

# 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, while leaving unrestricted the response of variables to monetary policy shocks. We consistently find that an increase in the fed funds rate induces a contraction in real activity. We also show that the identification strategy in Uhlig (2005), which imposes sign restrictions on the impulse responses to a monetary shock, implies a counterfactual systematic component of monetary policy. This finding accounts for the difference in results with Uhlig (2005), who found that contractionary monetary policy shocks have no clear effect on real GDP.

*JEL classification:* E52; C51

*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 increase in the fed funds rate induces a reduction in real activity.<sup>1</sup> 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.<sup>2</sup>

The consensus 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.<sup>3</sup> Under his identification, the conventional wisdom vanishes.

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 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

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<sup>1</sup>A 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.

<sup>2</sup>Researchers 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 \(2016\)](#).

<sup>3</sup>More 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](#)).

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 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 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.<sup>4</sup>

Our results under the baseline identification show that a tightening of monetary policy has contractionary effects on output and prices. The endogenous 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 minimal number of restrictions. Under the alternative identification scheme, we find again that monetary policy shocks induce a decline in real economic activity, while they have no economically discernible effect on prices. Accordingly, the muted response of prices induces a persistently elevated response of the fed funds rate. All told, our analysis consistently shows that a tightening of monetary policy has contractionary effects on output while addressing [Uhlig's \(2005\)](#) critique.

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

While the sign and zero restrictions that constitute the backbone of our identification are intuitive and based on simple economic theory, implementation is not straightforward. We 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 identification strategies employed in this paper and in [Uhlig \(2005\)](#) share important common features. First, as already mentioned, they do not impose restrictions on the response of output to monetary policy shocks. Thus, the sign and size of the effects of monetary policy shocks on output are left for the data to decide. Second, they only restrict one structural equation rather than the entire system. Hence, the resulting SVARs are partially identified. Third, they only impose a minimal number of restrictions and the resulting models are set-identified.<sup>5</sup> 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 models 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. That is, the identification scheme in [Uhlig \(2005\)](#) violates our restrictions and does not provide sufficient discipline to the systematic behavior of monetary policy. Through the lenses of our model, and as discussed in [Leeper, Sims, and Zha \(1996\)](#), a corollary to this finding is that the shocks identified in [Uhlig \(2005\)](#) are not 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 models. The drawback is that the identified set of models might be very large and include models with questionable implications

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<sup>5</sup>[Inoue and Kilian \(2013\)](#) define a model to be partially identified when only a subset of structural shocks is identified, and define a model 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.

that have a substantial impact on inference. 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 model. 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 sign restrictions on the long-run coefficients that describe the response of monetary policy to current and lagged output and prices.<sup>6</sup> Results are also 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 models. 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.

## 2 Estimation and Identification

In this section, we first describe the SVAR model 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,  $\varepsilon_t$  is an  $n \times 1$  vector of structural shocks,  $\mathbf{A}_\ell$

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

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,  $\nu$  is the lag length, and  $T$  is the sample size. The vector  $\varepsilon_t$ , 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 model 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) model 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, since the model described in equation (1) is 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 resulting models are partially identified. Moreover, since we impose fewer than  $n - 1$  zero restrictions, the resulting structural models 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  $\varepsilon_{1t}$  denotes the first entry of  $\varepsilon_t$ ,  $\mathbf{a}_{\ell,1}$  denotes the first column of  $\mathbf{A}_\ell$  for  $0 \leq \ell \leq \nu$ , and  $a_{\ell,ij}$  denotes the  $(i, j)$  entry of  $\mathbf{A}_\ell$  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  $\mathbf{a}_{\ell,1}$  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 \(2005\)](#).<sup>7</sup> 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 and 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

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

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.<sup>8</sup>

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 model 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 prices unrestricted. The sign of the restrictions are widely supported by theoretical and empirical studies on monetary policy rules, but 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.<sup>9</sup> 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.<sup>10</sup> Despite all the arguments listed above, some researchers find it implausible that a central bank can react to economic conditions within a month. This critique

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<sup>8</sup>See [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.

