The Systematic Component of Monetary Policy in SVARs: An Agnostic Identification Procedure

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Abstract

This paper studies the effects of monetary policy shocks using structural VARs. We achieve identification by imposing sign and zero restrictions on the systematic component of monetary policy. Importantly, our identification scheme does not restrict the contemporaneous response of output to a monetary policy shock. Using data for the period 1965-2007, we consistently find that an increase in the federal funds rate induces a contraction in output. We also find that monetary policy shocks are contractionary during the Great Moderation. Finally, we show that the identification strategy in Uhlig (2005), which imposes sign restrictions on the impulse response functions to a monetary policy shock, does not satisfy our restrictions on the systematic component of monetary policy with high posterior probability.

Keywords: SVARs; Monetary policy shocks; Systematic component of monetary policy.

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1. Introduction

Following the seminal work of Sims (1980), a long literature based on structural vector autoregressions (SVARs) has consistently found that an unexpected increase in the federal funds rate induces a reduction in real activity. This intuitive result has become the cornerstone rationale behind New Keynesian dynamic stochastic general equilibrium (DSGE) models, which include a variety of nominal and real frictions to generate the contractionary effects of monetary policy shocks.

This view, however, has been challenged by Uhlig (2005). The essence of Uhlig’s (2005) critique is that conventional identification strategies impose a questionable zero restriction on the contemporaneous response of output to a monetary policy shock. Therefore, he proposes to identify a shock to monetary policy by imposing sign restrictions only on the responses of prices and nonborrowed reserves to this shock, while imposing no restrictions on the response of output. Under his identification, unexpected increases in the federal funds rate appear to be expansionary—the median posterior response of output is positive for more than three years—although the posterior probability bands of the impulse response functions (IRFs) are very wide. More recently, Ramey (2016) reiterated this critique and showed that various identification strategies—including those based on the narrative monetary surprises constructed by Romer and Romer (2004)—impose a zero contemporaneous response of output to monetary policy shocks. When this restriction is relaxed, monetary policy tightenings become expansionary in the short run.

In this paper, we propose an alternative identification scheme that identifies monetary policy shocks without restricting the response of output. In particular, we impose sign and zero restrictions on the monetary equation in order to discipline how monetary policy is systematically related to macroeconomic variables. Our approach is motivated by the fact that policy choices in general, and monetary policy choices in particular, do not evolve independently of economic conditions: “Even the harshest critics of monetary authorities would not maintain that policy decisions are unrelated to the economy” (Leeper, Sims, and Zha (1996); p. 1). Following the seminal work of Taylor (1993), interest rate rules that describe how monetary policy systematically responds to changes in output and prices have
become an essential ingredient of New Keynesian DSGE models. We follow this practice, but
instead of detailing a full-blown model in the DSGE tradition, we just impose a minimal
number of fairly uncontroversial restrictions to capture the essence of the many specifications
of the systematic component of monetary policy studied in the literature.

Our identification strategy imposes the restriction that the contemporaneous response
of the federal funds rate to an increase in output and prices be positive. We leave the
response of the federal funds rate to commodity prices unrestricted and assume that the
contemporaneous response to the remaining variables in the system is zero. The restrictions
imposed by our identification scheme encompass a large empirical and theoretical literature
on monetary policy rules. For instance, Taylor-type rules widely used in DSGE models either
postulate or estimate a positive response of the short-term interest rate to changes in prices
and output. While the sign and zero restrictions on the monetary equation that constitute the
backbone of our identification approach are intuitive and based on simple economic theory,
their implementation is not straightforward. We use the Bayesian paradigm and employ the
approach proposed by Arias, Rubio-Ramirez, and Waggoner (2018b).

The results are as follows. We find that the impulse response function of output to a
contractionary monetary policy shock is negative with high posterior probability for more than
two years. The posterior distribution of the impulse response function of prices does not rule
out the price puzzle, but has most of its mass on the negative side. The systematic response
of monetary policy to the decline in real activity and prices leads to a more accommodative
policy stance, characterized by a persistent decline in the federal funds rate that follows the
initial tightening. The IRFs of output, prices, and the federal funds rate to a monetary policy
shock are broadly consistent with those obtained in the workhorse New Keynesian DSGE
model estimated by Smets and Wouters (2007). This result is remarkable because it shows
that Smets and Wouters’ (2007) results are robust to the large class of SVARs consistent
with our restrictions. Thus, we find that a contractionary monetary policy shock is indeed
contractionary with high posterior probability while addressing Uhlig’s (2005) and Ramey’s
(2016) critique.

These results are obtained using monthly data from January 1965 to June 2007. Barakchian
and Crowe (2013) and Ramey (2016) point out that the contractionary effects of monetary policy shocks found by most identification strategies are not robust to restricting the sample to the Great Moderation. By contrast, we find that our identification does not suffer from this lack of stability; our results are robust to starting the sample in January 1983.

Our structural parameters are partially identified, because we only identify one structural shock, and set identified, because we just impose a few zero restrictions. Although partial and set identification is appealing, it is a double-edged sword. The appeal of this methodology is that results are robust to a wide range of SVARs. The drawback is that the set of structural parameters satisfying the restrictions might be very large and include structural parameters with questionable implications that have substantial impact on inference. This concern was first expressed by Kilian and Murphy (2012) using a SVAR of the global market for crude oil. Our identification strategy is not immune to this drawback, a situation we address by running a thorough sensitivity analysis. Our main result—that output drops with very high posterior probability after a monetary policy shock—is robust to various specifications of our identification scheme.

