Monetary Policy Neutrality? Sign Restrictions Go to Monte Carlo*

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Abstract

Two new-Keynesian DSGE models in which contractionary monetary policy shocks generate recessions are estimated with U.S. data. Either models are then employed in a Monte Carlo exercise to generate artificial data with which VARs are estimated. VAR monetary policy shocks are identified via sign restrictions. Our VAR impulse responses replicate Uhlig's (2005, *Journal of Monetary Economics*) evidence on unexpected interest rate hikes having ambiguous effects on output. The mismatch between the true (DSGE-consistent) responses and those produced with sign-restriction VARs is shown to be due to the low relative strength of the signal of the shock. We conclude that Uhlig's (2005) findings are not inconsistent with microfounded DSGE models featuring nominal frictions and in which monetary policy is not neutral.

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1 Introduction

The conventional view on the effects of monetary policy shocks is the following. An unexpected policy rate hike increases the real interest rate, depresses aggregate demand, and pushes inflation down in the short-run. An intriguing exercise by Uhlig (2005), however, casts doubts on this transmission mechanism. Working with a VAR estimated with post-WWII U.S. data, Uhlig (2005) shows that the response of output to a monetary policy shock is surrounded by a large amount of uncertainty. As a matter of fact, output may increase or decrease following a shock that triggers conventional reactions in other macroeconomic indicators.

This result is thought-provoking. As stated by Uhlig (2005, p. 406),

> *" "Contractionary" monetary policy shocks do not necessarily seem to have contractionary effects on real GDP. One should therefore feel less comfortable with the conventional view and the current consensus of the VAR literature that has been the case so far."*

This result is thought-provoking. In the light of this finding, Uhlig (2005, p. 382) concludes that

> *"Neutrality of monetary policy shocks is not inconsistent with the data."*

This paper shows that Uhlig's (2005) intriguing result is *consistent* with the conventional view on the real effects of monetary policy shocks. In short, we show that ambiguous effects of a monetary policy tightening on output may be found with VARs estimated with artificial data generated by structural models in which *monetary policy is non-neutral*. We do so by setting up a Monte Carlo exercise in which the Data Generating Process (DGP) is a new-Keynesian DSGE model predicting "textbook" effects as for the short-run reaction of output to monetary policy shocks. Two state-of-the-art, microfounded DSGE models of the business cycle are estimated with U.S. quarterly data and alternatively exploited to generate artificial data with which we feed our VARs. Monetary policy shocks are identified by imposing a set of widely-accepted, model-consistent restrictions on the modeled variables. Following Uhlig (2005), we leave the reaction of output *unconstrained* at all horizons.

Our results read as follows. The estimated DSGE model of the business cycle predicts a phase of economic bust and deflation after a policy tightening. However, our VARs return quite uncertain indications as for the reaction of output. In particular, about 2/3 of the responses conditional on an unexpected policy tightening turn out to be *positive*, a result consistent with Uhlig's (2005) evidence. In other words, our exercise replicates Uhlig's (2005) finding in a controlled environment in which monetary policy shocks *do* exert an influence on the U.S. business cycle. This result proves that an ambiguous reaction of output to a monetary policy shock in sign-restriction VARs is *not* inconsistent with monetary policy shocks triggering macroeconomic reactions in line with the conventional view. Further investigations show that our result is driven by the relatively little role played by policy shocks in influencing the variance of the forecast error of output (as well as the remaining macroeconomic indicators). Given the weakness of the signal, the estimated monetary policy "shock" is actually a combination of all shocks hitting the economic system. In particular, supply shocks contaminate the estimated dynamic responses and induce a positive output reaction. Sign restrictions are shown to correctly identify the negative effects on output exerted by policy shocks in alternative environments in which such shocks play a (counterfactually) larger role as for the volatility of output. Therefore, *in principle*, nothing is wrong with the sign restrictions methodology. However, sign restrictions are more likely to be a powerful procedure to recover the effects of a given shock (in our case, the monetary policy shock) the stronger is the "signal" associated to such a shock, a result in line with Paustian (2007) and Canova and Paustian (2011). Therefore, the uncertain reaction of output to monetary policy shocks may be due to identification issues, more than representing a truly genuine empirical fact.[1]

The robustness of our results is checked by implementing a variety of perturbations of the baseline exercise. These involve the use of different sets of sign restrictions, the length of the pseudo-data sample, and the employment of a medium-scale model à la Smets and Wouters (2007) as DGP. Importantly, our robustness checks show that our results are robust to the imposition of restrictions which allow us to identify other shocks (non-policy demand shocks, supply shocks); are robust to an analysis conducted in population, which controls for sampling uncertainty therefore isolating the role of identification uncertainty; and to an alternative model belonging to the class of models currently employed in central banks and academic circles to conduct policy analysis.

[1] We note that, as a matter of fact, Uhlig (2005) never explicitly claims that his result is not consistent with conventional wisdom. What our paper shows is that models in line with conventional wisdom are very likely to produce an outcome like the one proposed by Uhlig (2005). As just stated, this result is robust to a variety of perturbations of our baseline scenario. The search for DSGE models *not* implying VAR reactions as those in Uhlig (2005), and which are therefore "rejected" by the data (as processed by such VARs), is left to future research.

Finally, we move to actual U.S. data and estimate a trivariate VAR to model inflation, output, and the nominal interest rate with quarterly U.S. data, 1984:I-2008:II. The same set of robust sign restrictions employed in our Monte Carlo exercises is employed to identify the monetary policy shock. Our results corroborate Uhlig's findings, in that a huge uncertainty surrounding the reaction of output is found. In the light of our Monte Carlo experiments, we interpret such evidence as being fully consistent with monetary policy non-neutrality.

The paper develops as follows. Section 2 presents and estimates a standard new-Keynesian DSGE model with U.S. data. Such model is employed as a DGP in Section 3, which sets up our Monte Carlo experiment. In this Section we contrast the impulse responses generated with our estimated DSGE with those coming from the sign-restriction VARs in a controlled environment. Section 4 collects our robustness checks. Section 5 deals with actual U.S. data, which are used to estimate a VAR and identify the effects of the U.S. monetary policy shocks during the great moderation phase. Section 6 concludes.

2 A DSGE model as DGP

2.1 Model presentation

We work with a standard DSGE model. The log-linearized version of the model is the following:

$$\pi_t = \xi_1 E_t \pi_{t+1} + \xi_2 \pi_{t-1} + \xi_3 y_t + \xi_4 \varepsilon_t^{\pi}, \tag{1}$$

$$y_t = \varphi_1 E_t y_{t+1} + \varphi_2 y_{t-1} - \varphi_3 (R_t - E_t \pi_{t+1}) + \varphi_4 a_t, \tag{2}$$

$$R_t = (1 - \tau_R)(\tau_\pi \pi_t + \tau_y y_t) + \tau_R R_{t-1} + \varepsilon_t^R, \tag{3}$$

where $\xi_1 \equiv \beta\xi_4, \xi_2 \equiv \alpha\xi_4, \xi_3 \equiv \kappa\xi_4, \xi_4 \equiv (1+\alpha\beta)^{-1}, \varphi_1 \equiv \gamma, \varphi_2 \equiv (1-\gamma), \varphi_3 \equiv \sigma^{-1}, \varphi_4 \equiv \frac{(\rho_a - 1)(1+\nu)}{(\sigma+\nu)}$. Eq. (1) is an expectational new-Keynesian Phillips curve (NKPC) in which π_t stands for the inflation rate, β represents the discount factor, y_t identifies the output gap, whose impact on current inflation is influenced by the slope-parameter κ, α identifies indexation to past inflation, and ε_t^{π} represents a supply shock (e.g., a "price mark-up" shock); γ is the weight of the forward-looking component in the intertemporal IS curve (2); σ^{-1} is the households' intertemporal elasticity of substitution; ν is the inverse of the Frisch labor elasticity, and a_t identifies a demand shock (e.g., a "technology" shock); τ_π, τ_y, and τ_R are policy parameters in the Taylor rule (3); the monetary policy shock ε_t^R allows for a stochastic evolution of the policy rate. All shocks are assumed to follow mutually independent AR(1) processes that feature autocorrelation coefficients $(\rho_\pi, \rho_a, \rho_R)$, respectively. The standard deviation of the structural innovations $u_t^i, i = (\pi, a, R)$ are $(\sigma_\pi, \sigma_a, \sigma_R)$.

This framework is extensively discussed in King (2000), Woodford (2003), and Carlstrom, Fuerst, and Paustian (2009). It has successfully been employed to conduct empirical analysis concerning the U.S. economy. Lubik and Schorfheide (2004) have investigated the influence of systematic monetary policy over the U.S. macroeconomic dynamics; Boivin and Giannoni (2006), Benati and Surico (2009), Canova (2009), and Lubik and Surico (2010) have replicated the U.S. great moderation; Benati (2008) and Benati and Surico (2008) have investigated the drivers of the U.S. inflation persistence. As shown in Section 4, however, our results are robust to the employment of a medium-scale model à la Smets and Wouters (2007).

