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DP11674

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MONETARY POLICY IN SVARS: AN
AGNOSTIC IDENTIFICATION
PROCEDURE**

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Rubio-Ramírez

***MONETARY ECONOMICS AND
FLUCTUATIONS***



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Discussion Paper DP11674
Published 30 November 2016
Submitted 30 November 2016

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JEL Classification: N/A

Keywords: N/A

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

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November 29, 2016

Abstract

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JEL classification: E52; C51

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

We thank conference and seminar participants at the 2014 Paris Workshop on Empirical Monetary Economics, Board of Governors of the Federal Reserve System, Federal Reserve Bank of Atlanta, Federal Reserve Bank of New York, Federal Reserve Bank of Philadelphia, Institute for Economic Analysis at the Universitat Autònoma de Barcelona, IMF, Macro Midwest Meeting Fall 2014, North Carolina State University, System Conference in Macroeconomics Fall 2014, and the University of Pennsylvania for comments and discussions, especially Tony Braun, Frank Diebold, Pablo Guerron-Quintana, Matteo Iacoviello, Jesper Linde, John Roberts, Frank Schorfheide, Enrique Sentana, Pedro Silos, Paolo Surico, Mathias Trabandt, Harald Uhlig, Rob Vigfusson, Daniel Waggoner, and Tao Zha. We also thank Mazi Kazemi for valuable research assistance. The views expressed here are the authors' and do not necessarily represent those of the Federal Reserve Bank of Atlanta or the Board of Governors of the Federal Reserve System. Juan F. Rubio-Ramírez acknowledges financial support from the National Science Foundation, Foundation Banque de France pour la Recherche, the Institute for Economic Analysis (IAE), the “Programa de Excelencia en Educacion e Investigacion” of the Bank of Spain, and the Spanish ministry of science and technology Ref. ECO2011-30323-c03-01. Duke University, BBVA Research, and Federal Reserve Bank of Atlanta

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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 fed funds rate induces a reduction in real activity.¹ 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.²

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 output response 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.³ Under his identification, contractionary monetary policy shocks appear to be expansionary—the median posterior response of output is positive for more than five years—although the posterior probability bands of the impulse response function are very wide.

In this paper, we propose two identification schemes that also identify monetary policy shocks without restricting the contemporaneous response of output. However, instead of imposing sign restrictions on impulse responses, we impose sign and zero restrictions on the monetary equation 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). Starting in the 1960s, Milton Friedman repeatedly emphasized how monetary aggregates reacted to measures of real activity. Following the seminal work of [Taylor \(1993\)](#), interest rate rules that describe how monetary policy systematically responds to changes in output and prices

¹A non-exhaustive list of studies supporting this view includes [Bernanke and Blinder \(1992\)](#); [Christiano, Eichenbaum, and Evans \(1996\)](#); [Leeper, Sims, and Zha \(1996\)](#); and [Bernanke and Mihov \(1998\)](#). [Christiano, Eichenbaum, and Evans \(1999\)](#) survey this extensive literature.

²Researchers also estimate New Keynesian models by matching the model-implied dynamic responses to a monetary policy shock with those implied by an SVAR; see, for instance, [Rotemberg and Woodford \(1997\)](#), [Christiano, Eichenbaum, and Evans \(2005\)](#), and [Christiano, Eichenbaum, and Trabandt \(2016\)](#).

³More precisely, a monetary policy shock that increases the fed funds rate has to induce a decline in prices—ruling out the well-known price puzzle ([Sims, 1992](#))—and in nonborrowed reserves—ruling out the liquidity puzzle ([Leeper and Gordon, 1992](#)).

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.

Under our baseline identification strategy, we impose the restriction that the contemporaneous response of the fed funds rate to an increase in output and prices be positive. We leave the response of the fed 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 the baseline identification 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.

Under our alternative identification strategy, we impose the restriction that the fed funds rate react contemporaneously only in response to changes in the quantity of money and in commodity prices, and that the contemporaneous response to changes in the quantity of money be positive. The alternative identification is inspired by the class of money rules described in [Leeper and Zha \(2003\)](#) and, compared to the baseline identification, it imposes the restriction that the monetary authority not react contemporaneously to output and prices, an appealing alternative to our baseline, as data for these variables are not available in real time.⁴

Contrary to [Uhlig \(2005\)](#), under the baseline identification, 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 also has most of its mass on the negative side but it does not rule out the prize puzzle. The systematic response of monetary policy to the decline in real activity and prices causes a medium-term drop in the fed funds rate. The impulse responses of output, prices, and the fed funds rate to a monetary shock closely resemble, quantitatively and qualitatively, 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. Under the alternative identification scheme, we find again that contractionary

⁴The alternative identification is also consistent with money rules in [Leeper, Sims, and Zha \(1996\)](#) and [Sims and Zha \(2006a,b\)](#).

monetary policy shocks also induce a decline in real activity with very high posterior probability, while they have no economically discernible effect on prices. After a brief period of positive response, the impulse response function of output is negative with high posterior probability for more than five years. All told, we consistently find that an unexpected increase in the fed funds rate has contractionary effects on output with high posterior probability while addressing Uhlig’s (2005) critique.

While the sign and zero restrictions that constitute the backbone of our identification are intuitive and based on simple economic theory, their implementation is not straightforward. We use the Bayesian paradigm and employ the algorithm proposed by Arias, Rubio-Ramirez, and Waggoner (2016) and specify conditionally agnostic prior distributions over the structural parameters. This prior specification ensures that no restriction other than the intended sign and zero restrictions is used to distinguish between observationally equivalent structural parameters. Arias, Rubio-Ramirez, and Waggoner (2016) also show that the prior distribution in Uhlig (2005) is conditionally agnostic over the structural parameters. Since our priors over the structural parameters are identical to those used by Uhlig (2005), we know that differences in results with Uhlig (2005) cannot be due to the specification of the prior distributions; the differences can only be due to the identification schemes.

The identification strategies employed in this paper and in Uhlig (2005) also share important common features. First, as already mentioned, they do not impose restrictions on the response of output to monetary policy shocks. Second, they only restrict one structural equation rather than the entire system. Hence, the structural parameters are partially identified. Third, they impose sign restrictions. Thus, the structural parameters are set-identified.⁵ Despite all these similarities, results in the two papers are markedly different. To understand the relationship between our identification strategies and Uhlig’s (2005), we combine the two identification approaches.

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. Thus, when we reconcile the two approaches by combining both sets

⁵Inoue and Kilian (2013) define structural parameters to be partially identified when only a subset of structural shocks is identified and define structural parameters to be sign-identified when there are two or more sets of parameters that are observationally equivalent but satisfy the sign restrictions. We use the term set-identified instead of sign-identified because, in contrast to their paper, we impose both sign and zero restrictions.

of restrictions, monetary policy shocks remain 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 comparison with Uhlig (2005) reveals that set identification 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 a substantial impact on inference. This was first illustrated by Kilian and Murphy (2012) in the context of the global market for crude oil and by Inoue and Kilian (2013) in the same context used here. Clearly, our identification strategies are not immune to this drawback, a situation we address by running a thorough sensitivity analysis. For instance, to follow the blueprint of traditional SVARs, our identification schemes impose restrictions only on the contemporaneous response of the fed funds rate to the endogenous variables in the SVAR. But the systematic component of monetary policy might also depend on lagged economic variables. For this reason, we show that our results are robust to imposing additional sign restrictions on the long-run coefficients that describe the response of monetary policy to current and lagged output and prices.⁶ Our main result— that output drops with very high posterior probability after a monetary policy shock—is robust to various specifications of both of our identification schemes that add sign and zero restrictions to those discussed above.

The structure of this paper is as follows. In Section 2, we describe our baseline and alternative identification schemes. We also provide details about the data and the specification of the reduced-form VAR. In Section 3, we describe the results for our baseline and alternative identification schemes. In Section 4, we study the importance of imposing plausible restrictions on the systematic component of monetary policy by comparing the baseline identification with Uhlig (2005). In Section 5, we consider some robustness exercises around the specification of the monetary policy equations. In Section 6, we conclude.

⁶We define the long-run coefficients as in Sims and Zha (2006b).