Even though the identification strategies employed in this paper and in Uhlig (2005) share important common features—both papers partially and set identify the structural parameters while imposing no restrictions on the response of output—they document different effects of monetary policy shocks. In order to gain insights into the identification of monetary policy shocks and to better understand the difference between the papers, we combine both sets of restrictions. When doing that, we find that our restrictions substantially shrink the set of structural parameters originally identified by Uhlig (2005), while the sign restrictions on the responses of prices and nonborrowed reserves have only a modest impact on our results, although, importantly, they completely eliminate the price and liquidity puzzle. More importantly, contrary to Uhlig’s (2005) findings, when we reconcile the two approaches, a contractionary monetary policy shock is indeed contractionary. This does not mean that Uhlig’s (2005) restrictions are wrong; eliminating the price and liquidity puzzle is a reasonable idea, but it may not be enough to identify monetary policy shocks.

The structure of this paper is as follows. Section 2 describes our identification scheme
and provides details about the data and the specification of the reduced-form VAR. Section 3 describes the results. Section 4 assesses how our identification scheme fares during the Great Moderation. Section 5 highlights the importance of imposing plausible restrictions on the systematic component of monetary policy by comparing our identification with Uhlig (2005). Section 6 presents some robustness exercises around our specification of the monetary policy equation. Finally, Section 7 concludes.

2. Estimation and Identification

In this section, we first describe the SVAR and characterize the systematic component of monetary policy. We then discuss our identification strategy. Finally, we describe the data, reduced-form specification, and the choice of prior distributions.

2.1. Overview

Let us consider the following SVAR

\[ y_t' A_0 = \sum_{\ell=1}^{\nu} y_{t-\ell}' A_\ell + c + \varepsilon_t' \quad \text{for } 1 \leq t \leq T, \tag{1} \]

where \( y_t \) is an \( n \times 1 \) vector of endogenous variables, \( \varepsilon_t \) is an \( n \times 1 \) vector of structural shocks, \( A_\ell \) is an \( n \times n \) matrix of structural parameters for \( 0 \leq \ell \leq \nu \) with \( A_0 \) invertible, \( c \) is a \( 1 \times n \) vector of parameters, \( \nu \) is the lag length, and \( T \) is the sample size. The vector \( \varepsilon_t \), conditional on past information and the initial conditions \( y_0, \ldots, y_{1-\nu} \), is Gaussian with mean zero and covariance matrix \( I_n \) (the \( n \times n \) identity matrix). The SVAR described in equation (1) can be written as

\[ y_t' A_0 = x_t' A_+ + \varepsilon_t' \quad \text{for } 1 \leq t \leq T, \tag{2} \]

where \( A_+ = \begin{bmatrix} A_1' & \cdots & A_{\nu}' & c' \end{bmatrix} \) and \( x_t' = \begin{bmatrix} y_{t-1}' & \cdots & y_{t-\nu}' & 1 \end{bmatrix} \) for \( 1 \leq t \leq T \). The dimension of \( A_+ \) is \( m \times n \), where \( m = n \nu + 1 \). We call \( A_0 \) and \( A_+ \) the structural parameters. The reduced-form vector autoregression (VAR) implied by equation (2) is

\[ y_t' = x_t' B + u_t' \quad \text{for } 1 \leq t \leq T, \]
where $B = A + A^{-1}, u' t = \varepsilon A^{-1},$ and $E[u_t u'_t] = \Sigma = (A_0 A'_0)^{-1}$.

It is well-known that, since the structural parameters are not identified, to recover the structural shocks we need to impose some identification restrictions. As we see next, all of our identification schemes only restrict the monetary policy equation and, consequently, they only identify the monetary policy shock. Since we only identify one shock, the SVAR is partially identified. Moreover, we impose fewer than $n - 1$ zero restrictions. Thus, as shown in Rubio-Ramírez, Waggoner, and Zha (2010), the SVAR is set identified regardless of the number of sign restrictions that are imposed.

The vast majority of the papers in the literature using set identification impose sign restrictions on the impulse response functions (IRFs). Instead, as we explain next, our identification approach imposes sign and zero restrictions directly on the structural parameters. We do so using the Bayesian approach and the techniques developed in Arias, Rubio-Ramírez, and Waggoner (2018b).

### 2.2. The Systematic Component of Monetary Policy

Leeper, Sims, and Zha (1996); Leeper and Zha (2003); and Sims and Zha (2006a) emphasize that the identification of monetary policy shocks either requires or implies the specification of the systematic component of policy, which describes how policy usually reacts to economic conditions. In order to characterize the systematic component, it is important to note that labeling a structural shock in the SVAR as the monetary policy shock is equivalent to specifying the same equation as the monetary policy equation. Without loss of generality, we let the first shock be the monetary policy shock. Thus, the first equation of the SVAR,

$$y'_{t} a_{0,1} = \sum_{\ell=1}^{\nu} y'_{t-\ell} a_{\ell,1} + \varepsilon_{1t} \quad \text{for } 1 \leq t \leq T,$$

(3)

is the monetary policy equation, where $\varepsilon_{1t}$ denotes the first entry of $\varepsilon_t$, $a_{\ell,1}$ denotes the first column of $A_\ell$ for $0 \leq \ell \leq \nu$, and $a_{\ell,ij}$ denotes the $(i,j)$ entry of $A_\ell$ and describes the systematic component of monetary policy. From equation (3), it is clear that restricting the systematic component of monetary policy is equivalent to restricting $a_{\ell,1}$ for $0 \leq \ell \leq \nu$. We now turn to the description of our identification scheme.
2.3. The Identification Scheme