<sup>9</sup>Data on commodity prices are available in real time.

<sup>10</sup>An 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.



motivates the alternative identification whose defining feature is to rule out such contemporaneous responses.

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

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

where  $\psi_y = a_{0,61}^{-1} a_{0,11}$ ,  $\psi_p = a_{0,61}^{-1} a_{0,21}$ ,  $\psi_{p_c} = a_{0,61}^{-1} a_{0,31}$ ,  $\psi_{tr} = a_{0,61}^{-1} a_{0,41}$ ,  $\psi_{nbr} = a_{0,61}^{-1} a_{0,51}$ , and  $\sigma = a_{0,61}^{-1}$ . Equipped with this representation of the monetary policy equation, we summarize Restrictions 1 and 2 as follows.

**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,  $\psi_{p_c}$  remains unrestricted.*

Remark 1 makes clear that Restrictions 1 and 2 only restrict the structural parameters and set and partially identify the model; this is a key departure from [Christiano, Eichenbaum, and Evans \(1996\)](#), who instead exactly and fully identify the SVAR.<sup>11</sup> Thus, we allow for a set of models to be compatible with the sign and zero restrictions rather than a single one.<sup>12</sup>

## 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 model 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.

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<sup>11</sup>We 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  $\sigma > 0$ .

<sup>12</sup>[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.

**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 is still agnostic about the response of output to monetary policy.

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

Motivated by Sims and Zha (2006), 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.<sup>13</sup>

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

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

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

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<sup>13</sup>We 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  $\sigma > 0$ .

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 \(2014\)](#).<sup>14</sup>

## 2.5 Dataset, Reduced-Form Model, 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 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.<sup>15</sup> For the same reason, we have taken the reduced-form VAR specification described in [Uhlig \(2005\)](#).

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<sup>14</sup>We 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.

<sup>15</sup>We have crossed-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](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.

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.<sup>16</sup>

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

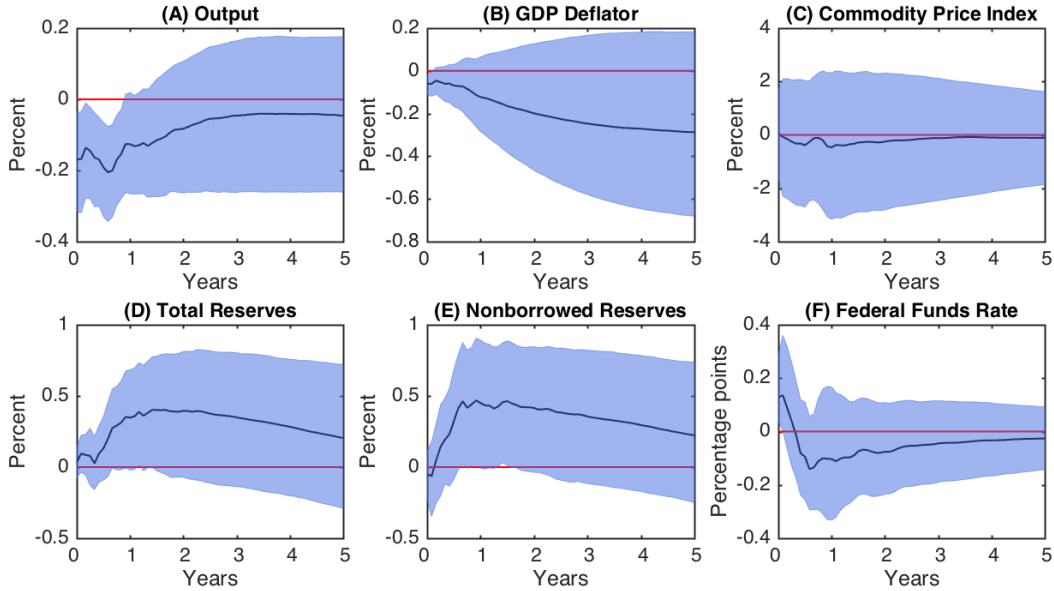
In this section we describe the results for our baseline and alternative identification schemes. We first present the IRFs to a contractionary monetary policy shock, and then we discuss the coefficients of the monetary policy equations associated with the two identification schemes.