2 Estimation and Identification

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

2.1 Overview

Let us consider the following SVAR

$$\mathbf{y}'_t \mathbf{A}_0 = \sum_{\ell=1}^{\nu} \mathbf{y}'_{t-\ell} \mathbf{A}_\ell + \mathbf{c} + \varepsilon'_t \quad \text{for } 1 \leq t \leq T, \quad (1)$$

where \mathbf{y}_t is an $n \times 1$ vector of endogenous variables, ε_t is an $n \times 1$ vector of structural shocks, \mathbf{A}_ℓ is an $n \times n$ matrix of structural parameters for $0 \leq \ell \leq \nu$ with \mathbf{A}_0 invertible, \mathbf{c} is a $1 \times n$ vector of parameters, ν is the lag length, and T is the sample size. The vector ε_t , conditional on past information and the initial conditions $\mathbf{y}_0, \dots, \mathbf{y}_{1-\nu}$, is Gaussian with mean zero and covariance matrix \mathbf{I}_n (the $n \times n$ identity matrix). The SVAR described in equation (1) can be written as

$$\mathbf{y}'_t \mathbf{A}_0 = \mathbf{x}'_t \mathbf{A}_+ + \varepsilon'_t \quad \text{for } 1 \leq t \leq T, \quad (2)$$

where $\mathbf{A}'_+ = \begin{bmatrix} \mathbf{A}'_1 & \dots & \mathbf{A}'_\nu & \mathbf{c}' \end{bmatrix}$ and $\mathbf{x}'_t = \begin{bmatrix} \mathbf{y}'_{t-1} & \dots & \mathbf{y}'_{t-\nu} & 1 \end{bmatrix}$ for $1 \leq t \leq T$. The dimension of \mathbf{A}_+ is $m \times n$, where $m = n\nu + 1$. We call \mathbf{A}_0 and \mathbf{A}_+ the structural parameters. The reduced-form vector autoregression (VAR) implied by equation (2) is

$$\mathbf{y}'_t = \mathbf{x}'_t \mathbf{B} + \mathbf{u}'_t \quad \text{for } 1 \leq t \leq T,$$

where $\mathbf{B} = \mathbf{A}_+ \mathbf{A}_0^{-1}$, $\mathbf{u}'_t = \varepsilon'_t \mathbf{A}_0^{-1}$, and $\mathbb{E}[\mathbf{u}_t \mathbf{u}'_t] = \mathbf{\Sigma} = (\mathbf{A}_0 \mathbf{A}'_0)^{-1}$.

It is well-known that 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 restrict only the monetary policy equation and, consequently, they only identify the monetary policy shock. Since we only identify one shock, the structural parameters are partially identified. Moreover, since we impose fewer than $n - 1$ zero restrictions, the structural parameters are also set identified

(Rubio-Ramírez et al., 2010).

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, both of our identification approaches impose sign and zero restrictions directly on the structural coefficients.

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 label the first shock to be the monetary policy shock. Thus, the first equation of the SVAR,

$$\mathbf{y}'_t \mathbf{a}_{0,1} = \sum_{\ell=1}^{\nu} \mathbf{y}'_{t-\ell} \mathbf{a}_{\ell,1} + \varepsilon_{1t} \quad \text{for } 1 \leq t \leq T, \quad (3)$$

is the monetary policy equation, where ε_{1t} denotes the first entry of ε_t , $\mathbf{a}_{\ell,1}$ denotes the first column of \mathbf{A}_ℓ for $0 \leq \ell \leq \nu$, and $a_{\ell,ij}$ denotes the (i, j) entry of \mathbf{A}_ℓ 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 $\mathbf{a}_{\ell,1}$ for $0 \leq \ell \leq \nu$. We now turn to the description of our two identification schemes that restrict the systematic component of monetary policy.

2.3 The Baseline Identification

Our baseline 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 baseline identification, our reduced-form VAR specification consists of six endogenous variables ordered as follows: 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 \(2005\)](#).⁷ We impose the following two restrictions on the monetary policy equation.

Restriction 1 *The fed 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 fed funds rate be 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 fed funds rate has only formally been the Federal Reserve’s policy instrument since 1997.⁸

The second part imposes the restriction that the fed funds rate 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 fed 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 fed funds rate is the monetary instrument, reserves do not contemporaneously enter the monetary equation.

We complement Restriction 1 with qualitative restrictions on the response of the fed funds rate to economic conditions, which we summarize as follows.

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

Restriction 2 imposes the restriction that the central bank contemporaneously increases the fed funds rate in response to an increase in output and prices, while leaving the response to commodity

⁷Details about the exact definition of each of the six variables, together with the reduced-form VAR specification, are provided in Section 2.5.

⁸See [Bernanke and Blinder \(1992\)](#); [Romer and Romer \(2004\)](#); and [Chappell Jr, McGregor, and Vermilyea \(2005\)](#) for details. [Christiano, Eichenbaum, and Evans \(1996\)](#) also study a monetary policy equation where nonborrowed reserves are the policy instrument. We do not explore this specification because the analysis in [Christiano, Eichenbaum, and Evans \(1996\)](#) is not robust to extending the sample beyond 1995. This is consistent with the view that nonborrowed reserves were used as an explicit policy instrument only in the early 1980s.

prices unrestricted.⁹ 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.¹⁰ In our identification, rather than modeling this complex information acquisition process, we simply assume that the central bank has access to data on output and prices within a month.¹¹ Despite all these arguments, some researchers find it implausible that a central bank can react to economic conditions within a month. This critique motivates the alternative identification whose defining feature is to rule out such contemporaneous responses.

We also emphasize that, while our identification strategy imposes sign restrictions on the systematic response of monetary policy to output and prices that are consistent with monetary rules embedded in DSGE models, it does not exploit, nor require, a one-to-one mapping between the structural parameters of the VAR and DSGE models. We use sign restrictions—as opposed to exact restrictions—precisely because we do not want to rely on a particular specification of the monetary policy rule.¹²

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

$$r_t = \psi_y y_t + \psi_p p_t + \psi_{pc} p_{c,t} + \psi_{tr} tr_t + \psi_{nbr} nbr_t + \sigma \varepsilon_{1,t}, \quad (4)$$

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.¹³

⁹Commodity prices are left unrestricted as in [Christiano, Eichenbaum, and Evans \(1996\)](#), [Leeper and Zha \(2003\)](#), and [Sims and Zha \(2006a\)](#).

¹⁰Data on commodity prices are available in real time.

¹¹An alternative approach is adopted by [Romer and Romer \(2004\)](#), who regress the monthly change in the fed funds rate on the output and prices forecast produced by the Federal Reserve Board.

¹²We also do not claim that our identification strategy encompasses all existing specifications of monetary rules ever used in the literature, as much as sign restrictions on impulse responses are not consistent with all new Keynesian DSGE models: for instance, in models where fiscal policy is active and monetary policy is passive, an increase in the policy rate induces an increase in prices.

¹³[Belongia and Ireland \(2015\)](#) estimate a VAR with time-varying parameters and characterize changes in the

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, ψ_{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.¹⁴

2.4 The Alternative Identification

The alternative identification is motivated by the work on money rules by [Leeper and Zha \(2003\)](#), and [Sims and Zha \(2006a,b\)](#), who assume that the monetary authority cannot react contemporaneously to output and prices. To implement the alternative identification, our reduced-form VAR specification consists of five endogenous variables. Compared to the specification used for the baseline identification, we replace total reserves and nonborrowed reserves with money, m_t . We impose the following two restrictions on the monetary policy equation.

Restriction 3 *The fed funds rate is the monetary policy instrument and it only reacts contemporaneously to money and commodity prices.*

Restriction 3 imposes the restriction that the fed funds rate respond contemporaneously only to money and commodity prices, two variables that are available to the Federal Reserve in real time. By contrast, the fed funds rate does not react contemporaneously to output and prices, two variables that—as we have discussed in the previous section—are not available in real time.

The appeal of the alternative identification compared to the baseline is that we take the more stringent view—shared by some—that the Federal Reserve cannot react within a month to changes in real activity. At the same time, the alternative identification still leaves the response of output to a monetary policy shock unrestricted.

Restriction 4 *The contemporaneous reaction of the fed funds rate to money is positive.*

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.

¹⁴We normalize the IRFs by imposing the restriction that the fed funds rate increase on impact in response to a contractionary monetary policy shock and that $\sigma > 0$.

Motivated by [Sims and Zha \(2006b\)](#), Restriction 4 imposes the restriction that the central bank increase the fed funds rate in response to an increase in money contemporaneously. As for the baseline identification, we leave the response to commodity prices unrestricted. We rewrite the monetary policy equation, concentrating on the contemporaneous coefficients, as

$$r_t = \psi_y y_t + \psi_p p_t + \psi_{p_c} p_{c,t} + \psi_m m_t + \sigma \varepsilon_{1,t}, \quad (5)$$

where $\psi_y = -a_{0,51}^{-1} a_{0,11}$, $\psi_p = -a_{0,51}^{-1} a_{0,21}$, $\psi_{p_c} = -a_{0,51}^{-1} a_{0,31}$, $\psi_m = -a_{0,51}^{-1} a_{0,41}$, and $\sigma = a_{0,51}^{-1}$. Equipped with this representation of the monetary policy equation, we summarize Restrictions 3 and 4 as follows.¹⁵

Remark 2 *Restriction 3 implies that $\psi_y = \psi_p = 0$, while Restriction 4 implies that $\psi_m > 0$. At the same time, ψ_{p_c} remains unrestricted.*

Note also that under Restriction 3, the monetary policy equation (5) becomes

$$r_t = \psi_m m_t + \psi_{p_c} p_{c,t} + \sigma \varepsilon_{1,t}. \quad (6)$$

This equation has three possible interpretations. The first, which is in line with how we specify equation (6), is that the fed funds rate responds to changes in the money supply and to changes in commodity prices. The second interpretation is that the money supply adjusts to changes in the fed funds rate and changes in commodity prices. This interpretation is consistent with [Sims and Zha's \(2006b\)](#) view of how monetary policy was conducted between 1979 and 1982. A third interpretation is simply that both the fed funds rate and the money supply respond to Fed actions, and that both indicators are important in describing the effects of monetary policy on the economy. This third interpretation is compatible with [Belongia and Ireland \(2014\)](#).¹⁶

¹⁵We normalize the IRFs by imposing the restriction that the fed funds rate increase on impact in response to a contractionary monetary policy shock and that $\sigma > 0$.