Our identification scheme is motivated by Taylor-type monetary policy rules widely used in DSGE models and, within the SVAR literature, is consistent with Christiano, Eichenbaum, and Evans (1996), who assume that the monetary authority can react contemporaneously to changes in economic activity and prices. To implement our identification, our reduced-form VAR specification, which we describe in detail in Section 2.4, consists of six endogenous variables: output, $y_t$; prices, $p_t$; commodity prices, $p_{c,t}$; total reserves, $tr_t$; nonborrowed reserves, $nbr_t$; and the federal funds rate, $r_t$. This selection of endogenous variables is standard in the empirical literature and has been used by, among others, Christiano, Eichenbaum, and Evans (1996); Bernanke and Mihov (1998); and Uhlig (2005).

Restriction 1. The federal funds rate is the monetary policy instrument and it only reacts contemporaneously to output, prices, and commodity prices.

Restriction 1 comprises two parts. The first part—which imposes the restriction that the federal funds rate is the policy instrument—is supported by empirical and anecdotal evidence. As documented by Sims and Zha (2006b), except for two short periods in the early 1970s and between 1979 and 1982—when the Federal Reserve explicitly targeted nonborrowed reserves—monetary policy in the U.S. since 1965 can be characterized by a direct or indirect regime targeting the federal funds rate, even though the federal funds rate has only formally been the Federal Reserve’s policy instrument since 1997.2

The second part imposes the restriction that the federal funds rate does not react to changes in reserves. Bernanke and Blinder (1992) and Christiano, Eichenbaum, and Evans (1996) include reserves in their specifications because in the mid-1990s—before the literature settled on the federal funds rate—they were viewed as alternative instruments for characterizing the conduct of monetary policy. Nevertheless, also in these papers, in the specifications that assume that the federal funds rate is the monetary policy instrument, reserves do not contemporaneously enter the monetary equation.

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2This is consistent with the view that nonborrowed reserves were used as an explicit policy instrument only in the early 1980s.
We complement Restriction 1 with qualitative restrictions on the response of the federal funds rate to economic conditions, which we summarize as follows:

**Restriction 2.** *The contemporaneous reaction of the federal funds rate to output and prices is positive.*

Restriction 2 imposes the condition that the central bank contemporaneously increases the federal funds rate in response to an contemporaneous increase in output and prices, while leaving the response to commodity prices unrestricted as in Christiano, Eichenbaum, and Evans (1996). The implied timing assumption deserves some justification. When central banks decide how to set the policy rate, they do not have data on output and prices available for the current month. Nonetheless, central banks have access to an enormous amount of real-time indicators (weekly employment reports, business surveys, financial market data) to learn about the current state of real activity and prices. In our identification, rather than modeling this complex information acquisition process or using Greenbook forecasts as in Romer and Romer (2004), we simply assume that the central bank has access to data on output and prices within a month.

Restriction 2 imposes sign restrictions on the systematic response of monetary policy rules to output and prices that are also consistent with monetary rules embedded in DSGE models. Yet, the implementation of this restriction does not exploit, nor require, a one-to-one mapping between the structural parameters of the VAR and DSGE models. We impose sign restrictions on these coefficients—as opposed to exact restrictions—precisely because they encompass different specifications of the monetary policy rule used in the DSGE literature.

Since our identification concentrates on the contemporaneous structural parameters, we can rewrite equation (3), abstracting from lag variables, as

\[ r_t = \psi_y y_t + \psi_p p_t + \psi_{pc} p_{c,t} + \psi_{tr} r_t + \psi_{nbr} nbr_t + \sigma \varepsilon_{1,t}, \]

where \( \psi_y = -a_{0.61}^{-1} a_{0.11}, \psi_p = -a_{0.61}^{-1} a_{0.21}, \psi_{pc} = -a_{0.61}^{-1} a_{0.31}, \psi_{tr} = -a_{0.61}^{-1} a_{0.41}, \psi_{nbr} = -a_{0.61}^{-1} a_{0.51}, \) and \( \sigma = a_{0.61}^{-1}. \) Equipped with this representation of the monetary policy equation,
we summarize Restrictions 1 and 2 as follows.\(^3\)

**Remark 1.** Restriction 1 implies that \(\psi_{tr} = \psi_{nbr} = 0\), while Restriction 2 implies that \(\psi_y, \psi_p > 0\). At the same time, \(\psi_{pc}\) remains unrestricted.

Remark 1 makes clear that Restrictions 1 and 2 only restrict the structural parameters and set and partially identify the SVAR; this is a key departure from Christiano, Eichenbaum, and Evans (1996), who instead exactly and fully identify the SVAR. Thus, we allow for a set of SVARs to be compatible with the sign and zero restrictions rather than a single one.