The solid lines in [Figure 1](#) show the posterior point-wise median IRFs of the endogenous variables

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<sup>16</sup>In 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.

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.

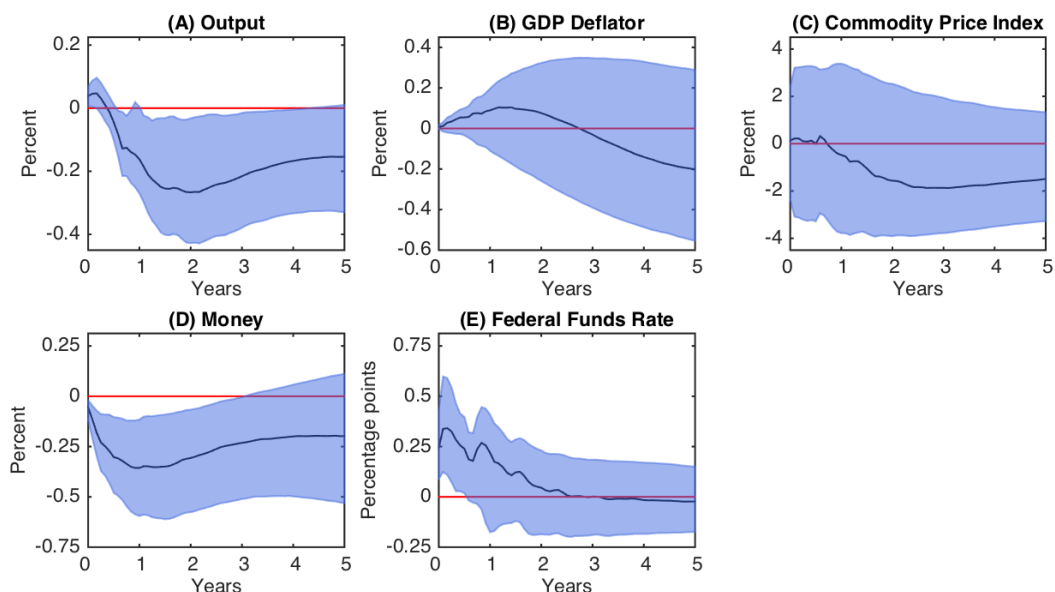
to a contractionary shock to monetary policy under the baseline identification scheme, while the shaded bands represent the corresponding 68 percent point-wise posterior probability bands.<sup>17</sup> A contractionary monetary policy shock leads to an immediate increase in the fed funds rate of around 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 models included in the identified set feature the price puzzle, our restrictions imply a substantial posterior probability mass on models that have 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 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

<sup>17</sup>All results are based on 10,000 draws from the posterior distribution of the structural parameters and all shocks are one standard deviation.

nonborrowed reserves are about zero when the fed funds rate is positive and increase only when the monetary stance loosens.

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.

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 \(2007\)](#). The response of inflation to a contractionary monetary shock builds up to a response of the price level in line with what was reported in Figure 1. The hump-shaped 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 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 estimated models 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 shock to monetary policy under the alternative identification scheme, while the shaded bands represent the corresponding 68 percent point-wise posterior probability bands. Qualitatively,

TABLE 1: Contemporaneous Coefficients in the Monetary Policy Equations

<i>(a) Baseline Identification</i>					
Coefficient	$\psi_y$	$\psi_p$	$\psi_{pc}$	$\psi_{ptr}$	$\psi_{nbr}$
	1.22	3.52	-0.02	0.00	0.00
	[0.34; 3.11]	[0.98; 9.88]	[-0.41; 0.32]		
<i>(b) Alternative Identification</i>					
Coefficient	$\psi_y$	$\psi_p$	$\psi_{pc}$	$\psi_m$	
	0.00	0.00	-0.01	0.83	
			[-0.66; 0.54]	[0.21; 3.22]	

