholesky identification scheme. 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. When excluding the timing issue as a possible source of

[15] Interestingly, the misspecified VAR is uncapable to distinguish between a monetary policy shock and a supply shock. This result provides formal support to Bernanke (2004), who stated: *"[...] 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."*

the simulated price puzzle, we are left with indeterminacy as the candidate for explaining the wedge between the DSGE model-based and the SVAR-based inflation reactions to a monetary policy shock under indeterminacy. Given the popularity of the recursive identification scheme in the literature, as well as the fact that the "price puzzle" has been mainly obtained by assuming a recursive economy, in the remainder of the paper we will mainly deal with SVARs estimated with a Cholesky scheme.

It is of interest to compare the impulse response functions obtained under determinacy with the two alternative identification schemes discussed previously. Figures 3 and 4 reveal that imposing a zero restriction on the contemporaneous reactions of output and inflation to a monetary policy shock introduces a hump-shaped pattern which is not present in the impulse responses of the DSGE model. In contrast, the identification based on sign restrictions in Figure 5 is capable of reproducing the shape of the reactions in the data generating process. This seems to suggest that the contemporaneous zero restrictions might be responsible for the empirical finding in the recursive VAR literature of hump-shaped responses of output and inflation to a policy shock.

5 Interpreting the price puzzle

This section explores the source of the systematic differences between the IRFs of the sticky price model and the IRFs of the SVARs, and assesses the extent to which misspecification can account for the price puzzle observed during the passive monetary policy regime.

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. Woodford (2003) shows that the solution of the system (1)-(4) is affected by the degree of systematic policy activism implemented by the monetary policy authorities. In particular, such solution is unique if and only if the following condition - i.e. the "Taylor principle" - is met:

$$\psi_\pi > 1 - \frac{(1-\beta)}{\kappa}\psi_x \tag{5}$$

If the constraint (5) is satisfied, the dynamics of the economy only depend on fundamentals and it is possible to re-write output, 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. Moreover, sunspot shocks may affect expectations and, ultimately, the equilibrium of the economic system. In particular, Lubik and Schorfheide (2004) show that when monetary policy is passive the evolution of the endogenous variables can be described as follows:

$$\underset{[3x1]}{\begin{bmatrix} x_t \\ \pi_t \\ R_t \end{bmatrix}} = \underset{[3x4]}{\Phi}^{IND} \underset{[4x1]}{\begin{bmatrix} \underset{[3x1]}{\varepsilon_t} \\ \underset{[1x1]}{\zeta_t} \end{bmatrix}} + \underset{[3x1]}{\Upsilon} \underset{[1x1]}{w_{1,t-1}} \tag{6}$$

where $w_{1,t-1}$ is a latent variable that follows the AR(1) process $w_{1,t} = \lambda_1 w_{1,t-1} + q_t$, and $\zeta_t \sim N(0, \sigma_\zeta^2)$ is a sunspot shock hitting the variables of interest. The sunspot shock may then hit inflation expectations, consequently influencing current inflation whose equilibrium path is described by eq. (6). The coefficient λ_1 is the stable eigenvalue of the system (1)-(4), the innovation q_t is a combination of structural and sunspot shocks while Φ^{IND} and Υ are matrices of convolutions of the parameters of the model.

The system (6) discloses three important insights. First, a tri-variate VAR in the 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 mis-specification is induced by monetary policy and comes in the form of an omitted variable. Third, the passive monetary policy rule generates "extra" dynamics with respect to the regime associated with an active policy rule.[16] While it is not possible to derive an analytical mapping between the series of $w_{1,t-1}$ and each variable in the system, it is worth exploring the extent to which, under indeterminacy, the omitted variable issue may be relevant for amending the price puzzle.

The role of omitted variables

When looking at the model (1)-(4), we may think of two different endogenous variables that are not explicitly and fully accounted for by our tri-variate VAR, namely inflation expectations and output gap expectations. Indeed, expected inflation and the expected output gap embed information about the monetary policy regime beyond the interest rate, inflation and the output gap. In theory, the inclusion of any of these two variables, or of a linear combination of the two, could ameliorate the misspecification problem. To assess the extent to which this is the case in practice, we run a battery of four-variate VARs in which a linear combination of expected inflation and expected output gap enters as additional regressor. Our search reveals that the combination that ameliorate the price puzzle most is the one in which expected inflation has weight one and expected output gap has weight zero.[17]

Figure 6 plots the response of the output gap, inflation and interest rate from the *augmented* four-variate recursive VARs 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

[16] As pointed out by Lubik and Schorfheide (2004, page 201), under indeterminacy the number of stable eigenvalues is generally larger than under determinacy, i.e. fewer "states" $w_{i,t-1}$ in eq. (6) are suppressed. Consequently, a richer autocovariance pattern may be expected.