### 2.4. Dataset, Reduced-Form VAR, and Prior Specification

Our dataset contains monthly U.S. data for the following variables: real GDP (for output), the GDP deflator (for prices), a commodity price index (for commodity prices), total reserves, nonborrowed reserves, and the federal funds rate. The monthly time series for real GDP and the GDP deflator are constructed using interpolation of the corresponding quarterly time series, as in Bernanke and Mihov (1998) and Mönch and Uhlig (2005). Real GDP is interpolated using the industrial production index, while the GDP deflator is interpolated using the consumer price index and the producer price index. The commodity price index is from Global Financial Data and corresponds to monthly averages of daily data. The remaining variables are retrieved from FRED, Federal Reserve Bank of St. Louis, using the following mnemonics: BOGNONBR (nonborrowed reserves), CPIAUCSL (consumer price index), FEDFUNDS (the federal funds rate), GDPC1 (real GDP), GDPDEF (GDP deflator), INDPRO (industrial production index), PPIFGS (producer price index), and TRARR (total reserves adjusted for changes in reserve requirements). All variables are seasonally adjusted except for the commodity price index and the federal funds rate.

The sample starts in January 1965 and ends in June 2007. This conservative cutoff ensures that we do not capture in our estimates the effects of the global financial crisis and

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\(^3\)Belongia and Ireland (2015) estimate a VAR with time-varying parameters and characterize changes in the Federal Reserve’s systematic component from 2000 to 2007. To do this, they use a representation of the monetary policy equation similar to equation (4) and the coefficients are identified by imposing a Cholesky ordering. Aastveit, Furlanetto, and Loria (2016) use a related approach to analyze whether the Federal Reserve’s systematic component has reacted to financial variables.
of unconventional monetary policy.\textsuperscript{4} Results reported in the following sections are robust to repeating the analysis using data at quarterly frequency. The reduced-form VAR specification uses 12 lags and does not include any deterministic term.

For the estimation of the model, we use a uniform-normal-inverse-Wishart distribution for the priors over the orthogonal reduced-form parameterization. As explained in Arias, Rubio-Ramirez, and Waggoner (2018b), the uniform-normal-inverse-Wishart distribution is characterized by four parameters; $UNIW(\nu, \Phi, \Psi, \Omega)$. Our choice of prior density parameterization is $\nu = 0$, $\Phi = 0_{n \times n}$, $\Psi = 0_{n \nu \times n \nu}$, and $\Omega^{-1} = 0_{n \nu \times n \nu}$. This parameterization, which is common in the literature, results in prior densities that are equivalent to those in Uhlig (2005). Nonetheless, our results are robust to using other parameterizations discussed in Arias, Rubio-Ramirez, and Waggoner (2018b).

3. Main Results

In this section, we describe our results. We first present the IRFs to a contractionary monetary policy shock, and then we discuss the estimated monetary policy equation associated with our identification scheme.\textsuperscript{5}

The solid lines in Figure 1 show the posterior point-wise median IRFs of the endogenous variables to a contractionary monetary policy shock, while the blue-shaded bands represent the corresponding 68 and 95 percent posterior probability bands. A contractionary monetary policy shock leads to an immediate median increase in the federal funds rate of around 20 basis points. The significant tightening in monetary policy leads to an immediate drop in output and to a protracted decline in prices. The response of output is negative with a high posterior probability for the first 18 months after the shock, and a zero response is almost at the boundary of the 95 percent confidence set near the trough, which occurs about 8 months after the shock. The response of prices is less precisely estimated, and there is a posterior

\textsuperscript{4}See for instance Brunnermeier (2009).

\textsuperscript{5}All results are based on 10,000 draws from the posterior distribution of the structural parameters and all shocks are of size one standard deviation. We report point-wise medians and posterior probability bands. We normalize the IRFs by imposing the restriction that the federal funds rate increase on impact in response to a contractionary monetary policy shock and that $\sigma > 0$. 

Figure 1: Impulse Responses to a Monetary Policy Shock

Note: IRFs to a one standard deviation contractionary monetary policy shock identified using Restrictions 1 and 2. The solid lines depict the point-wise posterior medians responses and the shaded bands represent the 68 and 95 percent equal-tailed point-wise posterior probability bands.

probability mass on structural models that imply the price puzzle. Yet, in Section 6 we show that imposing an additional zero restriction on the response of monetary policy to commodity prices is sufficient to reduce the posterior probability of models implying a rise in prices while leaving the response of output unchanged.

Following the decline in output and prices, the monetary authority loosens its stance shortly after the intervention, in line with our assumptions on the systematic component of monetary policy. The response of commodity prices is close to zero and not precisely estimated. On the reserves side, the median impact response of total and nonborrowed reserves is negative on impact and virtually zero thereafter.

The IRFs of output, prices, and the federal funds rate to a contractionary monetary policy shock depicted in Figure 1 share some important similarities to those documented in Figure 6, page 601, of Smets and Wouters (2007). The response of inflation to a contractionary

\[ \text{While in Smets and Wouters (2007) the monetary policy shock follows an AR(1) process, our IRFs are based on an i.i.d shock. Even so, in practice the difference is small, as the posterior for the AR(1) coefficient} \]
monetary policy shock builds up to a response of the price level roughly in line with what was reported in Figure 1. The shape of the response of output and the undershooting of the federal funds rate are also features shared by the two figures. This resemblance is important because it shows that the results in Smets and Wouters (2007), which they obtain by estimating a DSGE model that imposes several micro-founded cross-equation restrictions, are robust to the large class of SVARs that satisfy our minimal set of restrictions on the monetary policy equation.