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 16<sup>th</sup> and 84<sup>th</sup> percentiles of the posterior distributions are reported in brackets. See the main text for details.

the IRFs are similar to those plotted in Figure 1. 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 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  $\psi_y$  and  $\psi_p$  are 1.22 and 3.52, 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  $\psi_{pc}$  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  $\psi_y$  and  $\psi_p$  to zero. At the posterior median, the contemporaneous response of the fed funds rate to changes in money is slightly below 1, while the response to changes in commodity prices is  $-0.01$ , 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 \(2003\)](#).<sup>18</sup>

In combination, our results show that, for plausible specifications of the systematic component of monetary policy, contractionary monetary policy shocks induce a decline in real activity. Moreover, under our baseline identification strategy, these shocks also induce a significant decline in prices, and results are consistent with the effects of a contractionary monetary policy as documented in estimated DSGE models. Importantly, the identification schemes do not impose restrictions either on the response of output or on the response of prices to a monetary shock. 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 plausible restrictions on the systematic component of monetary policy for the identification of monetary policy shocks.<sup>19</sup> To this end, we compare our baseline identification to that of [Uhlig \(2005\)](#). This is a natural comparison because, while both approaches partially and set identify the SVAR and do not impose any restriction on the output response to monetary policy shocks, they obtain markedly different results: while we find that output drops after a contractionary monetary policy shock, [Uhlig \(2005\)](#) finds a muted, or even positive, response.

The comparison revolves around two exercises. We first show that the systematic component of monetary policy implied by [Uhlig \(2005\)](#) is counterfactual. We then show that a plausible systematic component of monetary policy—which we enforce by combining Uhlig’s identification with our restrictions on the systematic component—suffices to recover the conventional response of output.

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<sup>18</sup>Many 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.

<sup>19</sup>We provide a similar comparison for the alternative identification scheme in [Appendix A](#).



Uhlig (2005) identifies monetary policy shocks by imposing the following sign restrictions on IRFs.

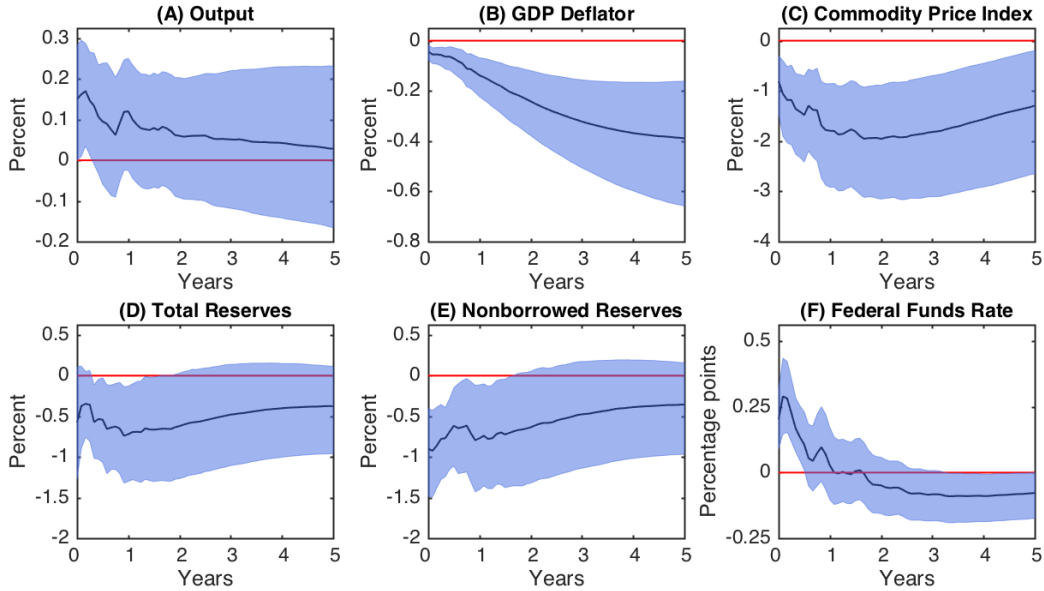
**Restriction 5** *A monetary policy shock leads to a negative response of the GDP deflator, commodity prices, and nonborrowed reserves, and to a positive response of the fed funds rate, all at horizons  $t = 0, \dots, 5$ .*