[17] These results, not presented for the sake of brevity, are available upon request.

are shown for the indeterminacy solution as the omitted variable problem is present in this case only. For the sake of comparison, the corresponding impulse response functions from the tri-variate VAR in Figure 3 are reproduced as dotted lines. The IRFs using the four-variate VAR augmented with expected inflation are displayed as pentagrams.

First and foremost, one may notice the substantial improvement in the estimated inflation reaction stemming from the four-variate, inflation expectations augmented SVAR. After departing from zero (by construction), the pentagrams suggest a *negative* realization of inflation, in line with the new-Keynesian model and in stark contrast to the indication coming from the tri-variate SVAR. Moreover, the difference with respect to the IRFs of the New-Keynesian model (solid lines) appears to be remarkably dampened.[18] Furthermore, a comparison with the dotted lines from the tri-variate VAR reveals that controlling for expected inflation accounts on its own for a large portion of the omitted variable problem that is behind the price puzzle detected by the structural VARs. An appreciable improvement in terms of short-run reactions of output and the policy rate is also present. As for the tri-variate VAR without inflation expectations, we notice a large reaction of inflation to a monetary policy shock, which clearly overestimates that suggested by the new-Keynesian model.[19]

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 the ability of VARs to predict future inflation but also, more importantly, for their ability to mimic the latent variable that arises only under indeterminacy. 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.

5.2 Assessing the role of inflation expectations

The previous results pose an important empirical question: 'What macroeconomic series can approximate *in practice* the omitted variable induced by a passive monetary policy?'. The New-Keynesian model used in this paper suggests that the omitted variable is indeed a *product* of the passive monetary policy regime. Equation (6) reveals that whenever this additional 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 the

[18] By construction, the VAR inflation response does not fall on impact due to the zero-restriction implied by the Cholesky identification scheme.

[19] Note that our SVARs suggest positive realizations of inflation in subsequent quarters, a behaviour qualitatively in line with that of the new-Keynesian model and ultimately driven by the matrices Φ^{IND} and Υ (see eq. (6)). Interestingly, inflation expectations appear to ameliorate the estimated inflation dynamics response also at later periods.

flavor of an adverse supply shock in that, as shown in the first row of Figures 3 to 5, 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 SVAR of Figure 6 appears to account for most of the difference of the responses of inflation and interest rate relative to the model.

The findings of the previous section suggest that expected inflation may provide a reasonable approximation for the omitted variable that emerges under the passive monetary regime. To bring this prediction to the data and augment the otherwise misspecified VAR, one needs to select a measure of inflation expectations that captures the view and sentiment of the private sector on inflation. The Federal Reserve Bank of Philadelphia makes available the Survey of Professional Forecasters (SPF), a collection of inflation and GDP forecasts based on the expectations of market participants.

To investigate the role of expected inflation, 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 (mean value) of the one-quarter ahead GDP inflation forecasts from the SPF. 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.

Figure 7 plots the results over the sub-sample 1968Q4-1979Q3. 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 SPF expected inflation while the dash-dotted lines represent error bands.

Two results stand out. First, the identification based on sign restrictions implied by the new-Keynesian model delivers now a *significantly negative* response of inflation on impact. This contrasts with the *significantly positive* response estimated with the tri-variate SVAR (see Figure 3), and thus suggests that expected inflation is indeed empirically important during the pre-Volcker regime. Second, the finding that the inflation response is statistically non-positive on impact is robust to the alternative identification based on zero-restrictions.

The impulse responses in figures 6 and 7 display some differences. It is worth noting, however, that we focus here on the (puzzling positive) reaction of inflation to a monetary policy tightening on impact. Furthermore, we have fixed the values of the parameters of the model rather than calibrating them so as to match the impulse responses.[20]

Adding expected inflation to the SVAR estimated over the sub-sample 1979Q4-2006Q4

[20] Canova and Sala (2009) show that the indirect inference based on matching impulse responses may lead to serious identification problems in a small scale DSGE model similar to the one used in this paper.

produces IRFs, not reported but available upon request, which are virtually identical to the IRFs from the estimated tri-variate SVAR in the output gap, inflation and federal funds rate only. We thus conclude that *only* when monetary policy is passive, inflation expectations contain marginal explanatory power for inflation and become helpful to identify a monetary policy shock. In Castelnuovo and Surico (2006), we show that the results in this section are robust to using the Greenbook inflation forecasts, which are prepared by the Fed staff before each meeting of the Federal Open Market Committee (see also Carboni and Ellison, 2009).

6 Conclusions

The contribution of this paper is twofold. At the empirical level, it corroborates the notion that the price puzzle is a sub-sample regularity related to the period that, in the empirical literature on monetary policy rules, is typically associated with a weak central bank response to inflation. These are the years prior to the appointment of Paul Volcker as Federal Reserve Chairman in August 1979. The VAR evidence presented here is robust to two different identification strategies based on zero restrictions and the sign restrictions implied by the New-Keynesian model.