Table 1 shows the posterior estimates of the contemporaneous coefficients for the monetary policy equations. Under our identification, the posterior medians of $\psi_y$ and $\psi_p$ are 0.84 and 2.73, respectively. That is, the federal funds rate reacts nearly one-to-one to contemporaneous movements in output and more than one-to-one to contemporaneous movements in prices. The posterior median of $\psi_{pc}$ is $-0.02$ and the coefficients on reserves are, by construction, equal to zero. Thus, our identification implies estimated coefficients of the systematic component of monetary policy that are broadly in line with conventional estimates found, for instance, in the DSGE literature. Not surprisingly, as we only impose sign restrictions, the support of the posterior distributions for these coefficients is wide. For this reason, in Section 6 we show that our results are robust to complementing the sign restrictions with upper bounds on the distribution of these coefficients.

In combination, our results show that, given our restrictions on the systematic component in Smets and Wouters (2007) has most of its mass on values below 0.25.
of monetary policy, contractionary monetary policy shocks induce a decline in real activity with high posterior probability. Moreover, given our identification scheme, the results are consistent with the effects of contractionary monetary policy shocks as documented in estimated DSGE models. In the next section we unveil why our results are substantially different from those in Uhlig (2005).

4. Monetary Policy during the Great Moderation

Ramey’s (2016) critical review of the literature on the identification of monetary policy shock raises two main concerns that challenge the consensus about the real effects of monetary policy. Her first concern—revitalizing Uhlig’s (2005) original critique—is that various identification strategies find contractionary effects of monetary policy only when imposing a zero restriction on the response of output to a monetary policy shock. We extensively discussed this issue in the previous section, where we showed that our identification does not hinge on such a restriction to find contractionary effects of monetary policy. Her second concern is sample stability. Most papers whose identification schemes imply a decline in output following a contractionary monetary policy shock when estimated on datasets starting in the 1960s imply the opposite result when estimated over the Great Moderation—that is, from the mid 1980s to 2007. For example, Ramey (2016) shows that Coibion’s (2012) identification scheme on data from 1983 to 2007 implies an expansion of industrial production in response to a contractionary monetary policy shock. This lack of robustness of standard identification schemes is also documented in Barakchian and Crowe (2013), who propose a new identification based on high frequency monetary policy surprises. Their identification implies contractionary effects of monetary policy during the Great Moderation.

In this section, we address this concern by applying our identification strategy, which consists of Restrictions 1 and 2, to the VAR model described in Section 2.4 but estimated on a shorter sample. In particular, we change the starting date of the sample to 1983:M1.

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7Similarly, Barakchian and Crowe (2013) show that Christiano, Eichenbaum, and Evans’s (1996) identification scheme applied to data from 1988 to 2007 implies that industrial production increases in response to a contractionary monetary policy shock.
so that the resulting sample spans the Great Moderation and a constant monetary policy regime, excluding years in which the Federal Reserve abandoned targeting the federal funds rate Coibion (2012); Ramey (2016).

Figure 2 plots the IRFs to a one standard deviation monetary policy shock. The contour of the IRFs is qualitatively similar to those reported in Figure 1. Importantly, monetary policy is contractionary, even though the median decline is smaller than in the full sample. The response of the federal funds rate to a monetary policy shock is also smaller compared to the response estimated for the full sample. The reason is a considerable decline in \( \sigma \), the standard deviation of the monetary policy shock described in Equation (4), which drops from 0.9 for the full sample to 0.3 for the Great Moderation. Thus, our identification is consistent with the conventional wisdom of a more systematic conduct of monetary policy by the Federal Reserve during the Great Moderation relative to the 1960s and 1970s. A key implication of our results is that, while during the Great Moderation monetary policy shocks might have
played a smaller role in driving business cycle fluctuations, their efficacy remained elevated: the impact elasticity of output to the federal funds rate, calculated as the ratio of the impact responses of output and the federal funds rate, is $-2.3$, against $-0.8$ for the full sample. An output elasticity of about $-2$ for the Great Moderation period is in line with the results in \textit{Gertler and Karadi (2015)}, whose sample spans both the Great Moderation and the global financial crisis.

Finally, Figure 2 also shows that, in response to a monetary policy shock, prices fall with higher posterior probability compared to the full sample. The result that only a small fraction of posterior draws imply the price puzzle contrasts with many identification schemes used in the literature, including the high frequency identification of \textit{Barakchian and Crowe (2013)}, who find either a positive or muted response of prices to monetary policy.

\section{Systematic Component of Monetary Policy in Uhlig (2005)}

In this section, we study the importance of imposing our restrictions on the systematic component of monetary policy for the identification of monetary policy shocks. To this end, we compare our identification to that of \textit{Uhlig (2005)}. This is a natural comparison because, while both approaches partially and set identify the SVAR, have the same prior density over the structural parameters, and do not impose any restriction on the response of output to monetary policy shocks, they imply markedly different results. While we find that the median response of output after a contractionary monetary policy shock is negative, \textit{Uhlig (2005)} finds a positive median response.

The comparison revolves around two exercises. First, we show that an identification strategy that combines \textit{Uhlig’s (2005)} sign restrictions on IRFs with our restrictions on the systematic component of monetary policy recovers the conventional response of output. Second, we rationalize this finding by showing that the systematic component of monetary policy implied by \textit{Uhlig’s (2005)} sign restrictions does not satisfy our restrictions on the systematic component. For this comparison we use data between 1965:M1–2003:M:12.

Before discussing the details of our analysis, let us briefly summarize \textit{Uhlig’s (2005)} restrictions for the sake of completeness. \textit{Uhlig (2005)} identifies monetary policy shocks by
imposing the following sign restrictions on IRFs.