¹⁶We have decided to follow the first interpretation. We could have written equation (6) consistently with either of the other two interpretations, but the normalization restrictions would have been different.

2.5 Dataset, Reduced-Form VAR, and Priors 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, money, and the fed 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 obtained from the St. Louis Fed’s website using the following mnemonics: BOGNONBR (nonborrowed reserves), CPIAUCSL (consumer price index), FEDFUNDS (the fed funds rate), GDPC1 (real GDP), GDPDEF (GDP deflator), INDPRO (industrial production index), PPIFGS (producer price index), M2SL (money), and TRARR (total reserves). All variables are seasonally adjusted except for the commodity price index and the fed funds rate.

To enhance comparability between our baseline identification and [Uhlig’s \(2005\)](#), we have reconstructed and updated [Uhlig’s \(2005\)](#) dataset covering the 1965:M1–2003M:12 period.¹⁷ For the same reason, we have taken the reduced-form VAR specification described in [Uhlig \(2005\)](#). Specifically, we use 12 lags of the endogenous variables and do not include any deterministic term. To implement our alternative identification, we estimate the same reduced-form VAR specification using the same sample period, but we replace total and nonborrowed reserves for money. We have repeated the analysis using both an extended version of the monthly dataset running until 2007:M12 and data at quarterly frequency until 2007:Q4. Results reported in the following sections are robust to these different specifications of the dataset and are available upon request.¹⁸

For the Bayesian estimation of the SVARs, we use the methods described in [Arias, Rubio-Ramirez, and Waggoner \(2016\)](#), and explore two alternative prior specifications. For the results

¹⁷We have cross-checked our data (constructed using the vintage as of May 2014) with the reconstruction of [Uhlig’s \(2005\)](#) dataset done by RATS, https://estima.com/procs_perl/uhligjme2005.zip, and we obtain almost identical results, despite the fact that the RATS dataset corresponds to a different vintage.

¹⁸In these robustness checks over the extended sample we stop in 2007 because, starting in 2008, there are movements in reserves of a different order of magnitude associated with the global financial crisis. Furthermore, the fed funds rate has been at the zero lower bound since November 2008, and our paper is concerned with the characterization of monetary policy in normal times.

shown in the paper, we choose priors that are conditionally agnostic over the structural parameters. That is, observationally equivalent structural parameters that satisfy the sign and zero restrictions have the same prior and posterior densities. Our results are robust to the use of priors that are conditionally agnostic over the IRFs: observationally equivalent IRFs that satisfy the sign and zero restrictions have the same prior and posterior densities. The choice of parameterizing the prior on the structural coefficients seems natural given our focus on restrictions on the systematic component of monetary policy.

To specify our conditionally agnostic priors over the structural parameters, we choose priors over the reduced-form parameters that are identical to those used by Uhlig (2005). Thus, any value of the structural parameters that satisfies both our sign and zero restrictions and the sign restrictions in Uhlig (2005) has the same weight in the prior. Thus, only differences in the identification schemes set our results apart.

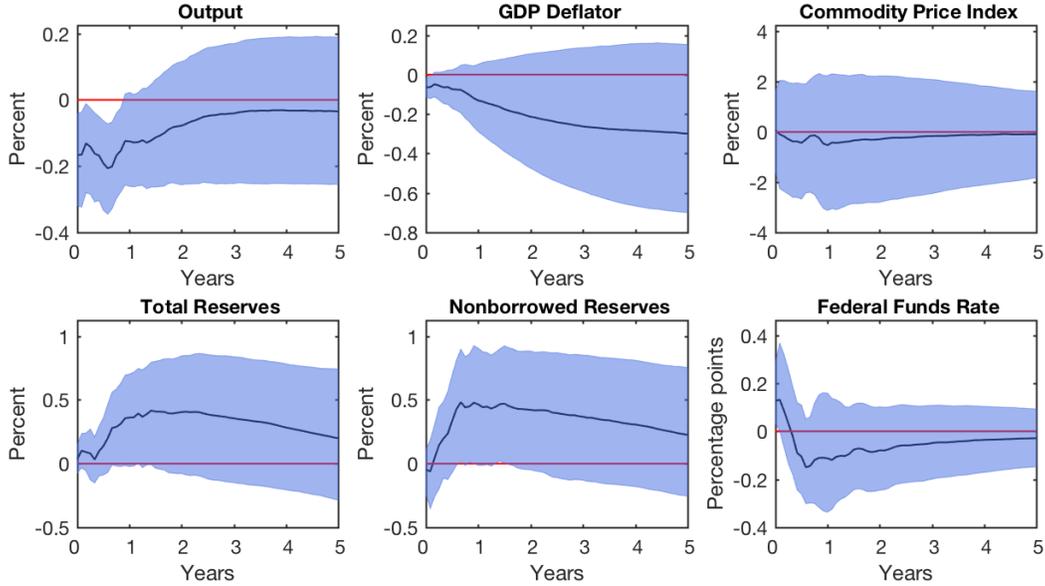
3 Main Results

In this section we describe the results for our baseline and alternative identification schemes. We first present the IRFs to a contractionary monetary policy shock, and then we discuss the coefficients of the monetary policy equations associated with the two identification schemes.

The solid lines in Figure 1 show the posterior point-wise median IRFs of the endogenous variables to a contractionary monetary policy shock under the baseline identification scheme, while the shaded bands represent the corresponding 68 percent point-wise posterior probability bands.¹⁹ A contractionary monetary policy shock leads to an immediate median increase in the fed funds rate of around 15 basis points. The significant tightening in monetary policy leads to an immediate drop in output—which lasts for about one and half years and is precisely estimated—and to a protracted decline in prices. While some structural parameters included in the identified set feature the price puzzle, our restrictions imply a substantial posterior probability mass on structural parameters that imply prices falling after a monetary tightening. By contrast, the response of commodity prices is close to zero and not precisely estimated. Following the decline in output and prices, the monetary

¹⁹All results are based on 10,000 draws from the posterior distribution of the structural parameters and all shocks are one standard deviation.

FIGURE 1: IMPULSE RESPONSES TO A MONETARY POLICY SHOCK
(Baseline Identification)



NOTE: The solid lines depict median responses of the specified variable to a contractionary monetary policy shock under the baseline identification; the shaded bands represent the 68 percent point-wise posterior probability bands.

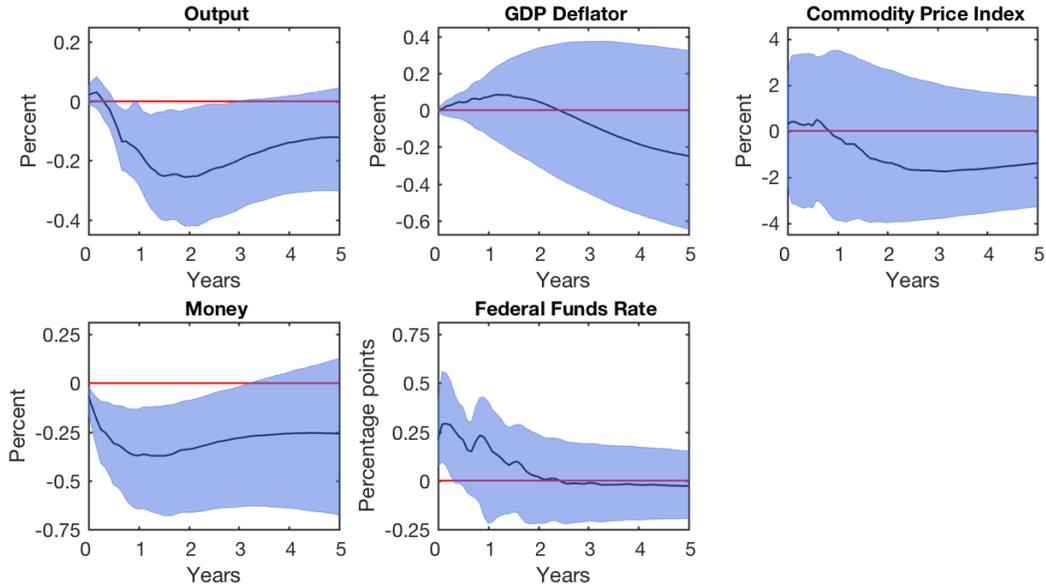
authority loosens its stance shortly after the intervention, in line with our assumptions on the systematic component of monetary policy.

On the reserves side, the median impact response of total and nonborrowed reserves is basically zero, turning positive thereafter. The latter response does not feature a liquidity puzzle, as nonborrowed reserves are about zero when the fed funds rate is positive and increase only when the monetary stance loosens.

The IRFs of output, prices, and the fed funds rate to a contractionary monetary policy shock depicted in Figure 1 are remarkably qualitatively and quantitatively similar to those documented in Figure 6, page 601 of [Smets and Wouters \(2007\)](#).²⁰ The response of inflation to a contractionary monetary policy shock builds up to a response of the price level in line with what was reported in Figure 1. The shape of the response of output and the undershooting of the fed funds rate are also features shared by the two figures. This close similarity is important because it shows that the

²⁰While in [Smets and Wouters \(2007\)](#) the monetary policy shock follows an AR(1) process, our impulse response functions are based on an i.i.d shock. Even so, in practice the difference is small, as the posterior for the AR(1) coefficient in [Smets and Wouters \(2007\)](#) has most of its mass on values below 0.25.