At the theoretical level, this paper employs a sticky price model of the U.S. 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.

The sticky price model produces, on impact, a positive inflation response to a monetary policy shock, *neither* under determinacy *nor* under indeterminacy. On the basis of Montecarlo simulations, we argue that the price puzzle can be the artifact of a specification error in the VARs. The mis-specification comes from the omission of a latent variable, which exists only when the monetary policy rule is passive. Expected inflation are found to approximate this omitted variable reasonably well, both in the theory and in the data. Our finding suggests that inflation expectations are key to identify correctly a monetary policy shock during a passive regime.

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Table 1. Model Parameters

Panel A: Structure of the Economy

β	κ	τ^{-1}	σ_g	σ_z
0.99	0.75	2.08	0.21	1.16

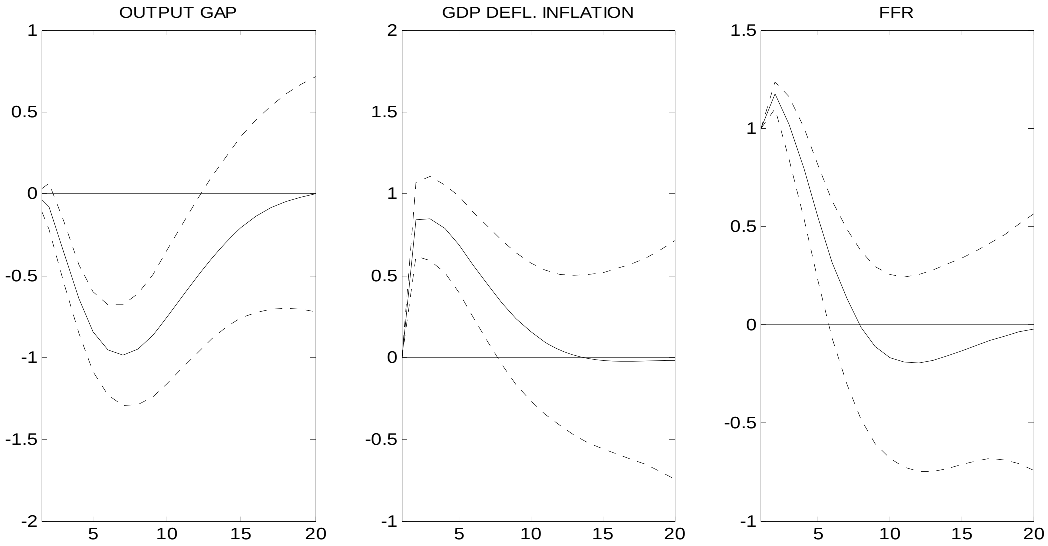
Panel B: Monetary Policy Rules and Sunspot Shock

Sub-sample	ψ_π	ψ_x	ρ_R	σ_R	σ_ζ
Indeterminacy	0.89	0.15	0.53	0.24	0.23
Determinacy	2.19	0.30	0.84	0.24	-

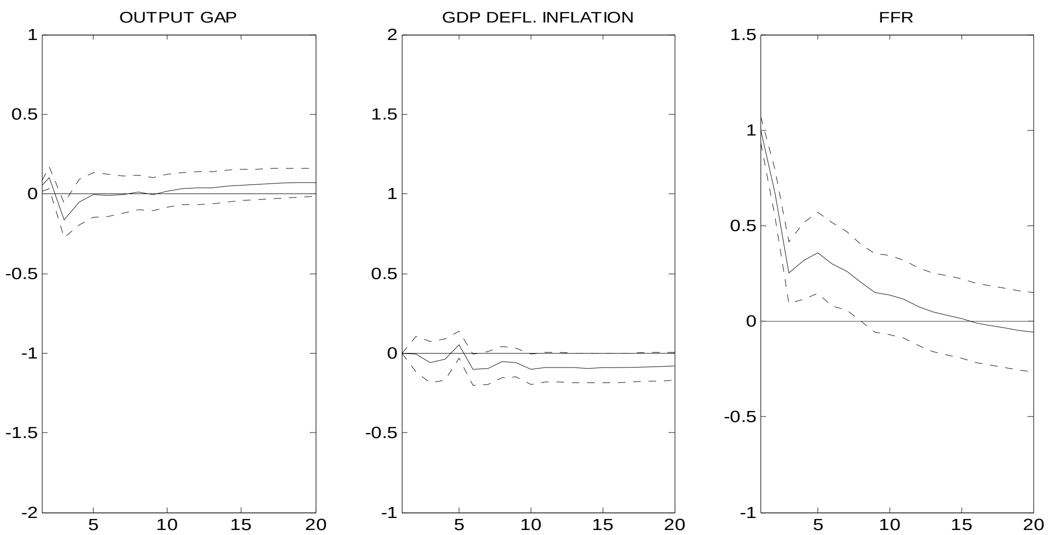
Note: The parameterization of the data generating process is borrowed from Lubik and Schorfheide (2004), Table 3.