**Restriction 3.** *A monetary policy shock leads to a negative response of prices, commodity prices, and nonborrowed reserves, and to a positive response of the federal funds rate, all at horizons $t = 0, \ldots, 5$.

Restriction 3 rules out the price puzzle (a positive response of prices following a monetary contraction) and the liquidity puzzle (a positive response of monetary aggregates). The solid lines in Figure 3 show the posterior median IRFs of the endogenous variables to a contractionary monetary policy shock under Restriction 3, while the shaded bands represent the corresponding 68 and 95 percent posterior probability bands. Figure 3 shows that, in response to a contractionary monetary policy shock identified only by imposing Restriction 3, neutrality of monetary policy shocks is not inconsistent with the data. Uhlig (2005) interprets this finding as evidence that the drop in output found in standard monetary SVAR models is linked to the Cholesky assumption that output does not respond contemporaneously to a monetary policy shock. In what follows we argue that our restrictions on the systematic component of monetary policy generate monetary non-neutrality without the need for this controversial zero restriction.

To this end, we explore the implications of combining Uhlig’s (2005) restrictions with our restrictions on the systematic component of monetary policy. As Arias, Rubio-Ramirez, and Waggoner (2018b) point out, the set of structural parameters identified by imposing both sign and zero restrictions—as in our identification—is of measure zero in the set of structural parameters identified by imposing only the sign restrictions as in Uhlig (2005). That is, the set of structural parameters that satisfy Restriction 3 violates Restriction 1 by construction. Thus, to understand the relative importance of the sign and zero restrictions on the systematic component of monetary policy, we first explore an identification that combines Restrictions 1 and 3.

The solid lines in Panel (a) in Figure 4 plot the posterior median IRFs of selected endogenous variables to a contractionary monetary policy shock under Restrictions 1 and 3, while the shaded bands represent the corresponding 68 and 95 percent posterior probability.
Figure 3: Impulse Responses to a Monetary Policy Shock

**Uhlig’s (2005) Identification**

![Impulse Response Diagrams](image)

**Note:** IRFs to a one standard deviation contractionary monetary policy shock identified using Restriction 3, corresponding to Uhlig’s (2005) identification scheme. The solid lines depict the point-wise posterior medians and the shaded bands represent the 68 and 95 percent equal-tailed point-wise posterior probability bands.

Compared to Figure 3, these restrictions are associated with a stronger positive response of output to a contractionary monetary policy shock during the first year. The IRFs of prices and the federal funds rate are both qualitatively and quantitatively similar to those reported in Figure 3. Thus, the zero restrictions we impose on the systematic response of monetary policy to reserves play a minor role in shaping the effects of a monetary policy shock.

Panel (b) in Figure 4 plots the posterior median IRFs of selected endogenous variables to a contractionary monetary policy shock under Restrictions 1, 2, and 3, that is, by combining Uhlig’s (2005) and our identification, while the shaded bands represent the corresponding 68 and 95 percent posterior probability bands. Under this identification, the median response of output is negative and the posterior probability bands are concentrated in negative numbers. Hence, we find that, even in combination with Uhlig’s (2005) restrictions on IRFs, an identification scheme that includes sign restrictions on $\psi_y$ and $\psi_p$ recovers a negative response...
Figure 4: Impulse Responses to a Monetary Policy Shock

(a) Responses to monetary policy shocks based on Restrictions 1 and 3

(b) Responses to monetary policy shocks based on Restrictions 1, 2, and 3

Note: IRFs to a one standard deviation contractionary monetary policy shock. The solid lines in panel (a) depict the point-wise posterior median responses identified using the sign restrictions on IRFs described in Restriction 3 and the zero restrictions on the systematic component described in Restriction 1, while those in panel (b) depict the posterior median responses identified using the restrictions on IRFs described in Restriction 3 and the zero and sign restrictions on the systematic component described in Restrictions 1 and 2; the shaded bands represent the 68 and 95 percent equal-tailed point-wise posterior probability bands.

To understand these results, the first row of Table 2 reports the posterior estimates of the contemporaneous coefficients on the monetary policy equation implied by Uhlig (2005). The posterior median of the output coefficient is $-0.35$ and the posterior distribution puts a sizable weight on negative values. Hence, Uhlig’s (2005) identification scheme implies a negative response of the federal funds rate to output. In addition, the posterior median responses of the federal funds rate to reserves are positive but small and not precisely estimated, so
### Table 2: Contemporaneous Coefficients in the Monetary Policy Equation
Identifications Based on Uhlig (2005)

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>$\psi_y$</th>
<th>$\psi_p$</th>
<th>$\psi_{pc}$</th>
<th>$\psi_{tr}$</th>
<th>$\psi_{nbr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Restriction 3[^a]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>-0.35</td>
<td>2.30</td>
<td>0.12</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>68% Prob. Interval</td>
<td>[-2.27; 0.91]</td>
<td>[-0.58; 7.19]</td>
<td>[-0.01; 0.37]</td>
<td>[-0.48; 0.72]</td>
<td>[-0.44; 0.70]</td>
</tr>
<tr>
<td>95% Prob. Interval</td>
<td>[-12.31; 13.97]</td>
<td>[-31.42; 33.65]</td>
<td>[-1.62; 1.76]</td>
<td>[-2.98; 3.89]</td>
<td>[-4.86; 4.01]</td>
</tr>
<tr>
<td><strong>Restrictions 1 &amp; 3[^b]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>-0.57</td>
<td>2.15</td>
<td>0.12</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>68% Prob. Interval</td>
<td>[-2.43; 0.22]</td>
<td>[ 0.64; 4.87]</td>
<td>[ 0.03; 0.31]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>96% Prob. Interval</td>
<td>[-11.20; 1.43]</td>
<td>[-2.58; 14.43]</td>
<td>[-0.05; 1.12]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** The entries in the table denote the posterior medians estimate of the contemporaneous coefficients in the monetary policy equation corresponding to two identification strategies. The 68 and 95 percent equal-tailed posterior probability intervals are reported in brackets. See the main text for details. [^a] Sign restrictions on IRFs as in Uhlig (2005). [^b] Sign restrictions on IRFs as in Uhlig (2005) and zero restrictions on the systematic component of monetary policy as described in Restriction 1.