2.2 Model estimation

We estimate the model (1)-(3) with Bayesian methods. We work with quarterly U.S. data, sample: 1984:I-2008:II. This sample roughly coincides with the great moderation, a period beginning in the mid-1980s (McConnell and Perez-Quiros (2000)). The choice of this sample allows us to control for policy parameters' instability (Clarida, Galí, and Gertler (2000) and subsequent contributions), heteroskedasticity of the structural shocks (Justiniano and Primiceri (2008)), and omitted variables as, e.g., real money balances, which may have played an important role in determining output in the 1970s (Castelnuovo (2012)). Moreover, instabilities concerning VARs estimated over the post-WWII and possibly due to the appointment of Paul Volcker as Federal Reserve Chairman in 1979 have been detected by Bagliano and Favero (1998), Boivin and Giannoni (2006), and Castelnuovo and Surico (2010). Our sample ends in 2008:II to exclude the acceleration of the financial crises began with the bankruptcy of Lehman Brothers in September 2008, which triggered non-standard policy moves by the Federal Reserve. We employ three observables. The output gap is computed as log-deviation of the real GDP with respect to the potential output estimated by the Congressional Budget Office. The inflation rate is the quarterly growth rate of the GDP deflator. For the short-term nominal interest rate we consider the effective federal funds rate expressed in quarterly terms (averages of monthly values). The source of the data is the Federal Reserve Bank of St. Louis' website. The vector $\boldsymbol{\theta} = [\beta, \upsilon, \kappa, \alpha, \gamma, \sigma, \tau_\pi, \tau_y, \tau_R, \rho_a, \rho_\pi, \rho_R, \sigma_a, \sigma_{\pi,}\sigma_R]^T$ collects the parameters characterizing the model. We set $\beta = 0.99$ and $\nu = 1$, a very standard calibration in the literature.[2] The remaining priors are collected in Table 1. Details on the Bayesian algorithm employed to estimate our DSGE model are relegated in our Appendix.

Our posterior estimates are reported in Table 1. All the estimated parameters take conventional values. The parameters of the policy rule suggest an aggressive conduct to dampen inflation fluctuations, and a high degree of policy gradualism; the estimated degree of price indexation (posterior mean) is 0.09 (90% credible set: $[0.01, 0.17]$); the estimated weight of the forward looking component in the IS curve is 0.78 (90% credible set: $[0.70, 0.86]$). A comparison involving actual series and the DSGE model's one-step ahead predictions confirms the very good-short term predictive power of our DGP (evidence confined in our Appendix).

3 Impulse responses: DSGE vs. SRVARs

3.1 Monte Carlo exercise

We now turn to our Monte Carlo exercise. Basically, we aim at comparing the true (DSGE-consistent) impulse responses with those produced with a VAR whose monetary policy shock is identified with sign restrictions. We calibrate the vector of our estimated structural parameters $\boldsymbol{\theta}$ of the DSGE framework with our posterior means. Then, we compute the DSGE model-consistent impulse responses conditional on $\boldsymbol{\theta}$ to an unexpected nominal interest rate hike, and store them in the $[3xHxJ]$ $\boldsymbol{DSGE\_IRFs}$ matrix, which accounts for the $[3x1]$ vector of variables we focus on, the $h \in \{1, ..., H\}$ step-ahead responses of interest, and the $j \in \{1, ..., J\}$ draws of such responses. Subsequently, we run the following algorithm. For $j = 1$ to J, we

1. feed our VARs with the artificial data $\boldsymbol{x}^j_{ps,[3:T]}$ (variables: inflation, output gap, nominal rate) generated with the DSGE model conditional on $\boldsymbol{\theta}$;

2. compute the impulse responses to a monetary policy shock with sign restrictions (as explained below);

3. store them in the $[3xHxJ]$ $\boldsymbol{SRVAR\_IRFs}$ matrix.[3]

[2] Perturbations of this baseline calibration confirmed the robustness of our results.
[3] As shown by Carlstrom, Fuerst, and Paustian (2009), our DSGE model features a finite VAR(2)

We run this algorithm by setting the number of repetitions $K = 1,000$, the horizon of the impulse response functions $H = 15$, and the length of the pseudo-data sample $T = 98$. This sample numerosity coincides with that of the actual data sample (1984:I-2008:II) we employed to estimate our DSGE model.[4] Monetary policy shocks are normalized to induce an on-impact equilibrium reaction of the nominal rate equivalent to 25 quarterly basis points.

3.2 Sign restrictions

Sign restrictions represent a strategy to identify a structural shock in VAR analysis. In a nutshell, the idea is that of imposing *ex post* sign restrictions on a set of moments generated with the VAR, e.g., a set of impulse responses to a given shock. In our application, we estimate the reduced-form VAR coefficients $\boldsymbol{A}(L)$ and covariance matrix $\boldsymbol{\Lambda}$ from the data via OLS. Then, we orthogonalize the VAR residuals via an eigenvalue-eigenvector decomposition such that $\boldsymbol{\Lambda} = \boldsymbol{PDP}^T$, where $\boldsymbol{P}$ is the matrix of eigenvectors and $\boldsymbol{D}$ is the diagonal matrix of eigenvalues. The non-uniqueness of the MA representation of the VAR is exploited to provide a set of alternative proposals for the shock(s) of interest via the employment of three Givens rotation matrixes $\boldsymbol{Q}_{ij}(\omega)$, where $\omega \in (0, 2\pi)$, and $\boldsymbol{R} = \boldsymbol{Q}_{12}(\omega_1)\boldsymbol{Q}_{13}(\omega_2)\boldsymbol{Q}_{23}(\omega_3), \boldsymbol{RR}^T = \boldsymbol{I}_3$. The "impulse" matrix loading the VAR with candidate "shocks" is therefore given by $\widetilde{\boldsymbol{B}}(\boldsymbol{\omega}) = \boldsymbol{PD}^{1/2}\boldsymbol{R}(\boldsymbol{\omega})$. If the impulse responses to the "candidate" shock satisfy all the required restrictions, then the draw of the orthonormal vector $\boldsymbol{\omega}$ and the corresponding responses are retained. Otherwise, they are discarded. In so doing, we assign equal, strictly positive weight to the draws we retain (those that meet our restrictions), and assign zero prior weight to those that violate our constraints.[5] A non-exhaustive list of recent applications of the sign-restriction strategy to identify structural shocks includes Faust (1998), Canova and de Nicoló (2002), Peersman (2005), and Uhlig (2005). Rubio-Ramírez, Waggoner, and Zha (2010) propose an algorithm to compute the rotation matrix $\boldsymbol{R}$ efficiently. Such algorithm works well also when the number of variables in the vector is large and

representation in population. Hence, our VARs are estimated with two lags. Robustness checks dealing with the optimal choice of the VAR lag-length based on the Schwarz criterion supported the solidity of our results.

[4] To be clear, our results are robust to performing our analysis in population. In other words, the discrepancies between DSGE- and VAR-impulse responses are not due to a small-sample bias issue, but are instead genuinely related to an identification issue affecting sign-restriction VARs in this kind of exercises.

[5] Differently, one could set up a penalty function to penalize violations and reward large and correct responses. For an in-depth discussion, see Uhlig (2005).

several restrictions are imposed to identify more than one structural shock. Canova and Paustian (2011) propose an algorithm which derives a set of "robust" restrictions from a class of structural DSGE models that one may exploit to identify the shock(s) of interest with Vector Autoregressions. Fry and Pagan (2011) critically review the estimation of structural VARs with sign restrictions.

We identify the monetary policy shock by imposing "textbook" constraints on the impulse responses of inflation and the policy rate to a monetary policy shock. The signs to achieve identification are collected in Table 2. Such signs are "robust" in the sense of Canova and Paustian (2011), in that they hold true for a variety of different calibrations of the parameters of interest (result confined to the Appendix for the sake of brevity). Such constraints are imposed as for the first $K = 2$ quarters, i.e., the one in which the shock occurs and the following one. This choice is in line with Uhlig's (2005), which sets $K = 5$ but deals with monthly (as opposed to quarterly) data. Importantly, we leave the reaction of output unconstrained in order to let the (artificial) data free to speak as for the effects of an unexpected interest rate hike (on output itself). Notice that, in this Monte Carlo exercise, the set of restrictions associated to the monetary policy shock only is sufficient to identify such shock, in that only an unexpected contractionary monetary policy move is able to generate an on-impact negative (conditional) correlation between the short-term policy rate and inflation according to our DGP.[6] Section 4 documents the robustness of our results in presence of additional restrictions that identify two more shocks (price mark-up, technology).

3.3 Results

We recall our research question, which is:

> *"Suppose that the Data Generating Process is a standard DSGE framework in which monetary policy is not neutral. Would a VAR with sign restrictions imposed on the responses of inflation and the policy rate only be capable of uncovering the authentic reaction of output to a monetary policy shock?"*

[6] There are important differences between this exercise and Uhlig's (2005). Uhlig (2005) also considers total reserves, non-borrowed reserves, and a commodity price index, which he exploits to identify monetary policy shocks with actual data. In contrast, our exercise deals with a world in which inflation, output, and the policy rate are the only relevant variables, and non-borrowed reserves are just unmodeled. Another important difference regards the frequency of the data, which is monthly in Uhlig's case vs. quarterly in our exercise. Therefore, our exercise should be seen as inspired by Uhlig's (2005) findings, more than else.

Evidence. Figure 1 depicts the impulse responses to a monetary policy shock obtained with sign restrictions in our in lab-exercise. It collects ten randomly drawn realizations as well as pointwise 90% response intervals. The reaction of output turns out to be quite uncertain. Realizations suggesting a "boom" after a policy tightening are all but rare. Positive realizations do not only occur on impact, but also for a number of periods after the shock. When looking at this evidence, one could hardly interpret such monetary policy shock as truly "contractionary". However, this VAR evidence is, *by construction*, consistent with a "textbook" transmission of a monetary policy shock. Such evidence occurs in spite of a positive short-run reaction of the policy rate. Notice that a large number of policy rate realizations go negative from the third quarter onward (an evidence in line with Uhlig, 2005). However, one may easily verify that the real interest rate stays positive along all the horizons considered here. Therefore, a negative long-run interest rate is not the explanation for our frequently positive response of output.

As anticipated, the ambiguous reaction of output resembles the main finding in Uhlig (2005). He documents that, with 2/3 probability, an unexpected policy tightening will move real GDP *up* on impact. Figure 2 documents the uncertainty surrounding the on-impact output reaction. Realizations are more in favor of a *positive* reaction of output, which goes against conventional wisdom. The number of positive realizations amounts to 61%, which is very close to the 2/3 figure detected by Uhlig (2005).