Figure 1. IRFs to a Monetary Policy Shock
- Identification Based on Zero Restrictions -

Sub-sample 1966Q1-1979Q3



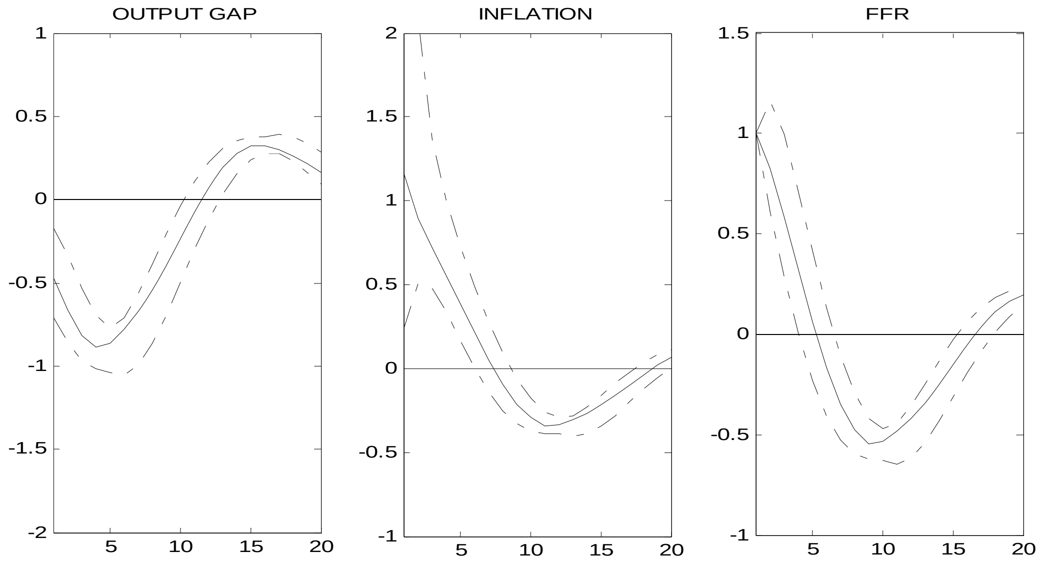
Sub-sample 1979Q4-2006Q4



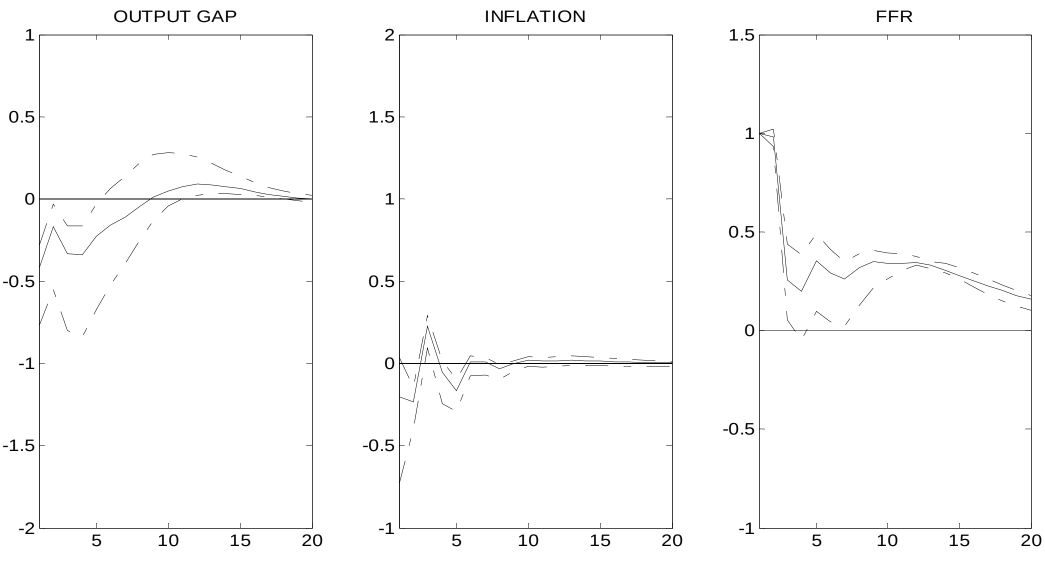
Note: Tri-variate VAR in CBO output gap, GDP deflator inflation, and federal funds rate. Identification achieved through a Cholesky (lower triangular) factorization of the variance-covariance matrix. Solid lines are point estimates, dotted lines are 16th and 84th percentile error bands computed via a Monte Carlo procedure (500 repetitions). Quarters on the x-axis, percentage points on the y-axis.