FIGURE 2: IMPULSE RESPONSES TO A MONETARY POLICY SHOCK
(Alternative Identification)



NOTE: The solid lines depict median responses of the specified variable to a contractionary monetary policy shock under the alternative identification; the shaded bands represent the 68 percent point-wise posterior probability bands.

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.

The solid lines in [Figure 2](#) show the posterior median IRFs of the endogenous variables to a contractionary monetary policy shock under the alternative identification scheme, while the shaded bands represent the corresponding 68 percent point-wise posterior probability bands. Compared to the baseline identification, the response of output is stronger and more persistent: it bottoms out at -0.3 percent about 2 years after the shock and remains below its pre-shock level for over 5 years. The response of prices shows a more pronounced price puzzle than in [Figure 1](#) but, as is the case for the response of commodity prices, it is not statistically significant at any horizon. The response of the fed funds rate is more persistent than under the baseline identification, with the stance tightening for the first 12 months and returning to its pre-shock level thereafter. The increase in the fed funds rate and the accompanying recession induce a significant and persistent decline in money. When comparing [Figures 1](#) and [2](#), we see that the uncertainty surrounding the estimates is similar.

TABLE 1: Contemporaneous Coefficients in the Monetary Policy Equations

(a) <i>Baseline Identification</i>					
Coefficient	ψ_y	ψ_p	ψ_{pc}	ψ_{ptr}	ψ_{nbr}
	1.18	3.59	-0.02	0.00	0.00
	[0.34; 3.08]	[0.99; 10.40]	[-0.40; 0.32]		
(b) <i>Alternative Identification</i>					
Coefficient	ψ_y	ψ_p	ψ_{pc}	ψ_m	
	0.00	0.00	-0.03	1.16	
			[-0.89; 0.66]	[0.30; 4.32]	

NOTE: The entries in the table denote the posterior median estimates of the contemporaneous coefficients in the monetary equation under our baseline identification (panel (a)) and under our alternative identification (panel (b)). The 16th and 84th percentiles of the posterior distributions are reported in brackets. See the main text for details.

Table 1 shows the posterior estimates of the contemporaneous coefficients for the monetary policy equations. Under the baseline identification, tabulated in Panel (a), the posterior medians of ψ_y and ψ_p are 1.18 and 3.59, respectively. That is, the fed funds rate reacts by more than one-to-one to contemporaneous movements in output and prices. The posterior median of ψ_{pc} is -0.02 and the coefficients on reserves are, by construction, zero. Thus, our baseline 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. Moreover, the 68 percent posterior probability intervals are also well within the expected bounds.

Under the alternative identification, tabulated in Panel (b), we restrict ψ_y and ψ_p to zero. At the posterior median, the contemporaneous response of the fed funds rate to changes in money is slightly above 1, while the response to changes in commodity prices is -0.03 , similar to the response under the baseline identification. In summary, Panel (b) shows that, under the alternative identification, the systematic component of monetary policy is consistent with the empirical estimates of [Leeper and Zha \(2003\)](#).²¹

In combination, our results show that, given our restrictions on the systematic component of

²¹Many monetary policy equations considered in the DSGE literature include a coefficient for the lagged fed funds rate that is estimated to be positive. Under both the baseline and alternative identifications, only about 1 percent of the draws imply a negative coefficient on the lagged fed funds rate r_{t-1} . Moreover, imposing an additional restriction that forces the coefficients on either r_{t-1} , r_{t-3} , or r_{t-6} to be positive has no impact on our results.

monetary policy, contractionary monetary policy shocks induce a decline in real activity with high posterior probability. Moreover, given our baseline 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 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 baseline identification to that of Uhlig (2005).²² This is a natural comparison because, while both approaches partially and set identify the SVAR, have the same conditionally agnostic priors 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, Uhlig (2005) finds a positive median response. The comparison revolves around two exercises. We show that an identification strategy that combines Uhlig’s identification with our restrictions on the systematic component recovers the conventional response of output and we rationalize this finding by showing that the systematic component of monetary policy implied by Uhlig (2005) does not satisfy our restrictions.

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

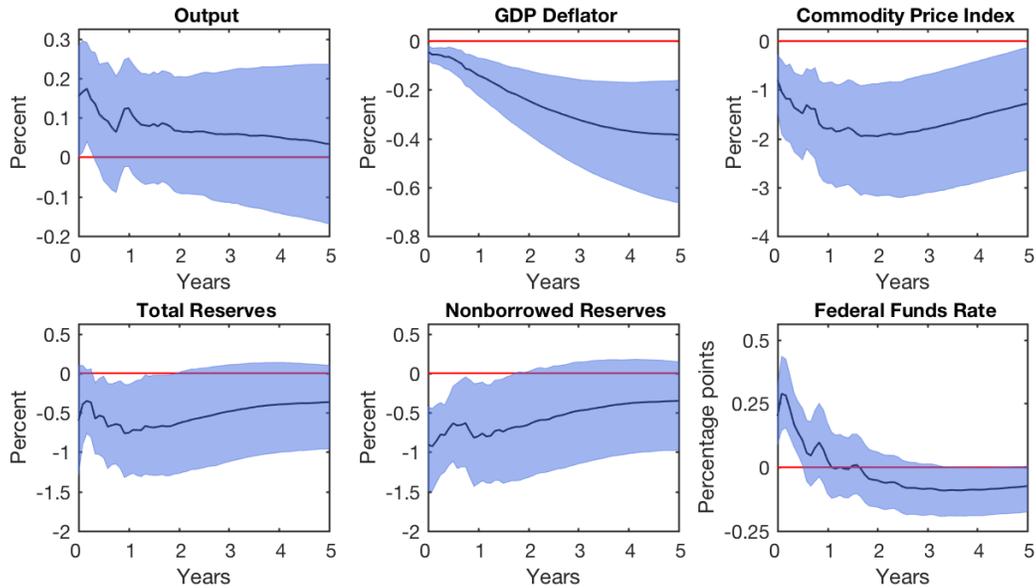
Restriction 5 *A monetary policy shock leads to a negative response of prices, commodity prices, and nonborrowed reserves, and to a positive response of the fed funds rate, all at horizons $t = 0, \dots, 5$.*

Restriction 5 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 5, while the shaded bands represent the corresponding 68 percent point-wise posterior probability bands. This figure replicates the IRFs depicted in Figure 6 in Uhlig

²²We provide a similar comparison for the alternative identification scheme in Appendix A.

(2005). The median response of output is positive, and in the short run, the 68 percent point-wise posterior probability bands do not contain zero. Prices—whose response is restricted to be negative for six months—decline persistently, bottoming out more than 5 years after the shock. Finally, the response of the fed funds rate is positive on impact and becomes negative 18 months after the shock.

FIGURE 3: IMPULSE RESPONSES TO A MONETARY POLICY SHOCK
(Uhlig (2005) Identification)



NOTE: The solid lines depict median responses of the specified variable to a contractionary monetary policy shock under the identification of Uhlig (2005); the shaded bands represent the 68 percent point-wise posterior probability bands.

Figure 3 shows that, in response to a contractionary monetary policy shock identified only by imposing Restriction 5, neutrality of monetary policy shocks is not inconsistent with the data. Furthermore, Uhlig (2005) suggests that a drop in output seems to be linked to restricting its contemporaneous response after a monetary policy shock to be zero. 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 restriction.

To this end, we explore the implications of combining Uhlig’s restrictions with our restrictions on the systematic component of monetary policy for the IRFs to a contractionary monetary policy shock. As Arias, Rubio-Ramirez, and Waggoner (2016) point out, the set of structural parameters identified by imposing both sign and zero restrictions—as in our baseline identification—are of measure zero

in the set of structural parameters identified by imposing only the sign restrictions. That is, the set of structural parameters that satisfy Restriction 5 violates Restriction 1 by construction. Thus, to understand the relative importance of the sign and zero restrictions on the systematic component, we first explore an identification that combines Restrictions 1 and 5.

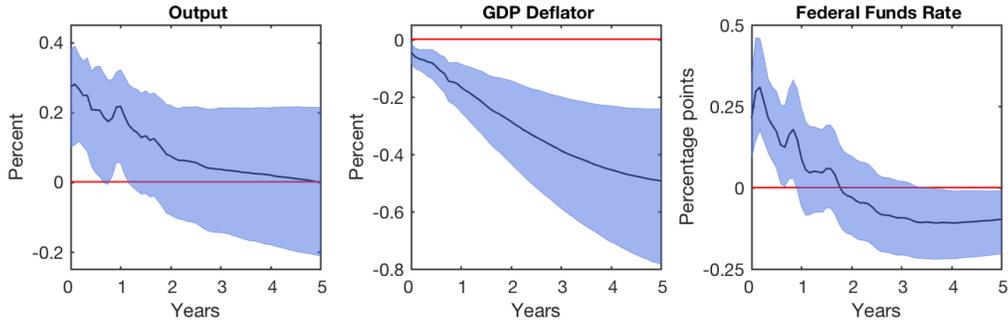
The solid lines in Panel (a) in Figure 4 plot the posterior median IRFs of selected endogenous variables to a contractionary monetary policy shock under Restrictions 1 and 5, while the shaded bands represent the corresponding 68 percent point-wise posterior probability bands. Compared to Figure 3, this set of restrictions is associated with a stronger positive response of output to a contractionary monetary policy shock. The IRFs of prices and the fed funds rate are both qualitatively and quantitatively similar to those reported in Figure 3. As expected, adding more restrictions makes the posterior estimates more precise.