Of course, the advantage of conducting a Monte Carlo analysis is that of being in the position of contrasting moments obtained with a given exercise (in this case, impulse responses to a monetary policy shock identified with sign restrictions conditional on estimated VARs) with true, DGP-related moments (impulse responses conditional on the DSGE model we are working with). Figure 3 proposes this comparison. The true reactions of inflation and output (red dashed lines with diamonds) to a monetary policy shocks are negative (the zero value is outside the estimated Bayesian 90% credible set, not shown here). This is not surprising, in light of the fact that the DSGE model (1)-(3) features a standard demand channel that implies a negative correlation between the real ex-ante interest rate and output conditional on monetary policy shocks. However, all the pointwise median reactions suggested by our structural VARs differ substantially from the true responses. In particular, the reaction of output is clearly wrongly signed, and persistently so.

A possible drawback of this exercise is the way in which we compute the median VAR responses. We do so by appealing to the empirical distribution constructed with all the $\omega^{(j)}$, that induce impulse responses meeting our constraints. Fry and Pagan (2011) identify two possible drawbacks in doing so. Call $C_{ik,h}^{(j)}$ the set of responses of a variable i to a shock k at a horizon h, where j indexes the value of the estimated responses in the set of the theory-consistent models $j \in \{1, ..., J\}$. First, for a given j, $med(C_{ik,h}^{j})$ may very well be none of the selected theory-consistent models. Second, assume that all $med(C_{ik,h}^{(j)})$, $j \in \{1, ..., J\}$ are actually selected models. As a matter of fact, nothing guarantees that, for whatever pair of different (h_1, h_2), $(med(C_{ik,h_1}^{(j)}), med(C_{ik,h_2}^{(j)}))$ is generated by the same model. Fry and Pagan (2011) suggest a way to search for the single model j whose associated responses are as close as possible to the medians shown in Figure 3.[7]

The Fry-Pagan median impulse responses are also reported in Figure 3. Interestingly, negligible differences arise as for the reactions of inflation and the policy rate to a monetary policy shock. More importantly for this study, the reaction of output is also robust to the Fry-Pagan way of constructing the median, at least as for the run dynamics. The two medians start differing from the sixth quarter after the shock. The Fry and Pagan response suggests larger positive values and a delayed peak (at the seventh quarter vs. the fifth one in the case of the baseline median reaction). However, the main message is clearly confirmed when checked via the Fry-Pagan lenses, i.e., median measures suggest a positive reaction of output in a context in which, as a matter of fact, such reaction in negative. Hence, in the remainder of the paper, we will focus on the pointwise median.[8]

Importantly, what our simulations show is that, even conditional on a standard demand channel effectively being at work, an agnostic identification procedure like the one based on sign-restrictions *may* produce findings interpretable as support to the monetary neutrality hypothesis. This may happen (and, in our simulations, it does happen) even if shocks are not rare, but actually hit the economic system in each period. Moreover, our exercise shows that the evidence provided in Figures 1 and 2 is fully-consistent with a "textbook" AD-AS new-Keynesian model and the transmission

[7]In seeking for such a single model, one has to recognize that the impulses need to be made unit-free by standardizing them. This is done by subtracting from each model-specific impulse response (conditional on a given horizon h) its median and dividing such difference by the standard deviation, where the median and the standard deviation are computed across all the retained models models - see Pagan and Fry (2011, p. 950-951).

[8]We focus on the pointwise median as opposed to alternative location measures such as the average response or trimmed means because of its larger precision in this context, as discussed in Canova and Paustian (2011). As proposed by Liu and Theodoridis (2012), an alternative choice (not entertained here) would be that of selecting a unique rotation matrix on the basis of a minimum-distance criterion involving the on-impact impulse vectors of the VAR and a (possibly misspecified) DSGE models.

of monetary policy impulses embedded in it. Of course, Uhlig's (2005) evidence is *not necessarily* the outcome of an exercise conducted by employing realizations generated by an (unknown) DGP featuring a new-Keynesian Phillips curve, a dynamic IS equation, and a Taylor rule. But, in light of our exercise, this is a possibility to consider.

Understanding the drivers. What is the driver of our results? Our interpretation hinges upon the low relative contribution that monetary policy shocks exert on the variance of the forecast errors of the modeled variables. As shown in Paustian (2007) and Canova and Paustian (2011), sign restrictions work well when the contribution of the shock one aims at identifying to the volatilities of the endogenous variables is large enough with respect to variance explained by the remaining shocks, i.e., when the "signal" is strong enough. According to our estimated DSGE model, the contribution of policy shocks in explaining the forecast error variance of our variables is low, i.e., it amounts to about 10%, 4%, and 21% as for inflation, output, and the policy rate, respectively (figures referring to the variance of one-year ahead forecast errors).

If the signal associated to the monetary policy is weak, what it may happen is that the estimated "shock" is actually a combination of all the true, structural disturbances hitting the economic system. Formally, $\widehat{u}_t^R = \phi_R^R u_t^R + \phi_R^\pi u_t^\pi + \phi_R^a u_t^a$, where $\widehat{u}_t^R$ is the monetary policy shock estimated by the sign restrictions VAR, and $\phi_R^i, i = (\pi, a, R)$ are the loadings taken by the true structural shocks. As discussed in Paustian (2007) and Fry and Pagan (2011), the larger the standard deviation of the shock one is after (the monetary policy shock, in our context) with respect to the remaining ones, the smaller the loadings associated to the remaining shocks (ϕ_R^π and ϕ_R^a in this context).

Two exercises are conducted to scrutinize this hypothesis. The first one re-runs our Monte Carlo exercise by selecting some shocks out.[9] Figure 4 depicts the reaction of output in three alternative scenarios to the baseline one. The first one is the scenario in which the demand shock is suppressed (top-right panel). The outcome of this experiment should be judged by contrasting it to the baseline case (depicted in the top-right panel to ease comparability). It is possible to see that things go even worse than in the baseline scenario, in that the reaction of output as suggested by the VAR is even more distant than the one in the benchmark case. This suggests that i) the demand shock enters the linear combination which determines $\widehat{u}_t^R$, and ii) the loading ϕ_R^a is negative. In other words, $\widehat{u}_t^R$ picks up also the dynamics of output after a negative demand shock. An interesting scenario is that in which the supply shock is muted (bottom-left panel).

[9] Technically, we do so by setting the standard deviations of the shocks we aim at selecting out to $10^{-3} > 0$ to avoid singularity issues.

It is easy to see that i) the reaction of output is largely negative; ii) it suggests in fact a deeper recession than the true one. Therefore, $\widehat{u}_t^R$ picks up also the effects of a negative supply shock on output, and such shock is the responsible of the positive reaction of output in our benchmark simulations. Finally, and as expected, when the monetary policy shock is made the sole responsible of the macroeconomic volatilities in our economy (bottom-right panel), the VAR reaction perfectly recovers the true effects of a monetary policy shock. This is not surprising, in that shutting down the volatilities of the (non-policy) demand and supply shocks is equivalent to imposing $\phi_R^\pi = \phi_R^a = 0$. Consequently, $\widehat{u}_t^R$ perfectly recovers the conditional correlations induced by the true monetary policy shock u_t^R.

We conduct a second exercise to support the role of monetary policy shock's signal in our VAR context. In this exercise, the standard deviation of the monetary policy shock in our DSGE model (otherwise calibrated with our posterior means) is counterfactually inflated. Figure 5 collects the results of our simulations. Evidently, the stronger the signal, the more precise the estimation of the median effect of the monetary policy shock on output. An increase of 25% of the standard deviation of output leads to a substantial improvement in terms of (reduction of the) distance between the true response and that implied by our VAR estimates. Nevertheless, the sign of output is still wrong, also on impact. An increase of 50% of the standard deviation leads to an appreciable reduction in the "distortion", with the median reaction of output being correctly signed for the first two quarters. A (dramatic) increase of 400% of the standard deviation of the monetary policy shock in our estimated DSGE model leads to a spectacular performance by sign restrictions. Consistently, the percentage of wrongly signed output realizations falls as the signal becomes stronger. The responses of output, on impact, are wrongly signed in 46% of the cases when the standard deviation of the policy shock is scaled up by 25%, 37% of the times when it is scaled up by 50%, and just 2% of the times when the shock's standard deviation is multiplied by a factor of 5. However, this scenario features a counterfactually strong monetary policy shock, which is responsible of about 75%, 52%, and 87% of the forecast error variance of inflation, output, and the policy rate (again, these figures refer to the variance of the four-step ahead forecast errors). According to the estimates available in the literature, this is a different world with respect to the U.S. economy. Uhlig (2005) finds monetary policy shocks to be responsible of about 5-10% for the variations in real GDP at all horizons as for the period 1965-2003, monthly data. Similar estimates are proposed by Smets and Wouters (2007) with their DSGE structural analysis dealing with quarterly data, sample 1957-2004, and by Justiniano, Primiceri, and Tambalotti (2010), who analyze a similar sample. Christiano, Eichenbaum, and Evans (2005) analyze the sample 1965-1995 with a Cholesky-VAR and document a larger contribution of monetary policy shocks on output variation of about 38% (two-year ahead forecast error). However, the authors themselves advise to treat this conclusion with caution, in that the uncertainty surrounding this figure is large - the 5th percentile of the distribution suggests a much smaller contribution of about 15%. With the same methodology, Altig, Christiano, Eichenbaum, and Lindé (2011) find monetary policy shocks to be responsible for about 9% of the movements of the real GDP at business cycle frequencies in the sample period 1982-2008. Justiniano and Primiceri (2008) document the time-dependence of the contribution of such shock to output growth, but the largest realizations, which are estimated to occur in the mid-1970s and early-1980s, never exceed 15% (median values).[10]

Wrapping up, our simulations show that a possible reading of Uhlig's (2005) finding is the following. A particular set of sign restrictions imposed on VAR impulse responses may generate a very uncertain and often positive responses of output even in a world in which such responses are in line with conventional wisdom. This may occur due to the weakness of the signal associated to the policy shocks. Therefore, Uhlig's (2005) evidence if consistent with monetary policy shocks having the power of affecting the business cycle.