Figure 2. IRFs to a Monetary Policy Shock
- Identification Based on Sign Restrictions -

Sub-sample 1966Q1-1979Q3

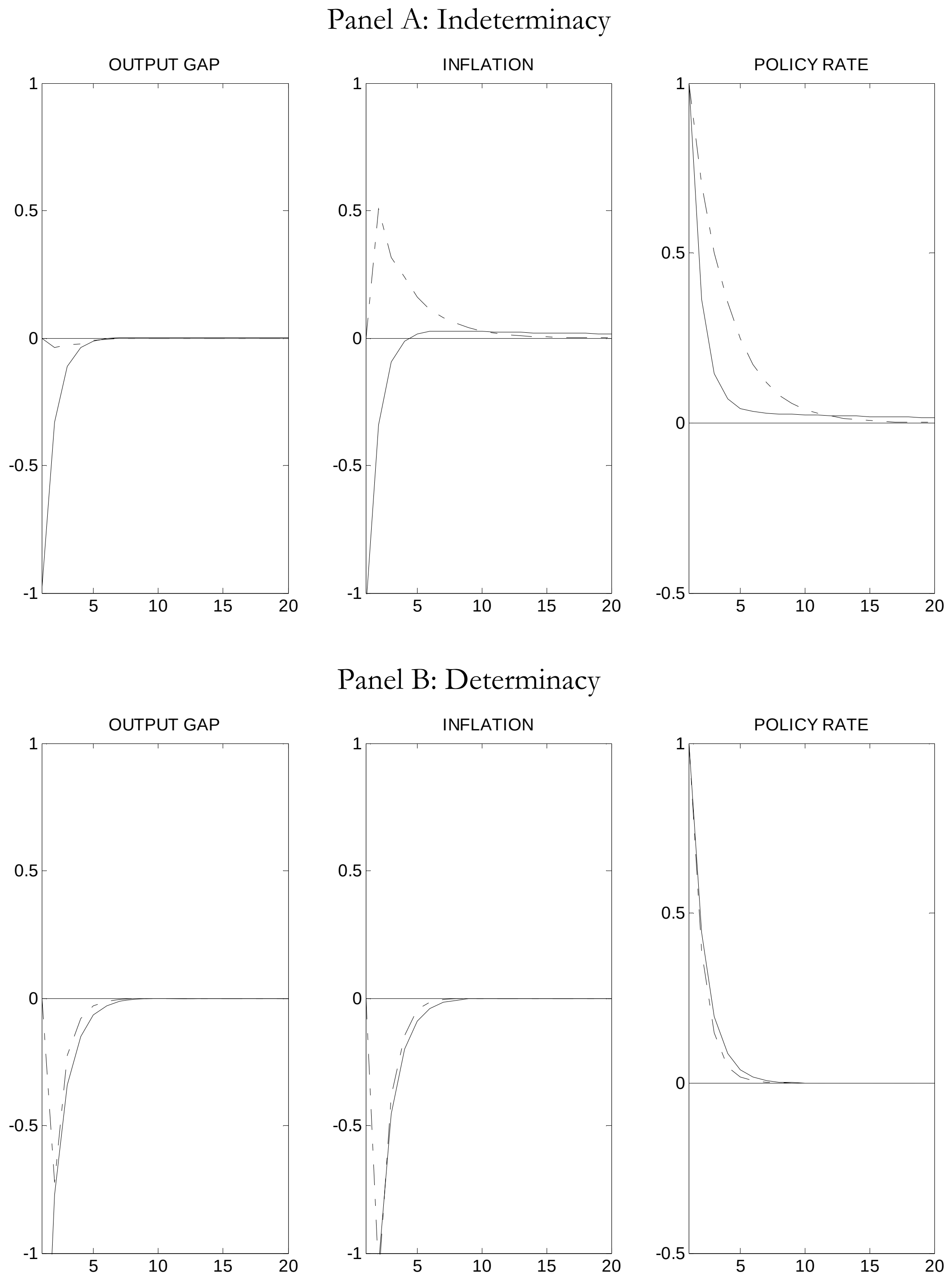


Sub-sample 1979Q4-2006Q4



Note: Tri-variate VAR in CBO output gap, GDP deflator inflation, and federal funds rate. Identification based on the sign restrictions. Solid lines are median estimates; dotted lines are 16th and 84th percentile error bands. Quarters on the x-axis, percentage points on the y-axis.