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 5, that is, by combining Uhlig (2005) and our baseline identification, while the shaded bands represent the corresponding 68 percent point-wise posterior probability bands. Under this identification, the output median response 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 impulse responses, an identification scheme that includes sign restrictions on ψ_y and ψ_p recovers a negative response of output to a monetary policy shock with high posterior probability without imposing the controversial zero restriction on output.

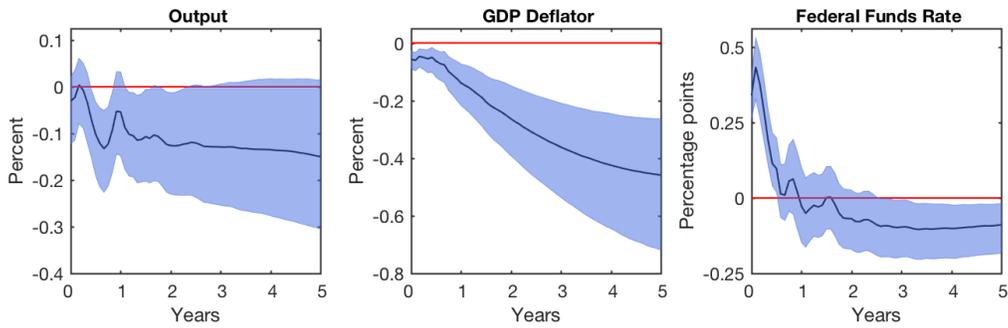
To shed light on these results, the first row of Table 2 reports the posterior estimates of the contemporaneous coefficients on the monetary policy equation implied by Uhlig (2005). The posterior median of the output coefficient is -0.47 and the posterior distribution puts a sizable weight on negative values. Hence, Uhlig (2005) implies a negative response of the fed funds rate to output. In addition, the posterior median responses of the fed funds rate to reserves are positive but small and not precisely estimated, so that large positive and negative coefficients are included in the set of admissible structural parameters. By contrast, the median response of the fed funds rate to prices is estimated to be 2.23 and the 68 percent probability interval contains mostly positive values.

As shown in the second row of Table 2, under Restrictions 1 and 5, the posterior distribution of

FIGURE 4: IMPULSE RESPONSES OF SELECTED VARIABLES TO A MONETARY POLICY SHOCK



(a) Responses to monetary policy shocks based on Restrictions 1 and 5



(b) Responses to monetary policy shocks based on Restrictions 1, 2, and 5

NOTE: The solid lines in panel (a) depict median responses to a contractionary monetary shock identified using the restrictions on IRFs described in Restriction 5 and the zero restrictions on the systematic component described in Restriction 1, while those in panel (b) depict median responses to a contractionary monetary policy shock identified using the restrictions on IRFs described in Restriction 5 and the zero and sign restrictions on the systematic component described in Restrictions 1 and 2; the shaded bands represent the 68 percent point-wise posterior probability bands.

ψ_y shifts to the left, making negative values considerably more likely—the posterior median of ψ_y moves from -0.47 to -1.32. The additional zero restrictions do not have a quantitatively relevant effect on the posterior distributions of ψ_p and ψ_{pc} . The shift toward more negative values in the posterior distribution of ψ_y seems to be accompanied by the more positive response of output to the monetary policy shock.

Table 3 tabulates the posterior probabilities that the structural parameters consistent with Uhlig’s restrictions violate the sign and zero restrictions imposed by the baseline identification. The first row confirms that the set of structural parameters that satisfy Restriction 5 imply $\psi_{tr} \neq 0$ and $\psi_{nbr} \neq 0$, thus violating Restriction 1. The posterior probability of drawing a negative coefficient on output

TABLE 2: Contemporaneous Coefficients in the Monetary Policy Equation
(Identifications Based on Uhlig (2005))

Coefficient	ψ_y	ψ_p	ψ_{p_c}	$\psi_{p_{tr}}$	ψ_{nbr}
Restriction 5 ^[a]	-0.47 [-2.69; 0.74]	2.23 [0.10; 7.30]	0.11 [0.00; 0.38]	0.11 [-0.47; 0.67]	0.04 [-0.38; 0.73]
Restrictions 1 & 5 ^[b]	-1.32 [-4.94; -0.02]	2.49 [0.74; 6.87]	0.16 [0.03; 0.51]	0.00	0.00

NOTE: The entries in the table denote the posterior medians estimate of the contemporaneous coefficients in the monetary equation corresponding to two identification strategies. The 16th and 84th percentiles of the posterior distributions 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) + zero restrictions on the systematic component of monetary policy described in Restriction 1.

and prices are 0.66 and 0.15, respectively, and the posterior probability of violating Restriction 2 is 0.79. The second row tabulates the same posterior probabilities under the identification that combines Restrictions 1 and 5, which imposes the constraint that $\psi_{tr} = 0$ and $\psi_{nbr} = 0$. The posterior probability of drawing a negative coefficient on output is 0.84, almost 20 percentage points higher than when we impose only Restriction 5. The posterior probability of drawing a negative coefficient on prices drops to 0.07, and the posterior probability of violating Restriction 2 is 0.90—a tad 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 baseline 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 5 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 fed funds rate to output and prices—suffices to generate a decline in output in response to a contractionary monetary policy shock.

TABLE 3: Probability of Violating Restrictions Imposed by the Baseline Identification

Probability	$P(\psi_{tr} \neq 0 \cup \psi_{nbr} \neq 0)$	$P(\psi_y < 0)$	$P(\psi_p < 0)$	$P(\psi_y < 0 \cup \psi_p < 0)$
Restriction 5 ^[a]	1.00	0.66	0.15	0.79
Restrictions 1 & 5 ^[b]	0.00	0.84	0.07	0.90

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 baseline 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) + zero restrictions on the systematic component of monetary policy described in Restriction 1.

5 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 baseline and alternative identifications with additional restrictions on the systematic component. In particular, we add sign restrictions on the long-run response of monetary policy to output, prices and money, and zero restrictions on the contemporaneous response to commodity prices, and we impose tighter bounds on the contemporaneous coefficients of output, prices and money. Finally, we conclude by exploring the IRFs under our baseline identification applied to a reduced-form VAR estimated with variables that enter in first-difference rather than in levels. To save on space, we only report responses for output, prices, and the fed funds rate.²³

5.1 Sign Restrictions on Long-Run Coefficients

Our baseline and alternative identification schemes impose restrictions only on the contemporaneous response of the fed funds rate. But the systematic component of monetary policy might depend on lagged economic variables. For this reason, we consider additional sign restrictions that discipline the response of monetary policy to current and lagged endogenous variables. In particular, we

²³The responses of other endogenous variables—unless otherwise noted—are similar to those described in Section 3 and are available on request.

follow [Sims and Zha \(2006b\)](#) and summarize the endogenous response by computing the long-run coefficients for output, prices, and money as follows:

$$\psi_{LR,y} = \frac{\sum_{\ell=0}^{\nu} \alpha_{y,\ell}}{\sum_{\ell=0}^p \delta_{r,\ell}}, \quad \psi_{LR,p} = \frac{\sum_{\ell=0}^{\nu} \alpha_{p,\ell}}{\sum_{\ell=0}^{\nu} \delta_{r,\ell}}, \quad \text{and} \quad \psi_{LR,m} = \frac{\sum_{\ell=0}^{\nu} \alpha_{m,\ell}}{\sum_{\ell=0}^{\nu} \delta_{r,\ell}},$$

where $\alpha_{y,0} = -a_{0,11}$, $\alpha_{y,\ell} = a_{\ell,11}$ for $\ell = 1, \dots, \nu$, $\delta_{r,0} = a_{0,61}$, $\delta_{r,\ell} = -a_{\ell,61}$ for $\ell = 1, \dots, \nu$, $\alpha_{p,0} = -a_{0,21}$, $\alpha_{p,\ell} = a_{\ell,21}$ for $\ell = 1, \dots, \nu$, $\alpha_{m,0} = -a_{0,41}$, $\alpha_{m,\ell} = a_{\ell,41}$ for $\ell = 1, \dots, \nu$. The long-run coefficients offer a parsimonious way to summarize the response of monetary policy to current and lagged output and prices. These coefficients are computed by asking what would be the response of the fed funds rate to a permanent increase in a certain variable, if all other variables remained constant.

We first explore a specification of our baseline identification that—in addition to [Restrictions 1](#) and [2](#)—imposes the following restriction on the long-run coefficients for output and prices.²⁴

Restriction 6 *The long-run reaction of the fed funds rate to output and prices is positive, i.e., $\psi_{LR,y}, \psi_{LR,p} > 0$.*

[Figure 5](#) reports the responses of output, prices, and the fed funds rate to a contractionary monetary policy shock identified under the baseline identification augmented with [Restriction 6](#). The median responses and 68 percent point-wise posterior probability bands of output and the fed fund rate are qualitatively similar to those reported in [Figure 1](#).