4 Robustness checks

We verify the robustness of our results to a number of perturbations to our baseline exercise. These perturbations consider the role of the identification of shocks other than the monetary policy shock, parameter uncertainty affecting the model employed as Data-Generating Process, the number of periods our sign restrictions are imposed, and the structure of our DGP. We analyze these perturbations in turn.

Identification of extra-shocks. Our three-equation DSGE model (1)-(3) features three shocks, i.e., a monetary policy shock, a supply (mark-up) shock directly influencing the inflation rate, and a demand (technology) shock that affects the output gap in

[10] One should however take into account the fact that these results may be due to the assumptions made when conducting the empirical investigations cited above. Faust (1998) shows that, if one is willing to search for a prior that places the largest possible mass on the impuse vector that explain the largest share of output variation, some 86% of the variance of output may be attributed to monetary policy shocks.

first place. In our baseline exercise, we appeal to the restrictions related to the monetary policy shock only. Paustian (2007) and Canova and Paustian (2011) suggest to use as many restrictions as possible to identify the effects of a given shock and distinguish it with respect to other disturbances in the economy. We then identify also the non-policy demand shock and the supply shock by imposing "textbook" sign-restrictions (consistent with our DSGE model) as indicated in Table 2. As shown in Figure 6 (top-row panels), which concentrates on the response of output, our result is robust to this perturbation of our analysis. Again, the pointwise mean reaction suggested by the VAR analysis takes the wrong sign on impact as well as in the subsequent quarters, suggesting a counterfactual positive reaction of output to a contractionary policy shock. As in our baseline case, the evidence is dramatically different when moving to an alternative world in which the standard deviation of the monetary policy shock is five times larger. In this latter case, the signal associated to the policy shock is clear enough, and the true effects on output are, as a matter of fact, recovered.

Sampling uncertainty. The analysis conducted so far deals involves two types of uncertainties, i.e., identification and sampling uncertainties. The former regards the ability of sign restrictions *per se* to recover the true effects of monetary policy shocks on output. The latter involves the discrepancies between VAR and DSGE reactions due to small-sample biases. To isolate the role played by the identification uncertainty, we rerun our exercises in population, which is shown in Figure 6 (intermediate panels). Under the benchmark calibration of the model, sign restrictions deliver a somewhat closer to zero, but still positive, reaction of output to a monetary policy shock. However, the on-impact distribution of the responses of output (not shown) implies a number of positive realizations as large as 58%. Moreover, the pointwise mean suggests counterfactually positive realizations of output after the shock as for all the quarters under scrutiny. Again, a quite different picture emerges when the signal is made much stronger, with the share of positive reaction of output dramatically falling down to zero.

Number of constrained horizons. When imposing sign restrictions, one of the key-choices is that of how many restrictions to place per each given shock/variable. Our baseline choice is $K = 2$, i.e., two periods (including the one in which the shock realizes). It is therefore of interest to check if our results are sensitive to a variation of K. We then triple it set $K = 6$. Figure 6 (bottom panels) shows that our results are robust to this perturbation. As a matter of fact, in the scenario in which the contribution of the monetary policy shock is counterfactually boosted up, the reaction of output replicates the true one just perfectly. This last result may be easily interpret in light of the fact that $K = 6$ is actually consistent with the true dynamics of output in response to a monetary policy shock in the DSGE model.

Smets and Wouters (2007) model as DGP. Our Monte Carlo results are clearly conditional on a set of assumptions, the most important one possibly being that of the DGP in place. Small-scale models like the one we employ in our baseline analysis have proved to be useful as for empirical investigations. However, they miss to consider a number of nominal and real frictions which may be relevant as for the modeling of the transmission of a monetary policy impulse to the real side of the economy and, eventually, output. Hence, we consider an alternative framework that is (one of those) currently used by central banks and research institutes, i.e., the Smets and Wouters (2007) model (see, for similar frameworks, Christiano, Eichenbaum, and Evans (2005) and Justiniano and Primiceri (2008)). We estimate this model with U.S. data, sample 1984:I-2008:II. (Our posterior estimates, along with the structure of the model, are confined to our Appendix.) Then, we calibrate such model with our posterior means and conduct our Monte Carlo exercise. Notice that, as in the case of the small-scale model, the *short-run* restrictions imposed on the responses of inflation and the policy rate are *theoretically sufficient* to achieve the identification of the monetary policy shock. This is so because, out of the seven shocks in Smets and Wouters' (2007) model, three of them (TFP shock, price mark-up shock, wage mark-up shock) induce a policy trade-off that implies a positive correlation between inflation and the policy rate in the short run. Other three shocks (risk-premium shock, investment shock, and fiscal spending shock) act as "demand" shocks, which also induce a positive correlation between inflation and the nominal interest rate in the first quarters after the shock. As a matter of fact, the only shock leading to a negative conditional correlation between inflation and the federal funds rate in the short run is the monetary policy shock.

Figure 7 (top panels) shows the outcome of our exercise. Again, when sticking to the baseline calibration, the average reaction of output (here expressed in growth rates) is at odds with respect to conventional wisdom.[11] Some 70% of the realizations of the distribution of the on-impact response of output to a monetary policy shock suggest a positive reaction. But, exactly as in the case of the small-scale model, this is a result due to the low strength of the signal associated to the monetary policy shock. If such strength is counterfactually increased, the picture changes drastically once again. In

[11] A VAR(2) is employed in these simulations. Our results are robust to the employment of a variety of alternative VAR(p) models, with p ranging from 3 to 16. Our qualitative message remains unchanged when employing either the log-level of output or the model-consistent output gap in place of the growth rate of output in our VARs.

particular, the average reaction of output as suggested by the VAR analysis nicely lines up with the true reaction as predicted by the Smets-Wouters model. The responses of inflation and the policy rate also turn out to be quite informative as for the true responses of those two variables.

Unfortunately, as already pointed out when dealing with the small-scale version of the DSGE framework, the magnified standard deviation of the monetary policy shock we deal with is clearly counterfactual. The estimated Smets and Wouters (2007) model conditional on the great moderation implies a contribution of the monetary policy shocks to output growth of about 5%, in line with the results in Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007). To have a sense of the likelihood of a larger contribution of such shock to the volatility of output, we conduct an alternative estimation in which we set the prior mean of the standard deviation of the policy shock to 0.60, a value five times as large as the one estimated in our baseline case. Moreover, we set the standard deviation of the $\mathcal{IG}$ distribution of such standard deviation of the policy shock to 0.25, much smaller than our baseline calibration (that is, 2). Our estimate of the standard deviation of the policy shock turns out to be larger, i.e., 0.16, and the contribution of such shock to the volatility of output is estimated to be twice as large, i.e., almost 10%. However, we also record a drop of the marginal likelihood of about 20 log-points, which indicates a much worse fit of the model, overall. According to our estimates, the scenario that should take place in order to have the VAR able to recover the true effects of a monetary policy shock is just very unlikely to occur.

The reason why we get a pointwise median reaction of output which is very different with respect to the one suggested by the Smets-Wouters mode in baseline scenario is that, again, the signal associated to the monetary policy shock is weak. This implies a density of reactions (satisfying our sign restrictions) that are due to a combination of shocks. Figure 8 plots the medians obtained by simulating the Smets-Wouters model in different scenarios characterized by the absence of one or more structural shocks. Shocks to the TFP, risk-premium, fiscal condition, and investment appear to exert a quantitatively negligible impact on the reaction of output (at least, when scrutinized individually) as registered by the pointwise median of the VAR responses. Differently, two supply shocks, i.e., those to the mark-ups, are clearly important drivers of such a reaction. In particular, when shutting the price mark-up shock off, the VAR gets the on impact sign right (but it overstates the impact of the policy shock), and it correctly captures the dynamic response over the horizons of interest. The wage-mark up shock clearly dampens the pointwise median response. In other words, these two shocks are wrongly picked out by our VARs act as policy shocks, while, as a matter of fact, act as negative supply disturbances. When jointly shutting these two shocks down, we actually obtain a negative reaction of output which overstates the true one (Figure not shown here for the sake of brevity). This implies that demand shocks also enter the linear combination of structural shocks which is interpreted by our VARs as pure monetary policy shocks, and they do so acting as negative demand shocks (on aggregate). Finally, and not surprisingly, when the true economy features the monetary policy shock only, the VAR is perfectly able to recover the true effects of a monetary policy innovation.

Restrictions on the response of output. An obvious way to fix the distortion affecting the response of output to a monetary policy shock would seem to be that of placing a sign restriction on the reaction of output. Of course, this is somewhat problematic for our study, whose aim is to offer a possible interpretation of the conditional correlation proposed by Uhlig (2005) that hinges upon the idea of *not* imposing such sign restriction on output - in general, if one wants to stay as agnostic as possible as regards the response of output, it seems natural not to impose any restriction on its reaction to the shock one is after. However, to have a sense of the impact of such a possible restriction, we run an exercise in which we ask our rotation matrices to return a non-positive reaction of output (on top of a non-negative reaction of the policy rate and a non-positive reaction of inflation) for the first $K = 2$ horizons. Therefore, a negative output reaction to an unexpected monetary policy tightening is now an assumption - and not a result - in the very short run. However, the remaining path of output is left unconstrained. Hence, the data are left free to tell how output behaves from the third period onward.

Figure 9 documents the outcome of our exercise, which is conducted with the small-scale new-Keynesian model as DGP. Two scenarios are proposed. The first one - top row panels - employs a calibration for our DGP in line with our estimated posterior means. An interesting result emerges. The reaction of output is estimated to be non positive for the first five periods, i.e., a longer horizon than the one involved by our sign restrictions. This is not entirely surprising, in the light of the fact that we are dealing with a VAR that well captures the persistence of the series. In other words, the "initial conditions" dictated by our sign restrictions matter for periods over those of the imposition of the signs, and work in favor of reducing the discrepancies between the true output response and the one estimated by the VAR.