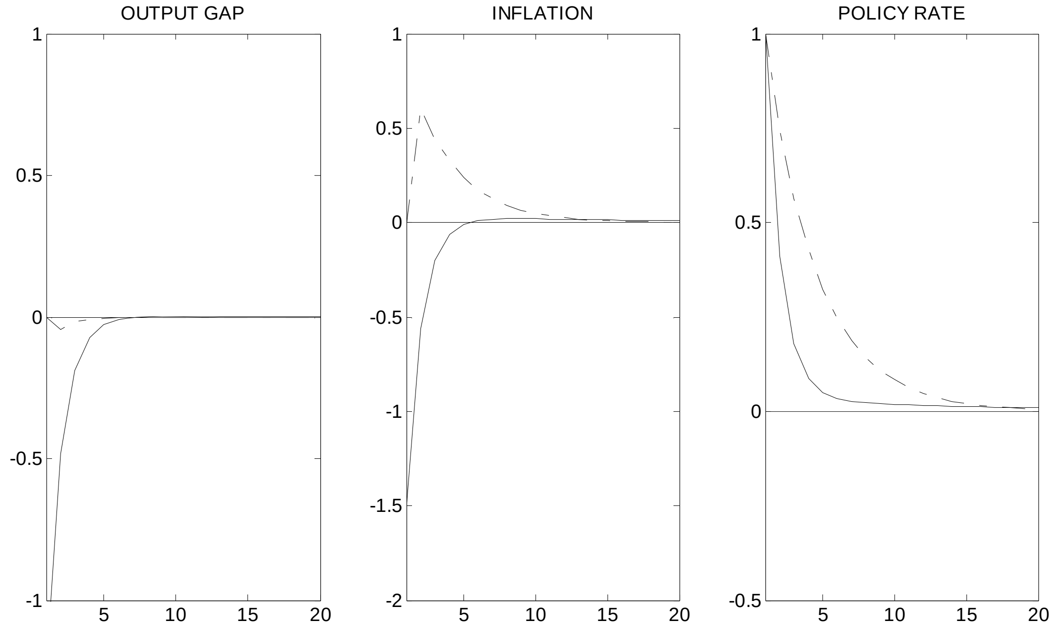
Figure 3. Impulse Response Functions to a Monetary Policy Shock: Structural Model vs. Structural VAR on simulated data



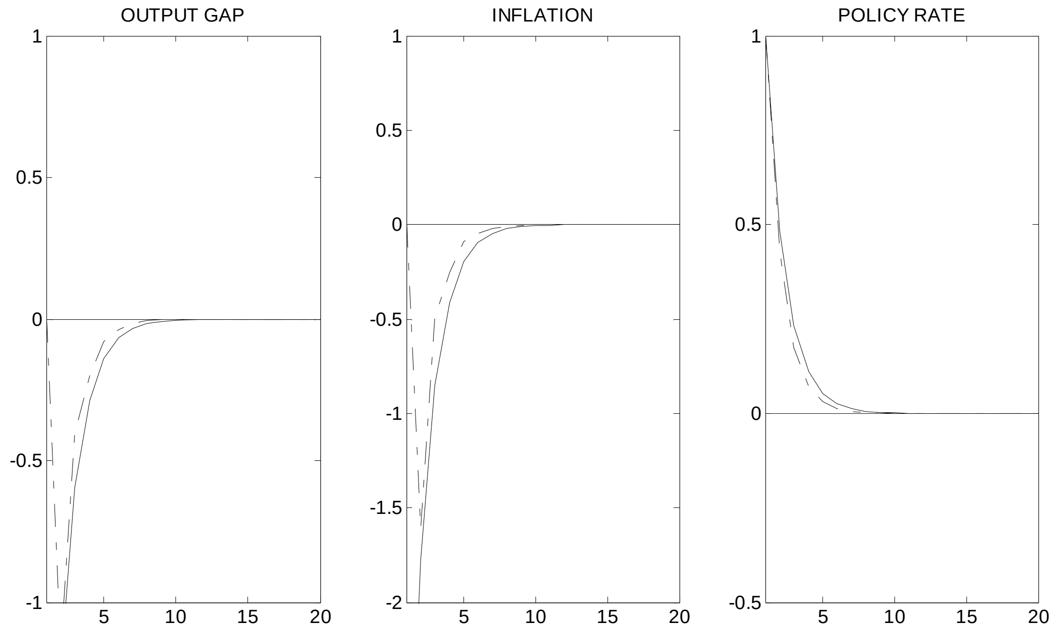
Note: Solid lines represent the *Structural model*. Dotted lines represent the *Structural VAR on simulated data*. The data generating process is the New-Keynesian model in the main text parameterized according to Table 1. The point estimates of the Structural VAR on simulated data are based upon 10,000 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. Quarters on the x-axis, percentage points on the y-axis.