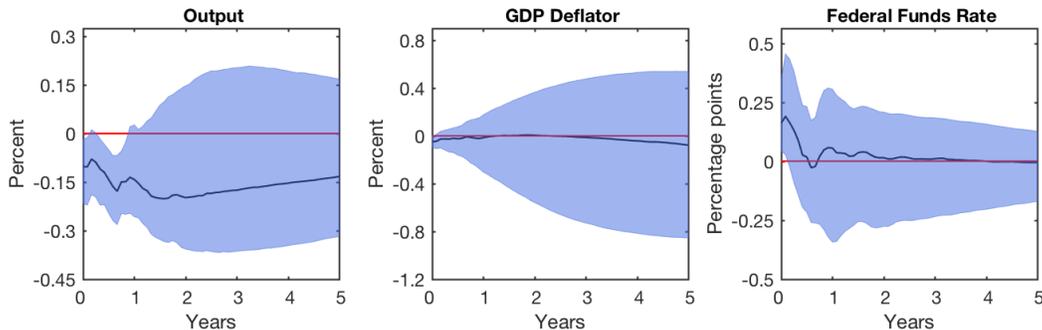
We also explore two specifications of our alternative identification. In the first specification we add the following sign restriction to the long-run coefficient on money.

Restriction 7 *The long-run reaction of the fed funds rate to money is positive, i.e., $\psi_{LR,m} > 0$.*

In the second specification we impose sign restrictions on the long-run coefficients on output, prices, and money. The idea is that—even if monetary policy does not react contemporaneously to output and prices—it is plausible to assume that the long-run reaction of the fed funds rate to changes in output and prices is positive.

²⁴The SVAR specifications used in this subsection include a constant, for consistency with [Sims and Zha \(2006b\)](#).

FIGURE 5: IMPULSE RESPONSES OF SELECTED VARIABLES TO A MONETARY POLICY SHOCK
(Baseline Specification with Restrictions on Long-Run Coefficients)



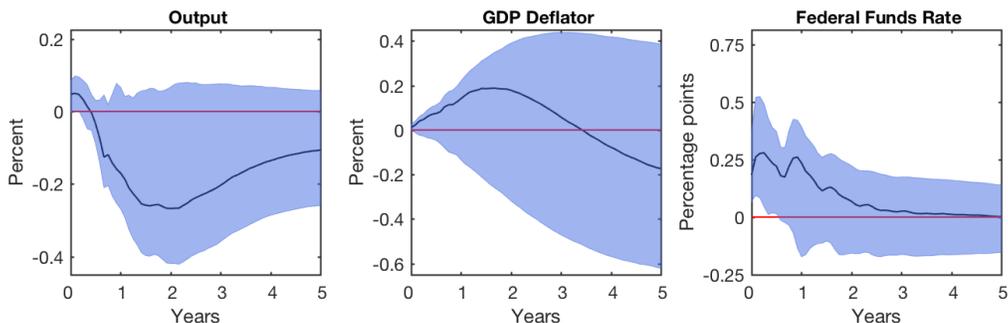
NOTE: The solid lines depict median responses of the specified variable to a contractionary monetary policy shock of size 1 standard deviation under the baseline identification augmented with Restriction 6; the shaded bands represent the 68 percent point-wise posterior probability bands.

Restriction 8 *The long-run reaction of the fed funds rate to money, output and prices is positive, i.e., $\psi_{LR,m}, \psi_{LR,y}, \psi_{LR,p} > 0$.*

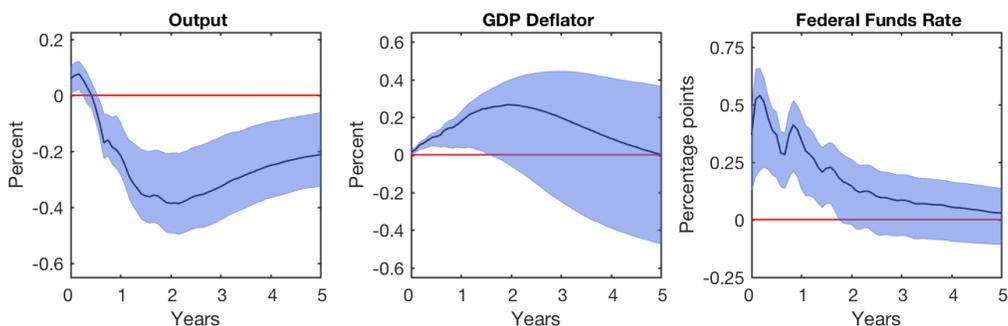
Figure 6 depicts the IRFs. As shown in Panel (a), under the alternative identification augmented with Restriction 7, the median responses of output, prices, and the fed funds rate to a contractionary monetary policy shock are similar to those reported in Figure 2, while the 68 percent point-wise posterior probability bands are slightly wider. By contrast, as shown in Panel (b), under the alternative identification augmented with Restriction 8, the decline in output is larger, more persistent, and more precisely estimated than under the alternative identification. At the same time, we observe a more pronounced and precisely estimated price puzzle. The positive response of prices to a contractionary monetary policy shock accounts for the persistent tightening in the monetary policy stance despite the decline in output.

Clearly, Figures 5 and 6 confirm that our main finding—that output drops following a contractionary monetary policy shock with very high posterior probability—is robust to more stringent characterizations of the systematic component of monetary policy that impose sign restrictions on the long-run coefficients of output, prices, and money.

FIGURE 6: IMPULSE RESPONSES OF SELECTED VARIABLES TO A MONETARY POLICY SHOCK
(Alternative Identification with Restrictions on Long-Run Coefficients)



(a) Responses to monetary policy shocks based on Restrictions 3, 4, and 7



(b) Responses to monetary policy shocks based on Restrictions 3, 4, and 8

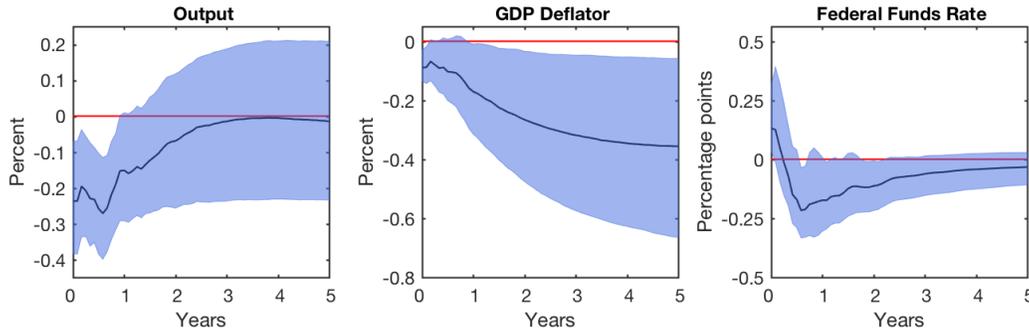
NOTE: The solid lines in panel (a) depict median responses to a contractionary monetary policy shock under the alternative identification augmented with Restriction 7, while those in panel (b) depict median responses to a contractionary monetary policy shock identified with the alternative identification under Restriction 8; the shaded bands represent the 68 percent point-wise posterior probability bands.

5.2 Zero Restriction on ψ_{pc}

Our baseline and alternative identification schemes follow [Christiano, Eichenbaum, and Evans \(1996\)](#), [Leeper and Zha \(2003\)](#), and [Sims and Zha \(2006a\)](#) by allowing the fed funds rate to respond to contemporaneous movements in commodity prices and by not imposing any restriction on ψ_{pc} . But in many specifications of the systematic component of monetary policy used in the empirical and theoretical literature, the fed funds rate does not respond directly to changes in commodity prices. For this reason, we add to our baseline and alternative identifications the restriction $\psi_{pc} = 0$.

Figure 7 plots the IRFs to a contractionary monetary shock when we add the restriction $\psi_{pc} = 0$ to our baseline identification scheme. The additional restriction leads to a slightly more pronounced

FIGURE 7: IMPULSE RESPONSES OF SELECTED VARIABLES TO A MONETARY POLICY SHOCK
(Baseline Identification with $\psi_{p_c} = 0$)

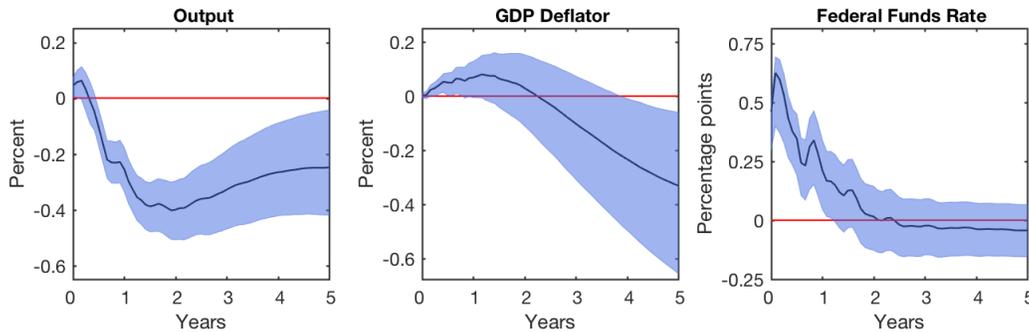


NOTE: The solid lines depict median responses of the specified variable to a contractionary monetary policy shock of size 1 standard deviation under the baseline identification augmented with the restriction $\psi_{p_c} = 0$; the shaded bands represent the 68 percent point-wise posterior probability bands.

drop in output and in prices and to narrower probability bands. Compared to Figure 1, the larger declines in output and prices induce a more pronounced medium-term loosening of policy.