That large positive and negative coefficients are included in the set of admissible structural parameters. By contrast, the median response of the federal funds rate to prices is estimated to be 2.30 and the 68 percent probability interval contains mostly positive values, yet the 95 percent probability interval exhibits significant uncertainty. As shown in the second row of Table 2, under Restrictions 1 and 3, the posterior distribution of $\psi_y$ shifts to the left, making negative values considerably more likely. The negative values in the posterior distribution of $\psi_y$ seem to induce the positive response of output to the monetary policy shock documented in Figure 3 and in Panel (a) of Figure 4.

Table 3 tabulates the posterior probabilities that the structural parameters consistent with Uhlig’s (2005) restrictions violate the sign and zero restrictions imposed by our identification. The first row confirms that the set of structural parameters that satisfy Restriction 3 implies $\psi_{tr} \neq 0$ and $\psi_{nbr} \neq 0$, thus violating Restriction 1. The posterior probabilities of drawing a negative coefficient on output and prices are 0.63 and 0.19, respectively, and the posterior
Table 3: Probability of Violating Restrictions Imposed by Our Identification

<table>
<thead>
<tr>
<th>Probability</th>
<th>(P(\psi_{tr} \neq 0 \cup \psi_{nbr} \neq 0))</th>
<th>(P(\psi_y &lt; 0))</th>
<th>(P(\psi_p &lt; 0))</th>
<th>(P(\psi_y &lt; 0 \cup \psi_p &lt; 0))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Restriction 3(^{[a]})</td>
<td>1.00</td>
<td>0.63</td>
<td>0.19</td>
<td>0.76</td>
</tr>
<tr>
<td>Restrictions 1 &amp; 3(^{[b]})</td>
<td>0.00</td>
<td>0.75</td>
<td>0.08</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Note: The entries in the table denote the individual and joint probabilities of two identification strategies based on Uhlig (2005) of violating the zero and sign restrictions on the coefficients of the monetary policy equation imposed by our identification. See the main text for details. \(^{[a]}\) Sign restrictions on IRFs as in Uhlig (2005). \(^{[b]}\) Sign restrictions on IRFs as in Uhlig (2005) and zero restrictions on the systematic component of monetary policy as described in Restriction 1.

The probability of violating Restriction 2 is 0.76. The second row tabulates the same posterior probabilities under the identification that combines Restrictions 1 and 3. The posterior probability of drawing a negative coefficient on output is 0.75, more than 10 percentage points higher than when we impose only Restriction 3. The posterior probability of drawing a negative coefficient on prices drops to 0.08, and the posterior probability of violating Restriction 2 is 0.77—marginally higher than the one reported in the first row.

In combination, Tables 2 and 3 show that most of the structural parameters included in the set identified by Uhlig (2005) imply a systematic component of monetary policy that violates the sign and zero restrictions that we impose in our identification. If one agrees with our restrictions, following Leeper, Sims, and Zha (1996); Leeper and Zha (2003); and Sims and Zha (2006a), a corollary to these findings is that the shocks identified by Restriction 3 are not monetary policy shocks. Moreover, we show that our restrictions substantially shrink the set of structural parameters originally identified by Uhlig (2005) and that excluding monetary policy equations with structural parameters that do not satisfy our restrictions—especially on the sign of the response of the federal funds rate to output and prices—suffices to generate a decline in output in response to a contractionary monetary policy shock.

6. Robustness

In the previous section we showed that while set identification is appealing because results are robust to a wide range of structural parameters, the set of admissible structural parameters might be very large and include structural parameters with questionable implications. Since
our identification strategies are not immune to this drawback, in this section we check the robustness of the results reported in Section 3 by augmenting our identification scheme with additional restrictions on the systematic component. In particular, (i) we add a zero restriction on the contemporaneous response of monetary policy to commodity prices; (ii) we impose tighter bounds on the contemporaneous response of monetary policy to output and prices; and (iii) we apply our identification to a reduced-form VAR estimated taking the log first difference of the series rather than their log levels (except for the federal funds rate). To save on space, we only report responses for output, prices, and the federal funds rate.  

6.1. Zero Restriction on $\psi_{pc}$

Our baseline identification scheme follows Christiano, Eichenbaum, and Evans (1996), Leeper and Zha (2003), and Sims and Zha (2006a) by not imposing any restriction on $\psi_{pc}$, which measures the contemporaneous response of monetary policy to movements in commodity prices. But in many specifications of the systematic component of monetary policy used in the empirical and theoretical literature, the federal funds rate does not respond directly to commodity prices. For this reason, we add to our identification the restriction $\psi_{pc} = 0$.