Said so, evident discrepancies between the true DSGE-based responses and those estimated with our VARs are still detected. Again, this has to do with the weak signal of the policy shock. As shown by the panels at the bottom of Figure 8, in a counterfactual world in which monetary policy shocks' contribution to output volatility is (substantially) inflated, we are able to recover the correct reaction of output.

5 SRVAR with actual U.S. data

So far, what we have shown is that, in a Monte Carlo context, sign restrictions imposed on a VAR to identify a monetary policy shock tend to return output responses not necessarily in line with the true ones. This Monte Carlo evidence replicates Uhlig's (2005) result. However, Uhlig works with monthly data, a richer VAR including extra variables (total reserves, non-borrowed reserves, a commodity price index) and with a sample (1965-2003) much longer than the one we employed to estimate our DSGE models, i.e., 1984:I-2008:II. Is the VAR evidence on an uncertain reaction of output robust to the employment of a trivariate VAR modeling the U.S. inflation, output gap, and federal funds rate as for the great moderation? To answer this question, we estimate such a trivariate VAR(4) with actual U.S. data, 1984:I-2008:II, and identify a monetary policy shock by imposing the same signs imposed in our baseline Monte Carlo exercise, i.e., a non-positive reaction of inflation and a non-negative reaction of the federal funds rate for $K = 2$. Our observables are defined as in Section 2.2. The choice of including a measure of the output gap is justified by two reasons. First, Giordani (2004) shows that a VAR including a measure of potential output is likely to return less distorted impulse responses to a monetary policy shock. Second, the inclusion of the output gap in our VAR estimated with actual data makes such VAR comparable to the ones employed in our Monte Carlo experiments.

Figure 10 reports the impulse responses over different horizons. One may easily notice the huge uncertainty surrounding the response of output, which clearly resembles the one produced with our Monte Carlo experiment and presented in Figure 1. The empirical density of the on-impact response of output to a monetary policy shock is presented in Figure 11. Again, the similarity with our Monte Carlo-based Figure 2 is striking. The share of on-impact positive realizations of output is even larger than that recorder by Uhlig, in that our density suggests that eight responses out of ten take a positive value.

Our evidence reinforces the empirical result proposed by Uhlig (2005) on the uncertain reaction of output to a monetary policy shock identified with sign restrictions. In the light of our Monte Carlo simulations, this evidence is the one a researcher should actually expect when dealing with data generated by a DGP that features a non-neutral monetary policy.

6 Conclusions

Two standard new-Keynesian DSGE models of the business cycle are estimated with U.S. data and alternatively used in Monte Carlo exercises to generate artificial data with which VARs are estimated. Sign restrictions are imposed to identify the effects of a monetary policy shock with such VARs. We replicate Uhlig's (2005) evidence on the ambiguous effects of a contractionary monetary policy shock on output. We show that this result may be due to the weak signal associated to the policy shock in this environment (i.e., to the low contribution of such shock to the dynamics of output). Sign restrictions are shown to correctly identify the negative effects on output in an alternative world in which the share of output variance explained by monetary policy shocks is counterfactually magnified. A VAR estimated with actual U.S. quarterly data, 1984:I-2008:II, returns a set of responses to a monetary policy shock in line with those generated with our Monte Carlo exercises. Our results reconcile Uhlig's (2005) evidence with the conventional view on the real effects of monetary policy shocks.

After stating what this paper is about, it is worth pointing out what this paper is *not* about. This paper does *not* represent, in any manner, a "rejection" of Uhlig's (2005) empirical findings. If anything, it is quite the opposite. Uhlig's (2005) empirical result is very intriguing because it is obtained with a clean VAR-based econometric investigation. As stressed by Uhlig (2012), the challenge is that of understanding why that result is there and what it implies as for macroeconomic modelling. Our exercise suggests that a researcher who believes in monetary policy non-neutrality should expect to get empirical results in line with Uhlig's (2005) when dealing with sign-restriction VARs that do not impose any constraints on the response of output to a monetary policy shock.

Finally, our paper contains a suggestion to practitioners working with sign restrictions. Canova and Paustian (2011) suggest to use robust sign restrictions to identify shocks of interest with VAR estimated with actual data, which can then be used to assess the ability of DSGE models to replicate the VAR responses to such identified shocks. In the light of our findings, the comparison between DSGE responses and VAR responses may be problematic in presence of shocks associated to weak signals. Our suggestion is to compare the VAR responses computed with actual data and identified via robust sign restrictions à la Canova and Paustian (2011) to VAR responses computed with pseudo data generated with DSGE models and identified via the same set of sign restrictions. In other words, our suggestion is to use the class of DSGE models one is interested into not only to isolate robust sign restrictions, but also to form a correct a-priori on what a VAR exercise run with actual data may actually deliver in terms of dynamics responses.

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Param.	*Interpretation*	*Priors*	*Posterior Means* [5h,95th]
β	Discount factor	*Calibrated*	0.99 [−]
v^{-1}	Frisch elasticity	*Calibrated*	1 [−]
κ	NKPC, slope	$\mathcal{N}(0.1, 0.015)$	0.12 [0.10,0.14]
α	Price indexation	$\mathcal{B}(0.5, 0.2)$	0.09 [0.01,0.17]
γ	IS, forw. look. degree	$\mathcal{B}(0.5, 0.2)$	0.78 [0.70,0.86]
σ	Inverse of the IES	$\mathcal{N}(3, 1)$	5.19 [3.95,6.45]
τ_π	T. Rule, inflation	$\mathcal{N}(1.5, 0.3)$	2.21 [1.85,2.56]
τ_y	T. Rule, output gap	$\mathcal{G}(0.3, 0.2)$	0.16 [0.05,0.25]
τ_R	T. Rule, inertia	$\mathcal{B}(0.5, 0.285)$	0.81 [0.77,0.86]
ρ_a	AR tech. shock	$\mathcal{B}(0.5, 0.285)$	0.89 [0.84,0.94]
ρ_π	AR cost-push shock	$\mathcal{B}(0.5, 0.285)$	0.98 [0.97,0.99]
ρ_R	AR mon. pol. shock	$\mathcal{B}(0.5, 0.285)$	0.43 [0.30,0.56]
σ_a	Std. tech. shock	$\mathcal{IG}(1.5, 0.2)$	1.50 [1.10,1.91]
σ_π	Std. cost-push. shock	$\mathcal{IG}(0.35, 0.2)$	0.09 [0.07,0.11]
σ_R	Std. mon. pol. shock	$\mathcal{IG}(0.35, 0.2)$	0.14 [0.12,0.15]

Table 1: **Bayesian estimates of the DSGE model.** *1984:I-2008:II U.S. data. Prior densities: Figures indicate the (mean,st.dev.) of each prior distribution. Legend: (N, B, G, IG) stand for (Normal, Beta, Gamma, Inverse Gamma) densities. Posterior densities: Figures reported indicate the posterior mean and the [5th,95th] percentile of the estimated densities. Details on the estimation procedure provided in the text.*

Shocks\Imposed signs	π	y	R
MP shock	$\leqslant$		$\geqslant$
Supply shock	$\geqslant$	$\leqslant$	$\geqslant$
Demand shock	$\leqslant$	$\leqslant$	$\leqslant$

Table 2: **Sign restrictions to achieve structural shocks' identification.** *Identification in the baseline case achieved by imposing restrictions for K=2 and as for the monetary policy shock only. Alternative scenarios discussed in the text. The measure of output employed in our Monte Carlo experiment are discussed in the text.*

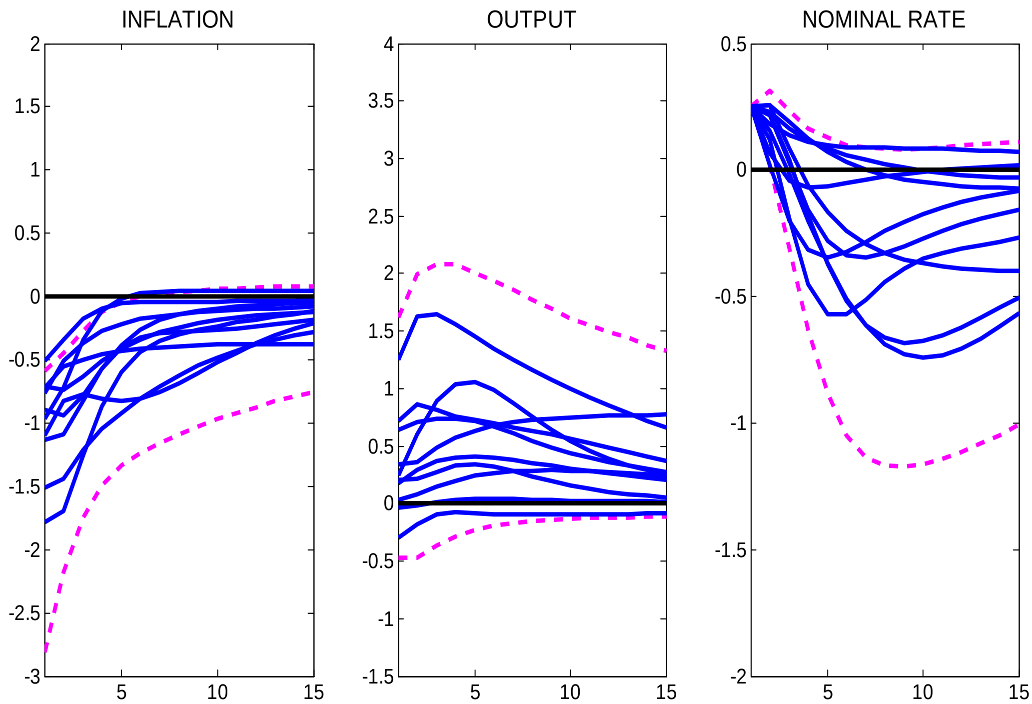

Figure 1: **Impulse response functions to a monetary policy shock identified with sign restrictions.** *Realizations conditional on sign restrictions imposed for K=2 and concerning the monetary policy shock only. Blue solid lines represent 10 randomly selected impulse responses meeting the imposed sign restrictions. Dashed magenta lines identify the 5th and 95th percentiles of the distribution. Figure based on 1,000 draws.*