Figure 4. Impulse Response Functions to a Monetary Policy Shock: Structural Model with Forward Looking Rule vs. Structural VAR on simulated data

Panel A: Indeterminacy



Panel B: Determinacy

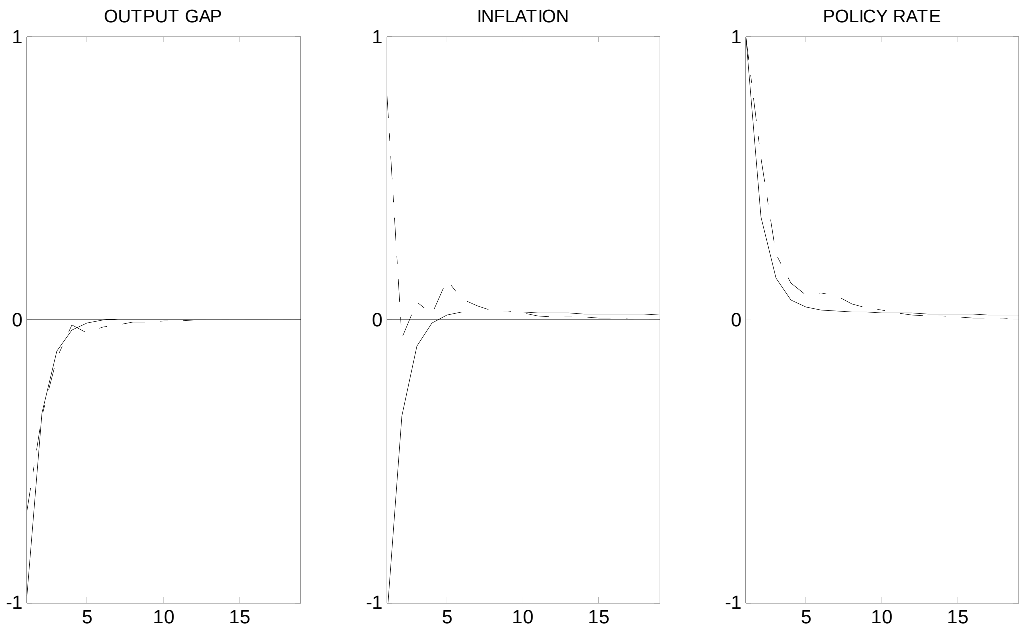


Note: Solid lines represent the *Structural model*. Dotted lines represent the *Structural VAR on simulated data*. The data generating process is the New-Keynesian model in the main text parameterized according to Table 1 with one-step ahead inflation expectations in the Taylor rule. The point estimates 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. Quarters on the x-axis, percentage points on the y-axis.

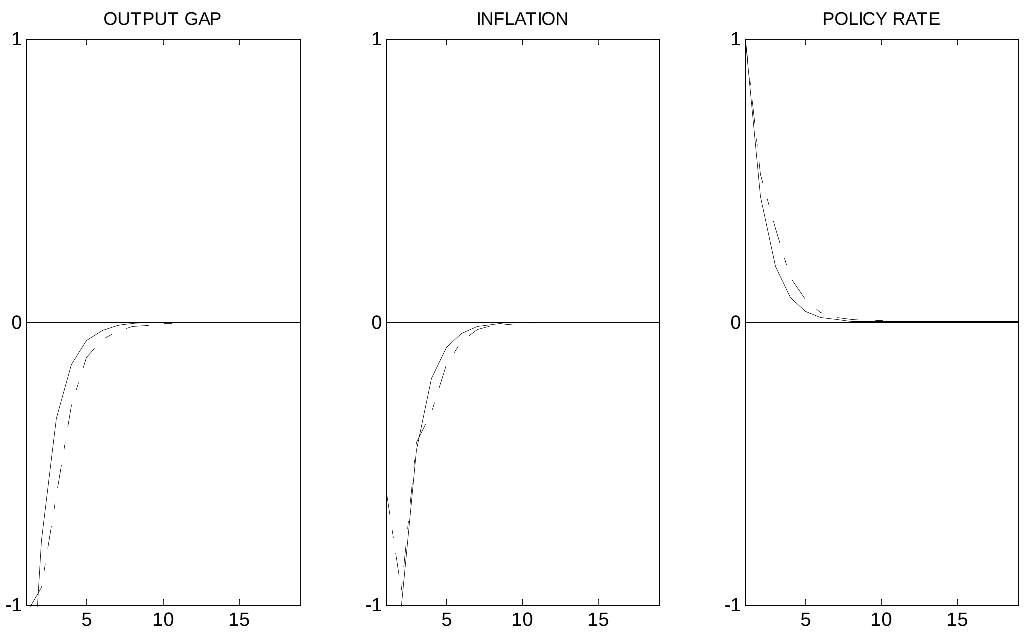
Figure 5. Impulse Response Functions to a Monetary Policy Shock: Structural Model vs. Structural VAR on simulated data