Figure 8 plots the IRFs to a contractionary monetary policy shock when we add the restriction $\psi_{p_c} = 0$ to our alternative identification scheme. Qualitatively, all IRFs are similar to those plotted in Figure 2 but more precisely estimated. The response of output is stronger. The response of prices shows a more pronounced price puzzle than in Figure 2. The response of the fed funds rate is more persistent, with the stance tightening for the first 18 months and returning to its pre-shock level thereafter.

FIGURE 8: IMPULSE RESPONSES OF SELECTED VARIABLES TO A MONETARY POLICY SHOCK
(Alternative Identification with $\psi_{p_c} = 0$)



NOTE: The solid lines depict median responses of the specified variable to a monetary policy shock of size 1 standard deviation under the alternative identification augmented with the restriction $\psi_{p_c} = 0$; the shaded bands represent the 68 percent point-wise posterior probability bands.

TABLE 4: Contemporaneous Coefficients in the Monetary Policy Equations

<i>(a) Baseline Identification</i>					
Coefficient	ψ_y	ψ_p	ψ_{pe}	ψ_{ptr}	ψ_{nbr}
	0.91	1.70	0.01	0.00	0.00
	[0.29; 2.13]	[0.52; 3.10]	[-0.23; 0.25]		
<i>(b) Alternative Identification</i>					
Coefficient	ψ_y	ψ_p	ψ_{pe}	ψ_m	
	0.00	0.00	-0.01	0.89	
			[-0.62; 0.56]	[0.25; 2.20]	

NOTE: The entries in the table denote the posterior median estimates of the contemporaneous coefficients in the monetary equation under our baseline identification augmented with the restrictions $\psi_y \in (0, 4)$ and $\psi_p \in (0, 4)$ (panel (a)) and under our alternative identification augmented with the restriction $\psi_m \in (0, 4)$ (panel (b)). The 16th and 84th percentiles of the posterior distributions are reported in brackets. See the main text for details.

5.3 Bounds on the Contemporaneous Coefficients

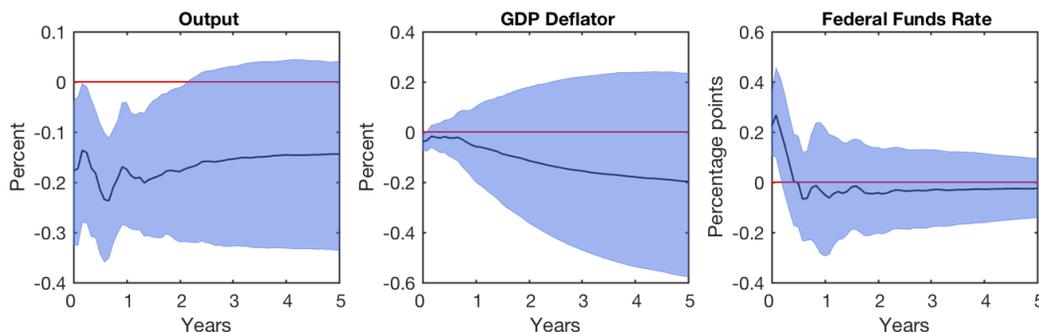
Our baseline and alternative identification schemes only impose the sign restrictions that the contemporaneous response of the fed funds rate to output, prices, and money has to be positive. Consequently, our identification schemes imply a wide support for the posterior distributions for these coefficients. A natural question is whether our results are robust to also imposing upper bounds for these coefficients, so that we can exclude implausibly large contemporaneous elasticities.

Panel (a) of Table 4 shows the posterior estimates of the contemporaneous coefficients for the monetary policy equation when we add to the baseline identification the restriction that ψ_y and ψ_p can only take values between 0 and 4. The posterior median for ψ_y is 0.91, and the 68 percent probability interval ranges from about 0.3 to 2.1. The posterior median for ψ_p is 1.7, and the 68 percent probability interval ranges from about 0.5 to 3.1. Compared to the coefficients associated with the baseline identification reported in Table 1, imposing the upper bound reduces the support of the posterior distributions and shifts the median estimates toward lower values. Panel (b) of Table 4 shows the posterior estimates of the contemporaneous coefficients for the monetary policy equation when we add to the alternative identification the restriction that ψ_m can only take values between 0 and 4. The posterior median of ψ_m is 0.89, and the 68 percent probability interval ranges

from 0.25 to 2.20, fairly similar to those reported in Table 1.

Figure 9 plots the IRFs to a contractionary monetary policy shock under the augmented baseline identification.²⁵ The bounds on the contemporaneous coefficients lead to a more persistent decline in output compared to the baseline identification, which, after five years, remains significantly below its pre-shock level. The drop in prices becomes slightly smaller and less significant. Importantly, the smaller contemporaneous coefficients on output and prices in the monetary rule imply that monetary policy does not loosen its stance as in the baseline identification despite a larger drop in output.

FIGURE 9: IMPULSE RESPONSES OF SELECTED VARIABLES TO A MONETARY POLICY SHOCK
(Baseline identification with $\psi_y \in (0, 4)$ and $\psi_p \in (0, 4)$)



NOTE: The solid lines depict median responses of the specified variable to a monetary policy shock of size 1 standard deviation under the baseline identification augmented with the restrictions $\psi_y \in (0, 4)$ and $\psi_p \in (0, 4)$; the shaded bands represent the 68 percent point-wise probability bands.

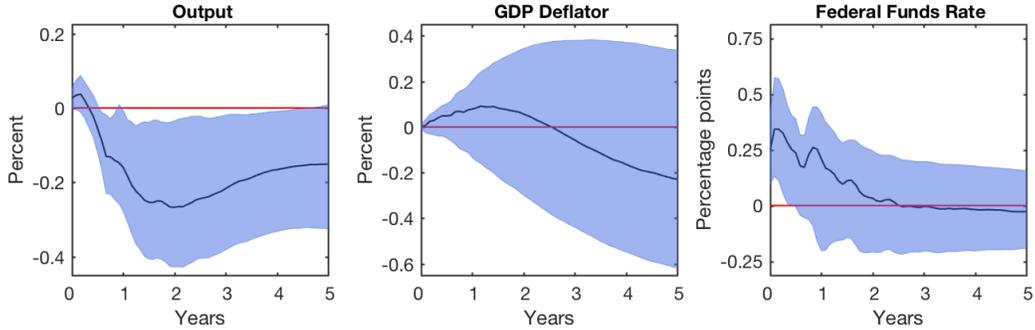
Figure 10 plots the IRFs to a contractionary monetary policy shock under the augmented alternative identification. Not surprisingly, similar posterior estimates for ψ_m with and without imposing the upper bound translate into very similar posterior estimates for the IRFs of output and prices. Nonetheless, results are similar to imposing a tighter bound of 2 on ψ_m .

5.4 Monetary Policy Equation in First Differences

Finally, in our baseline identification scheme, the fed funds rate responds to the level of output and prices. But researchers, especially those working with DSGE models, often consider Taylor-type

²⁵Results are robust to imposing an upper bound of 2 on ψ_y , and an upper bound of 3—also in combination with a lower bound of 1—on ψ_p .

FIGURE 10: IMPULSE RESPONSES OF SELECTED VARIABLES TO A MONETARY POLICY SHOCK
(Alternative identification with $\psi_m \in (0, 4)$)



NOTE: The solid lines depict median responses of the specified variable to a monetary policy shock of size 1 standard deviation under the alternative identification augmented with the restriction $\psi_m \in (0, 4)$; the shaded bands represent the 68 percent point-wise probability bands.

monetary policy equations in which the funds rate responds to inflation and some measures of economic activity, such as the output gap and/or GDP growth. To check the robustness of our results to this modification, we first re-estimate the reduced-form VAR in the first difference of all the variables but the fed funds rate, and then apply Restrictions 1 and 2 to the associated monetary policy equation.²⁶

$$r_t = \psi_y \Delta y_t + \psi_p \Delta p_t + \psi_{pc} \Delta p_{c,t} + \psi_{tr} \Delta tr_t + \psi_{nbr} \Delta nbr_t + \sigma \varepsilon_{1,t}, \quad (7)$$

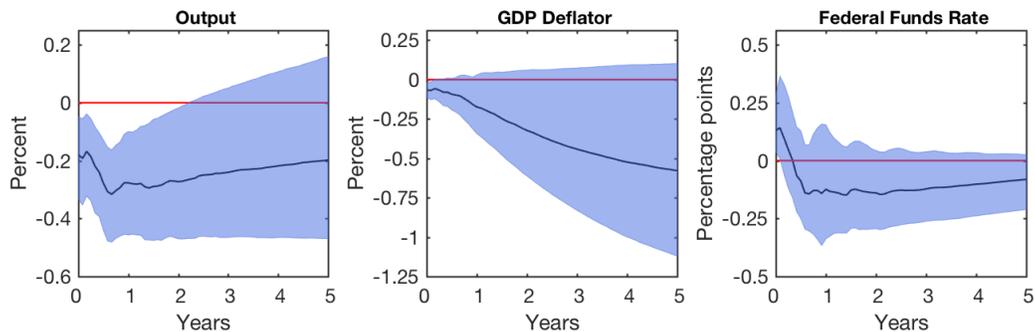
where $\sigma = a_{0,61}^{-1}$, and Δ denotes the first differences operator.