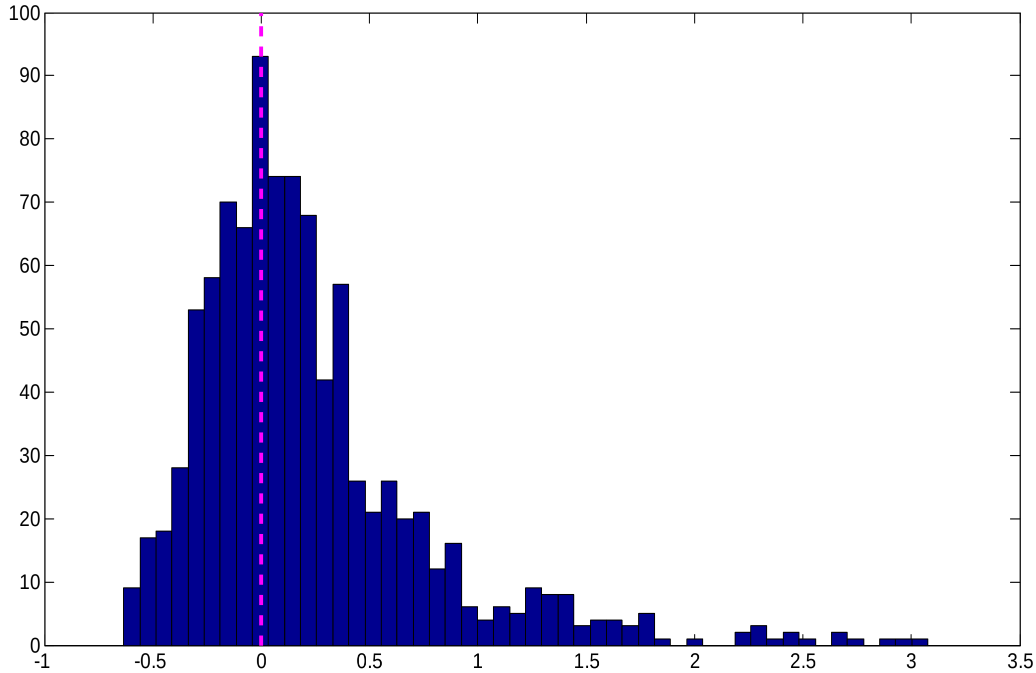

Figure 2: **On impact impulse response function of output to a monetary policy shock.** *Realizations conditional on sign restrictions imposed for K=2 and concerning the monetary policy shock only. On impact realizations (i.e., at horizon 0) only. Outliers excluded by trimming the realizations not belonging to the [2.5th,97.5th] percentiles interval out. Figure based on 1,000 draws.*

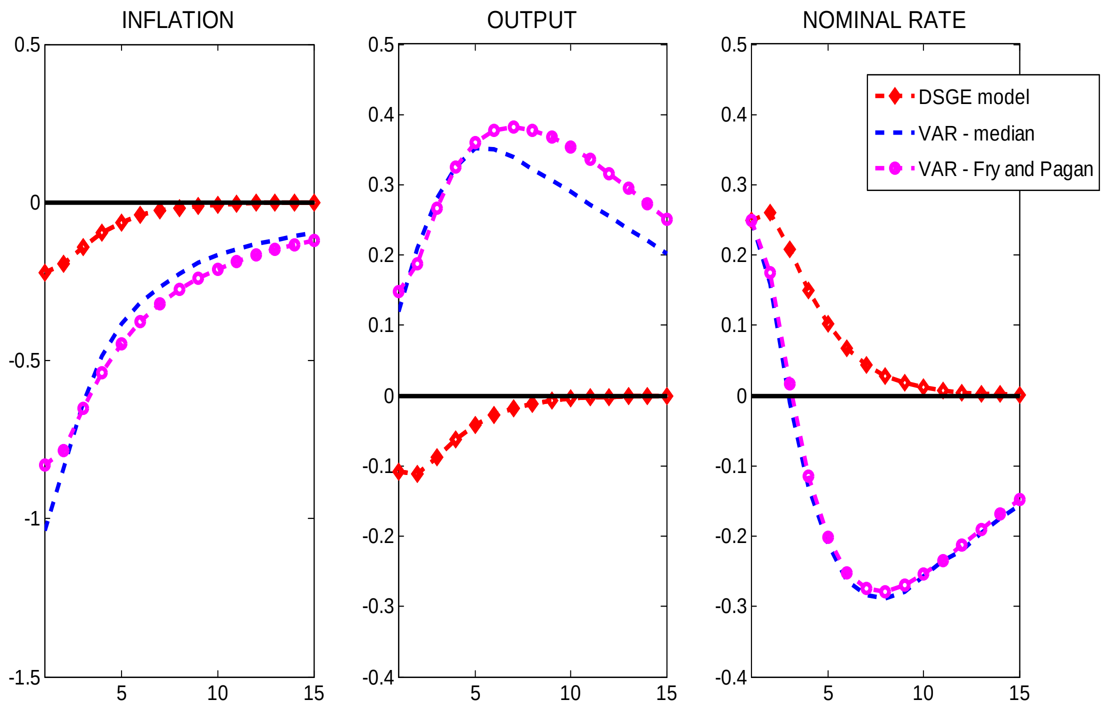

Figure 3: **Impulse responses to a monetary policy shock: DSGE vs. VAR.** *Realizations conditional on sign restrictions imposed for K=2 and concerning the monetary policy shock only. Red dashed lines with diamonds identify the reaction to a monetary policy shock conditional on the DSGE model calibrated with posterior-mean values. Blue dashed lines represent the median response across all the VAR impulse responses meeting the imposed sign restrictions. Magenta lines with circles represent the median VAR responses computed as suggested by Fry and Pagan (2011). Figure based on 1,000 draws.*

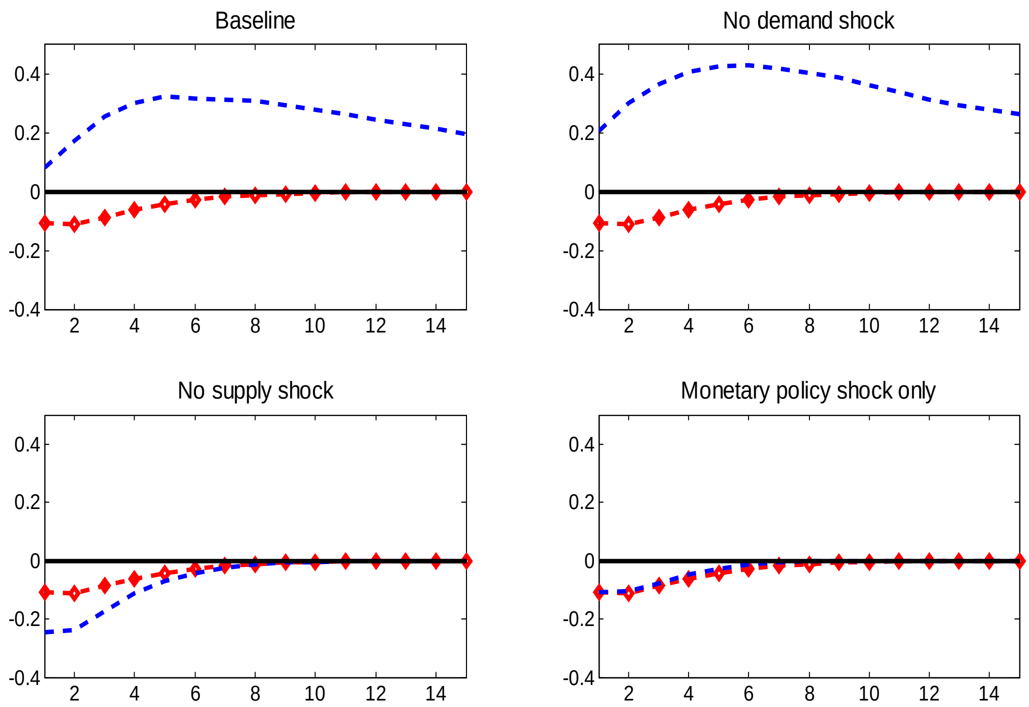

Figure 4: **Output response to a monetary policy shock: Selections of structural shocks.** *Top-left panel: Baseline case. Top-right panel: Simulations conditional on the monetary policy and supply shocks only. Bottom-left panel: Simulatios conditional on the monetary policy and demand shocks only. Bottom-right panel: Simulations conditional on the monetary policy shock only. Realizations conditional on sign restrictions imposed for K=2 and concerning the monetary policy shock only. Blue dashed lines represent the median response across all the VAR impulse responses meeting the imposed sign restrictions. Red dashed lines with diamonds identify the reaction to a monetary policy shock conditional on the DSGE model calibrated with posterior-mean values. Figure based on 1,000 draws.*