Identification Based on Sign Restrictions

Panel A: Indeterminacy

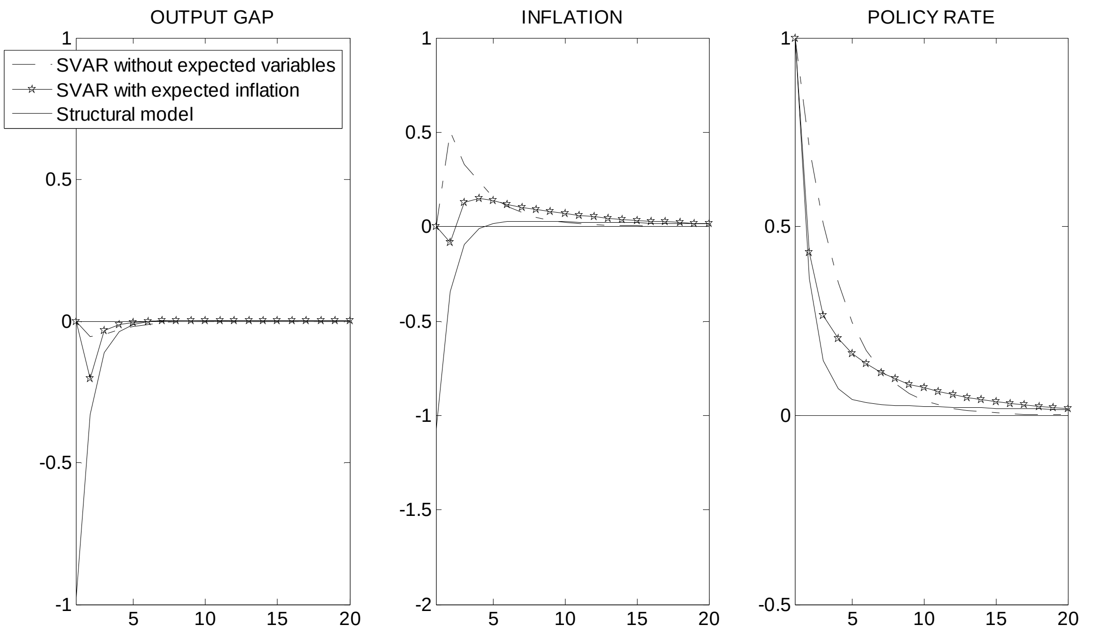


Panel B: Determinacy



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 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 as indicated in the text. Quarters on the x-axis, percentage points on the y-axis.

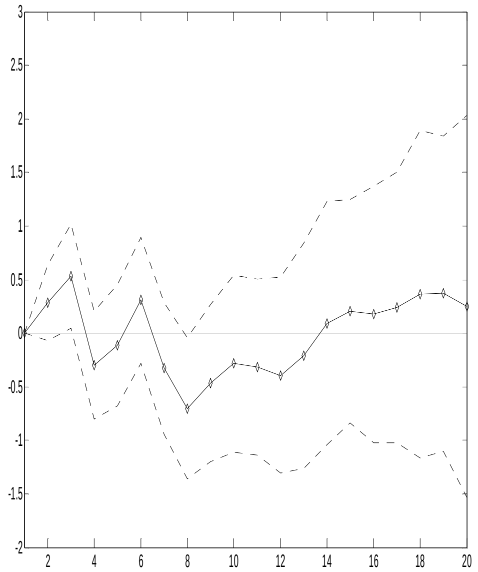
**Figure 6. Impulse Response Functions to a Monetary Policy Shock:
The Role of the Omitted Variable under Indeterminacy**



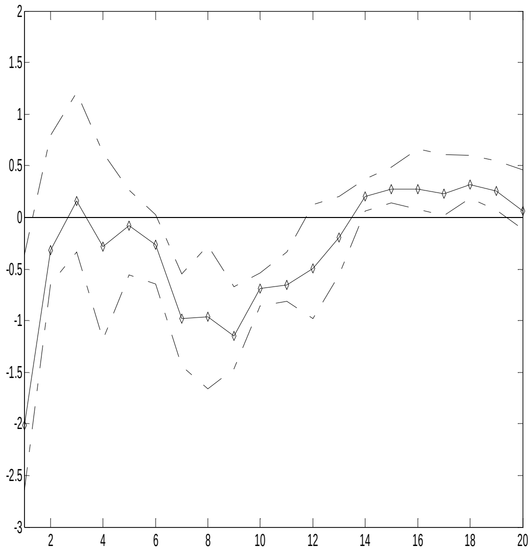
Note: Solid lines represent the *Structural model*. The point estimates of the Structural VAR on simulated data are based upon 10,000 repetitions. In each simulated sample, 100 extra observations are produced, and then discarded, to get a vector of stochastic initial conditions. Identification achieved 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. Quarters on the x-axis, percentage points on the y-axis.

Figure 7. Inflation Responses to a Monetary Policy Shock from Four-Variate Estimated SVARs *with* Expected Inflation: pre-Volcker period

Contemporaneous Zero restrictions



Sign Restrictions



Note: One-quarter ahead Survey of Professional Forecasters expected inflation (mean value), CBO output gap, GDP deflator inflation, and federal funds rate (bottom panels). Solid lines are median estimates, dotted lines represent error bands. Quarters on the x-axis, percentage points on the y-axis.