Figure 11 shows the posterior point-wise median IRFs of the endogenous variables to a contractionary shock to monetary policy when Restrictions 1 and 2 are imposed on equation (7), while the shaded bands represent the corresponding 68 percent point-wise posterior probability bands. Results are broadly consistent with those from the baseline 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 stance.

Thus, Figures 5-11 show that the result that a monetary policy shock that raises the fed funds rate lowers output in subsequent months with very high posterior probability is robust across

²⁶This specification includes a constant.

FIGURE 11: IMPULSE RESPONSES OF SELECTED VARIABLES TO A MONETARY POLICY SHOCK
(Baseline Specification — First Difference VAR)



NOTE: The solid lines depict median responses of the specified variable to a monetary policy shock of size 1 standard deviation under the baseline identification imposed on the reduced-form VAR estimated in first differences; the shaded bands represent the 68 percent point-wise probability bands.

different specifications.

6 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 decline in output with high posterior probability. Moreover, under our baseline identification, our responses for output, prices, and the fed funds rate closely resemble those from [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 do 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 on IRFs.

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Not-for-publication Appendix

A Comparison of the Alternative Identification to Uhlig (2005)

In this section we compare our alternative identification to the identification used in Uhlig (2005). To this end, we adapt the sign restrictions on the IRFs to the reduced-form VAR with money.

Restriction 9 *A monetary policy shock leads to a negative response of the GDP deflator, commodity prices, and money, and to a positive response of the fed funds rate, all at horizons $t = 0, \dots, 5$.*

Table 5 tabulates the probability of violating the sign and zero restrictions imposed by the alternative identification. As for the baseline identification, the first row shows that the set of models that satisfy Restriction 9 implies $\psi_y \neq 0$ and $\psi_p \neq 0$, thus violating Restriction 3, which imposes the restriction that the fed funds rate not react contemporaneously to output and prices. As shown in the second row of Table 5, the probability of drawing a negative ψ_m when we combine Restrictions 3 and 9 is 0.16, about the same as in the first row.

What are the consequences for the IRFs? Figure 12 plots the impulse responses of output, prices and the fed funds rate to an exogenous tightening of monetary policy identified by imposing Restriction 9. As in Uhlig's (2005) specification with reserves, an increase in the fed funds rate leads to an increase in output. The output response becomes negative after about six months, but zero is always included in the 68 percent probability bands. Therefore, there is no evidence that monetary policy shocks are contractionary when Restriction 9 is used to identify them: Uhlig's (2005) results survive the swap of reserves for money.

Panel (a) in Figure 13 plots the impulse responses associated with Restrictions 3 and 9.¹ Under this identification, the response of output is negative and similar to the response reported in Figure 2. Hence, combining the zero restrictions on the contemporaneous response of the fed funds rate to output and prices with Uhlig's restrictions on impulse responses suffices to recover the conventional effects of monetary policy on output. Panel (b) in Figure 12 confirms this result by presenting the results derived by combining Restrictions 3, 4, and 9: imposing an additional sign restriction on the

¹We do not report the impulse responses of commodity prices and money, as they are similar to those plotted in Figure 12. These responses are available upon request.

TABLE 5: Probability of Violating Restrictions Imposed by the Alternative Identification

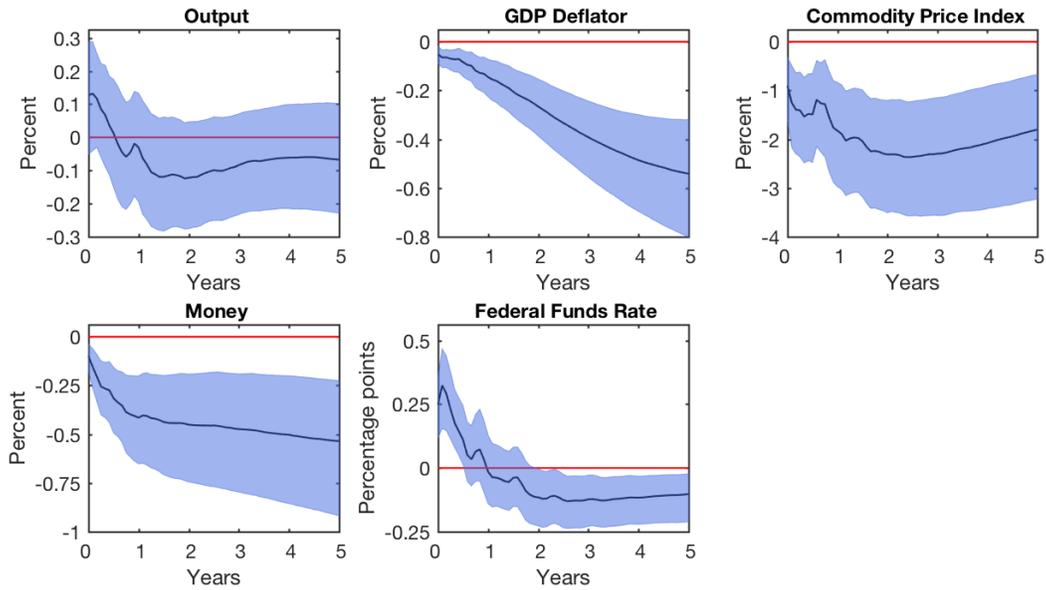
Probability	$P(\psi_y \neq 0 \cup \psi_p \neq 0)$	$P(\psi_m < 0)$
Restriction 9 ^[a]	1.00	0.20
Restrictions 3 & 9 ^[b]	0.00	0.16

NOTE: The entries in the table denote individual and joint probabilities of violating the zero and sign restrictions on the coefficients of the monetary policy equation imposed by our alternative identification for three identification strategies. See the main text for details.

^a Sign restrictions on impulse responses based on Uhlig (2005).

^b Sign restrictions on impulse responses based on Uhlig (2005) + zero restrictions on the systematic component of monetary policy described in Restriction 3.

FIGURE 12: IMPULSE RESPONSES TO A MONETARY POLICY SHOCK
(Uhlig (2005) Identification Using Money Instead of Reserves)



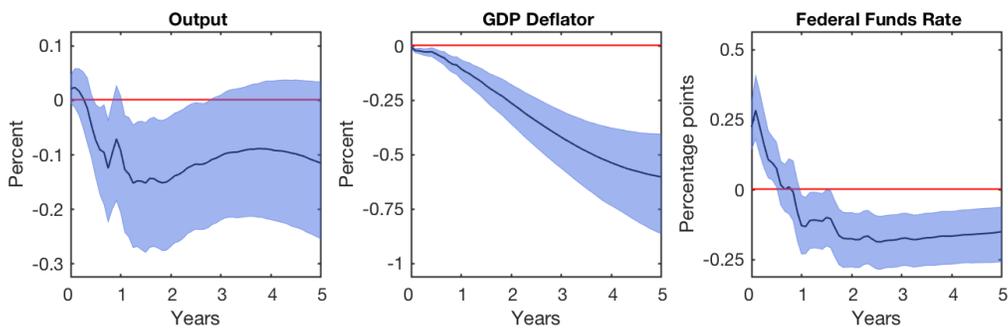
NOTE: The solid lines depict median responses of the specified variable to a contractionary monetary policy shock under the identification of Uhlig (2005); the shaded bands represent the 68 percent point-wise posterior probability bands.

contemporaneous response of the fed funds rate to money induces only minor changes in impulse responses compared to Panel (b).

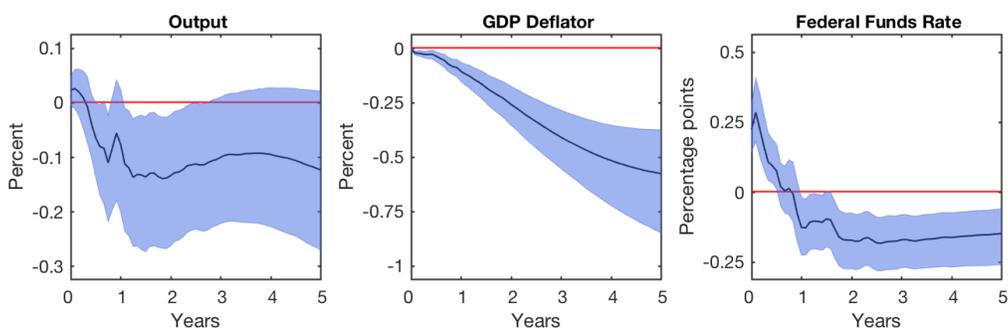
The comparison with Uhlig (2005) confirms the importance of disciplining the systematic component of monetary policy. In particular, we have consistently shown that it is essential to restrict the contemporaneous response of monetary policy to output and prices, either by imposing sign restrictions as under the baseline identification or by imposing zero restrictions as under the

alternative identification.

FIGURE 13: IMPULSE RESPONSES OF SELECTED VARIABLES TO A MONETARY POLICY SHOCK



(a) Responses to monetary policy shocks based on Restrictions 3 and 9



(b) Responses to monetary policy shocks based on Restrictions 3, 4, and 9

NOTE: The solid lines in panel (a) depict median responses to a monetary policy shock identified using the restrictions on impulse responses described in Restriction 9 and the zero restrictions on the systematic component described in Restriction 3, while those in panel (b) depict median responses to a monetary policy shock identified using the restrictions on impulse responses described in Restriction 9 and the zero and sign restrictions on the systematic component described in Restrictions 3 and 4; the shaded bands represent the 68 percent point-wise probability bands.