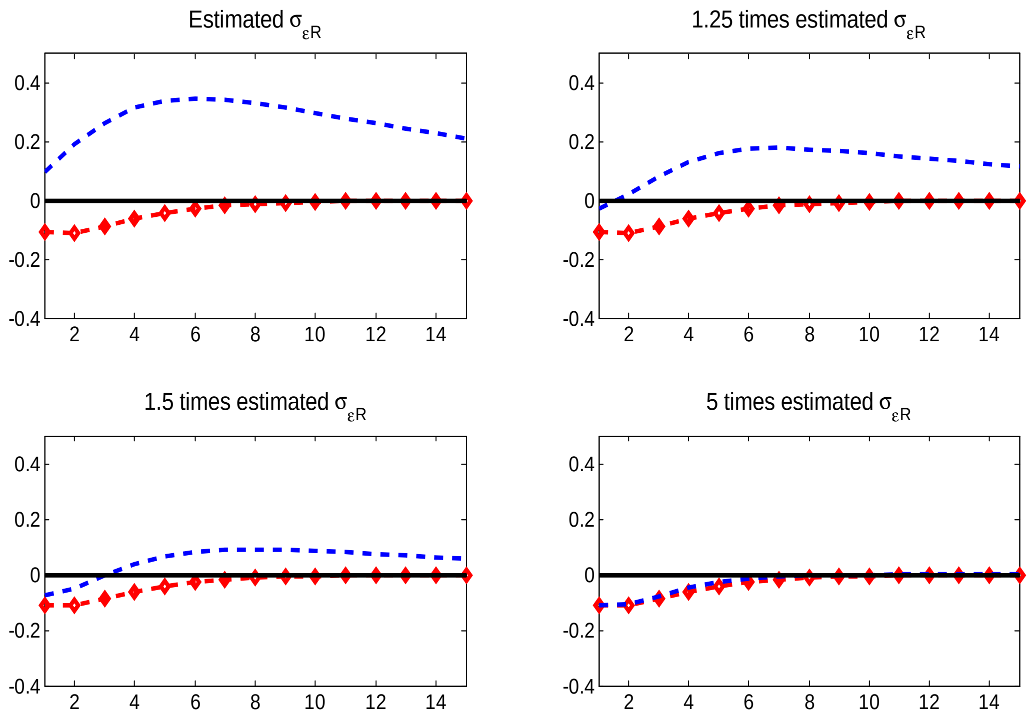

Figure 5: **Output response to a monetary policy shock: Role of the signal.** *Standard deviations of the monetary policy shock in the DGP increased by 25%, 50%, and 400% in panels [1,2], [2,1], and [2,2], respectively. Realizations conditional on sign restrictions imposed for K=2 and concerning the monetary policy shock only. Blue dashed lines represent the median response across all the VAR impulse responses meeting the imposed sign restrictions. Red dashed lines with diamonds identify the reaction to a monetary policy shock conditional on the DSGE model calibrated with posterior-mean values. Figure based on 1,000 draws.*

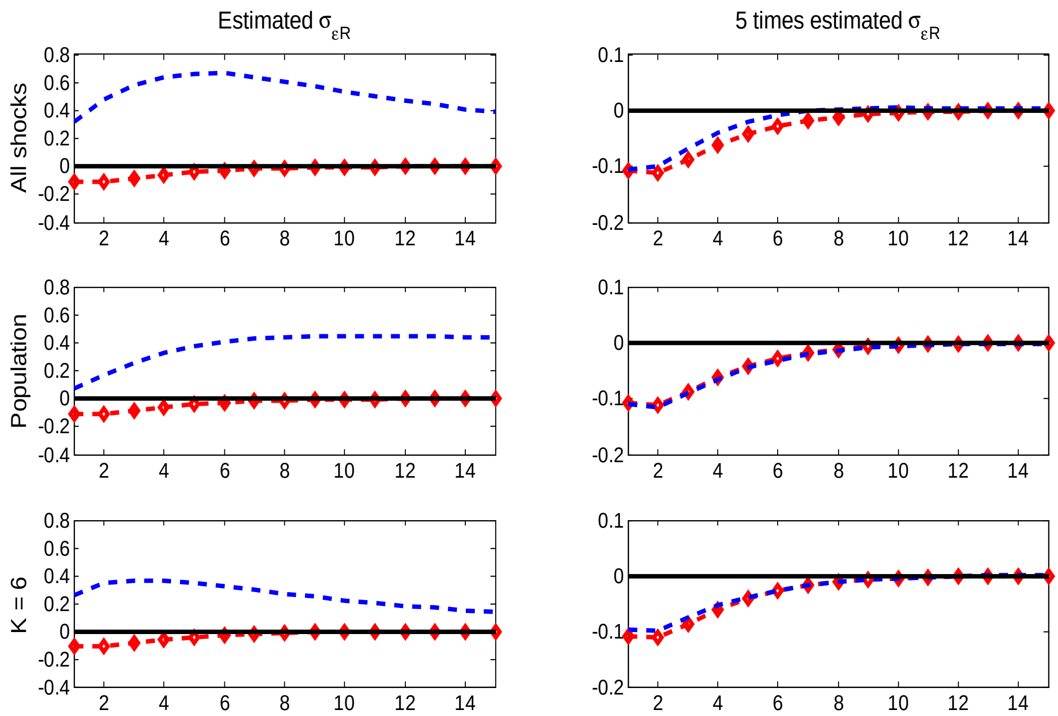

Figure 6: **Output response to a monetary policy shock: Robustness checks.** *Perturbation of the baseline case as follows. "All Shocks": All three shocks (monetary policy shock, mark-up shock, technology shock) are jointly identified. "Population": Simulations conducted conditional on a sample size equal to 10,000 observations. "K = 6": Sign restrictions imposed over the period of the shock and the following five periods. Standard deviations of the monetary policy shock in the DGP increased by 400% in panels [1,2], [2,2], and [3,2]. Realizations conditional on sign restrictions imposed for K=2 and concerning the monetary policy shock only where not otherwise specified. Blue dashed lines represent the median response across all the VAR impulse responses meeting the imposed sign restrictions. Red dashed lines with diamonds identify the reaction to a monetary policy shock conditional on the DSGE model calibrated with posterior-median values where not otherwise specified. Figure based on 1,000 draws.*

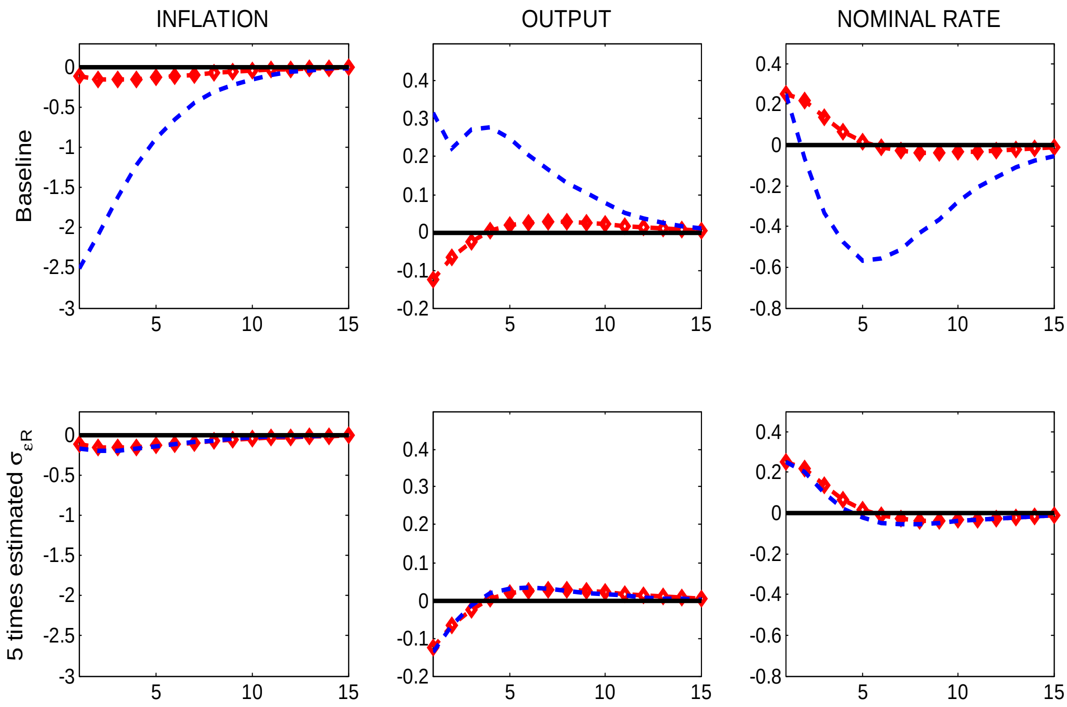

Figure 7: **Relevance of the strength of the policy shock signal in the Smets-Wouters (2007) model.** *Realizations conditional on sign restrictions imposed for K=1 and concerning the monetary policy shock only. Blue dashed lines identify the median response across all the VAR impulse responses meeting the imposed sign restrictions. Dashed red lines with diamonds: Reaction to a monetary policy shock conditional on the Smets-Wouters (2007) DSGE model calibrated with posterior-mean values. Standard deviations of the monetary policy shock in the DGP increased by 400% in panels [2,1], [2,2], and [2,3]. "Output" expressed in growth rates. Figure based on 1,000 draws.*

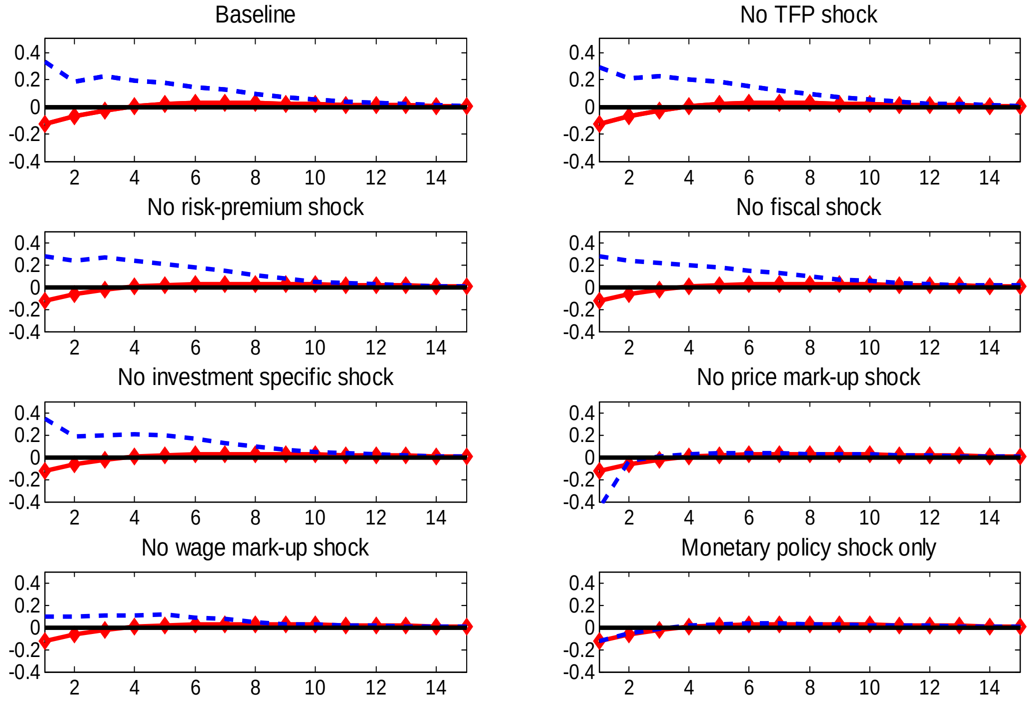

Figure 8: **Output response to a monetary policy shock: Selections of structural shocks in the Smets-Wouters model.** *Top-left panel: Baseline case, all shocks. Other panels: Perturbation of the baseline case implemented by switching off one or more shocks. Blue dashed lines represent the median response across all the VAR impulse responses meeting the imposed sign restrictions. Red dashed lines with diamonds identify the reaction to a monetary policy shock conditional on the DSGE model calibrated with posterior-mean values. Figure based on 1,000 draws.*