**Figure 5:** Impulse Responses to a Monetary Policy Shock

Additional Restriction: $\psi_{pc} = 0$

Note: IRFs to a one standard deviation contractionary monetary policy shock identified using Restrictions 1, 2, and the additional restriction $\psi_{pc} = 0$. The solid lines depict the point-wise posterior medians and the shaded bands represent the 68 and 95 percent equal-tailed point-wise posterior probability bands.

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$^8$The responses of other endogenous variables are in line with those described in Section 3 and are available in Section III of Arias, Caldara, and Rubio-Ramirez (2018a).
Figure 5 plots the IRFs to a contractionary monetary policy shock when we add the
restriction $\psi_{pc} = 0$ to our identification scheme. The additional restriction leads to a slightly
more pronounced drop in output and in prices. In particular, the set of models implying the
price puzzle is substantially reduced compared to our baseline identification. Compared to
Figure 1, the larger declines in output and prices induce a more pronounced medium-term
loosening of policy.

6.2. Bounds on the Contemporaneous Coefficients

Since our baseline identification scheme imposes only sign restrictions on the contempora-
neous response of the federal funds rate to output and prices, the posterior distributions for
these coefficients have a wide support. A natural question is whether our results are robust
to imposing upper bounds that exclude implausibly large values of these coefficients.

**Figure 6: Impulse Responses to a Monetary Policy Shock**

**Additional Restrictions:** $\psi_y \in (0, 4)$ and $\psi_p \in (0, 4)$

Note: IRFs to a one standard deviation contractionary monetary policy shock identified using Restrictions
1, 2, and the bounds $\psi_y \in (0, 4)$ and $\psi_p \in (0, 4)$. The solid lines depict the point-wise posterior median
responses and the shaded bands represent the 68 and 95 percent equal-tailed point-wise posterior probability
bands.

When we add to our identification the restriction that $\psi_y$ and $\psi_p$ can only take values
between 0 and 4, the posterior median for $\psi_y$ is 0.65, the 68 percent probability interval
ranges from 0.19 to 1.53, and the 95 percent probability interval ranges from 0.03 to 3. The
posterior median for $\psi_p$ is 1.56, the 68 percent probability interval ranges from 0.47 to 3.02,
and the 95 percent interval ranges from 0.07 to 3.81. Compared to the coefficients reported in Table 1, the upper bound reduces the support of the posterior distributions and shifts the median estimates toward lower values.

Figure 6 plots the IRFs to a contractionary monetary policy shock under this augmented identification. The bounds on the contemporaneous coefficients lead to a more persistent decline in output compared to our identification, which, after five years, remains significantly below its pre-shock level. The drop in prices becomes slightly smaller and less significant.

6.3. Monetary Policy Equation in First Differences

Finally, in our identification scheme, the federal funds rate responds to the level of output and prices. But researchers, especially those working with DSGE models, often consider Taylor-type monetary policy equations in which the federal funds rate responds to inflation and some measures of economic activity, such as the output gap and GDP growth. For this reason, we study the robustness of our results to rules where monetary policy responds to the change in prices and output. We do so by first estimating the reduced-form VAR in the first difference of all the variables but the federal funds rate. We also allow for a constant term. We then apply Restrictions 1 and 2 to the monetary policy equation. Abstracting from lag variables and the constant term, the monetary policy equation can be written as

$$ r_t = \psi_y \Delta y_t + \psi_p \Delta p_t + \psi_p c \Delta p_{c,t} + \psi_{tr} \Delta tr_t + \psi_{nbr} \Delta nbr_t + \sigma \varepsilon_{1,t}, $$

where $\sigma = a_{0.61}^{-1}$, and $\Delta$ denotes the first differences operator.

Figure 7 shows the posterior median IRFs of the endogenous variables to a contractionary shock to monetary policy when Restrictions 1 and 2 are imposed on equation (5), while the shaded bands represent the corresponding 68 and 95 percent posterior probability bands. Results are broadly consistent with those from our specification. Even so, there are some differences: the drop in output is larger and the negative response of prices is also more pronounced. The sharper drop in output and prices leads to a more significant loosening of the monetary policy stance.

Summing up the results of this section, Figures 5-7 show that the decline in output
Figure 7: Impulse Responses to a Monetary Policy Shock
VAR with Variables in First Difference

Note: IRFs to a one standard deviation contractionary monetary policy shock identified imposing Restrictions 1 and 2 on the reduced-form VAR estimated in first differences. The solid lines depict the point-wise posterior median responses the shaded bands represent the 68 and 95 percent equal-tailed posterior probability bands.

following an exogenous monetary policy tightening has a high posterior probability across different specifications of the reduced-form VAR model and of the identification assumptions.

7. Conclusion

This paper characterizes the effects of monetary policy shocks in the United States using set-identified SVARs. Key to our approach is that we identify monetary policy shocks by imposing restrictions on the systematic component of monetary policy. Our restrictions encompass a vast literature on monetary policy rules. We consistently find that monetary policy shocks induce a decline in output with high posterior probability. Moreover, under our identification, the responses for output, prices, and the federal funds rate resemble those found in Smets and Wouters (2007).

We compare our results to those of Uhlig (2005) and show that the set of structural parameters satisfying Uhlig’s (2005) restrictions does not satisfy our restrictions on the monetary policy rule. When we reconcile the two approaches by combining both sets of restrictions, monetary policy shocks remain contractionary. In this sense, our conclusions are similar to those in Kilian and Murphy (2012), who also emphasize the appeal of combining sign restrictions on both the structural parameters and the IRFs.
References