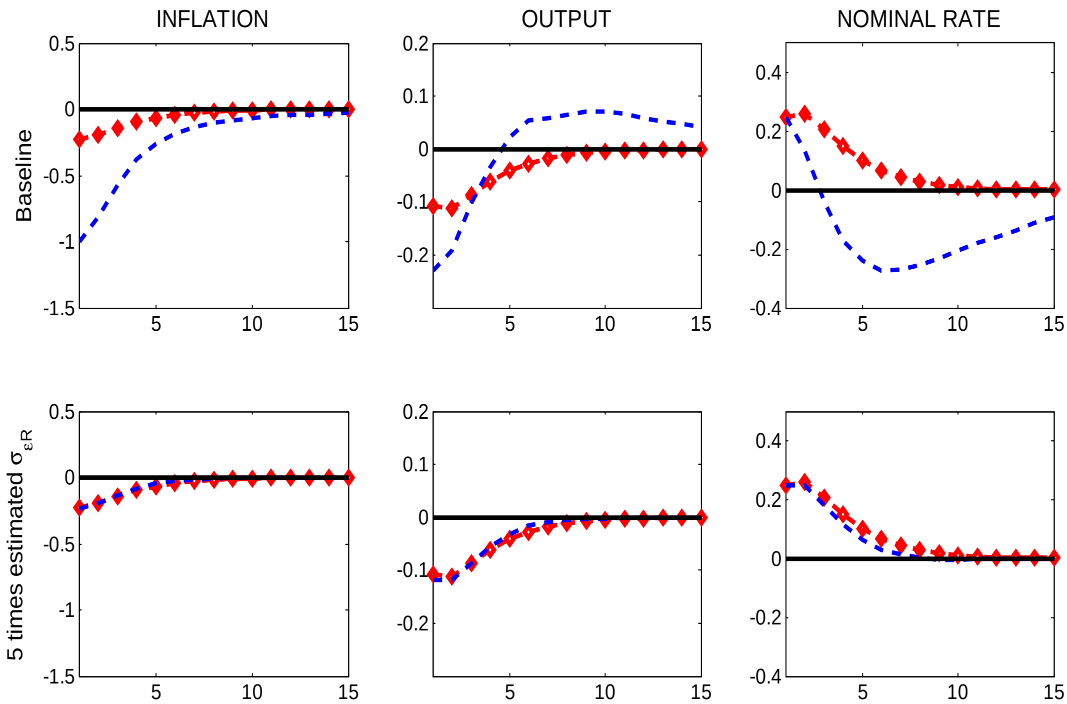

Figure 9: **Sign imposed on output, small-scale model.** *Realizations conditional on sign restrictions imposed for K=2 and concerning the monetary policy shock only. Blue dashed lines identify the median response across all the VAR impulse responses meeting the imposed sign restrictions. Dashed red lines with diamonds: Reaction to a monetary policy shock conditional on the small-scale DSGE model calibrated with posterior-mean values. Standard deviations of the monetary policy shock in the DGP increased by 400% in panels [2,1], [2,2], and [2,3]. Figure based on 1,000 draws.*

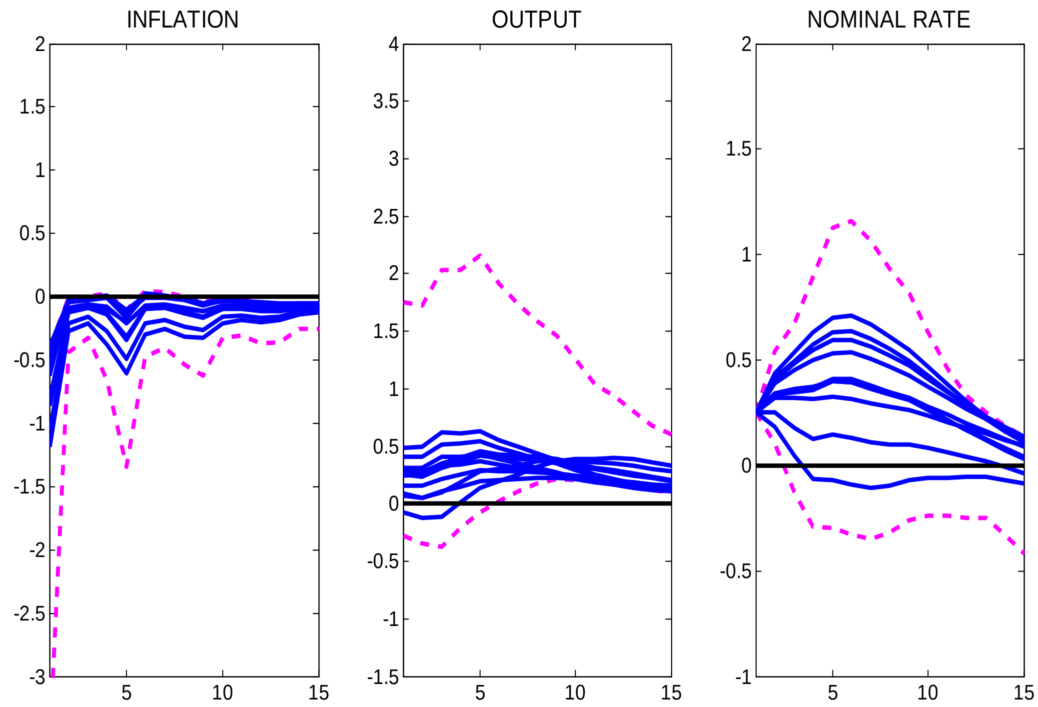

Figure 10: **Impulse response functions to a monetary policy shock identified with sign restrictions - actual U.S. data.** *Realizations conditional on sign restrictions imposed for K=2 and concerning the monetary policy shock only. Blue solid lines represent 10 randomly selected impulse responses meeting the imposed sign restrictions. Dashed magenta lines identify the 5th and 95th percentiles of the distribution. Figure based on 1,000 draws.*

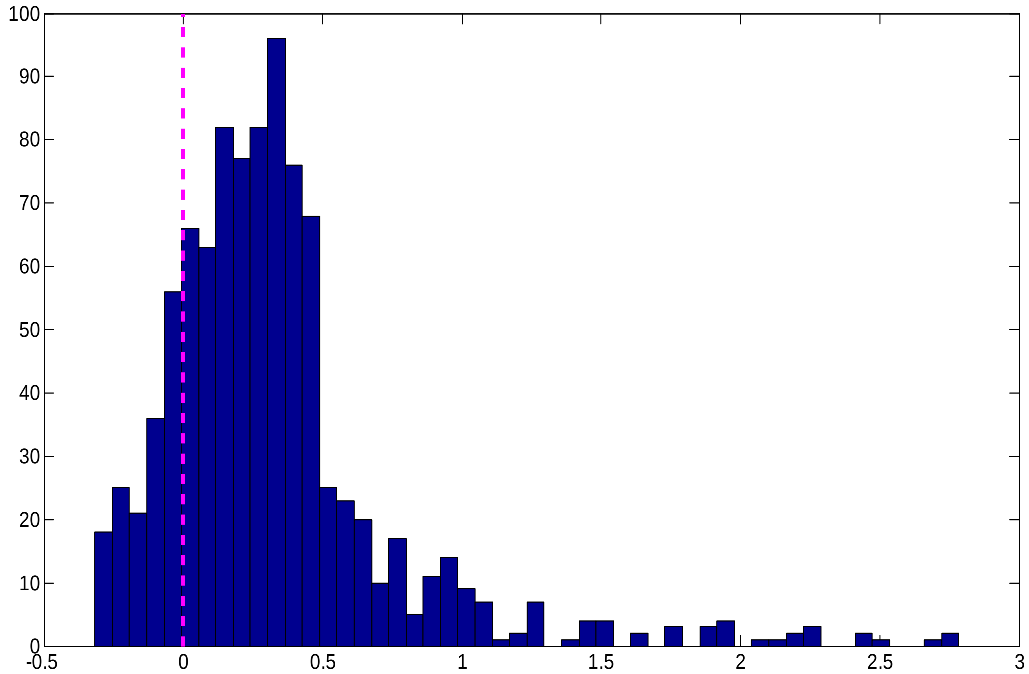

Figure 11: **On impact impulse response function of output to a monetary policy shock - actual U.S. data.** *Realizations conditional on sign restrictions imposed for K=2 and concerning the monetary policy shock only. On impact realizations (i.e., at horizon 0) only. Outliers excluded by trimming the realizations not belonging to the [2.5th,97.5th] percentiles interval out. Figure based on 1,000 draws.*