Restriction 5 only 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 shock to monetary policy 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 (2005). The 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 shows that, in response to a contractionary monetary policy shock identified only by imposing Restriction 5, output does not drop. At least for the first year, this drop is precisely estimated. Hence, under this identification scheme, neutrality of monetary policy shocks is not inconsistent with the data. Furthermore, Uhlig (2005) claims that a drop in output can only be obtained if one controversially restricts its contemporaneous response after a monetary policy shock to be zero. In what follows we argue that it is not this controversial restriction but a plausible specification of the systematic component of monetary policy that is the key to generating monetary non-neutrality.

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 -0.43 and the posterior distribution puts a sizable weight on negative values. Hence, Uhlig (2005) implies a counterfactual 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

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.

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

Coefficient	$\psi_y$	$\psi_p$	$\psi_{pc}$	$\psi_{ptr}$	$\psi_{nbr}$
Restriction 5 <sup>[a]</sup>	-0.43 [-2.54; 0.82]	2.25 [0.11; 7.21]	0.11 [0.00; 0.37]	0.10 [-0.48; 0.67]	0.05 [-0.40; 0.70]
Restrictions 1 & 5 <sup>[b]</sup>	-1.29 [-5.11; -0.05]	2.56 [0.74; 7.14]	0.15 [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 16<sup>th</sup> and 84<sup>th</sup> percentiles of the posterior distributions are reported in brackets. See the main text for details.

<sup>a</sup> Sign restrictions on IRFs as in Uhlig (2005).

<sup>b</sup> Sign restrictions on IRFs as in Uhlig (2005) + zero restrictions on the systematic component of monetary policy described in Restriction 1.

models. By contrast, the response of the fed funds rate to changes in prices seems plausible, with a posterior median estimate of 2.25 and the interval containing the 68 percent of the posterior distribution mostly spanning positive values.

As Arias, Rubio-Ramirez, and Waggoner (2016) point out, the set of models identified by

imposing both sign and zero restrictions—as in our baseline identification—are of measure zero in the set of models identified by imposing only the sign restrictions. That is, the set of models that satisfy Restriction 5 violate Restriction 1 by construction. Thus, to understand the role of the zero restrictions, we explore an identification that combines Restrictions 1 and 5. As shown in the second row of Table 2, under this identification, the posterior distribution of  $\psi_y$  shifts to the left, making negative values considerably more likely—the posterior median of  $\psi_y$  moves from -0.43 to -1.29. The additional zero restrictions do not have a quantitatively relevant effect on the posterior distributions of  $\psi_p$  and  $\psi_{pc}$ .

Table 3 tabulates the posterior probabilities that the models consistent with Uhlig’s restrictions violate the sign and zero restrictions imposed by the baseline identification. The first row confirms that the set of models 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 and prices are 0.66 and 0.16, 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 that  $\psi_{tr} = 0$  and  $\psi_{nbr} = 0$ . The posterior probability of drawing a negative  $\psi_y$  is 0.84, almost 20 percentage points higher than when we impose only Restriction 5. The posterior probability of drawing a negative  $\psi_p$  drops to 0.01, and the posterior probability of violating Restriction 2 is 0.84—similar to the one reported in the first row.

In combination, Tables 2 and 3 shows that most of the models included in the set identified by Uhlig (2005) imply a counterfactual systematic component of monetary policy that violates the sign and zero restrictions that we impose in our baseline identification. Following Leeper, Sims, and Zha (1996); Leeper and Zha (2003); and Sims and Zha (2006a), a corollary to the findings reported in Tables 2 and 3 is that the shocks identified by Restriction 5—in isolation or combined with Restriction 1—are not monetary policy shocks.

We now 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. The solid lines in Panel (a) in Figure 4 plot the posterior median IRFs of selected endogenous variables to a contractionary shock to monetary policy under Restrictions 1 and 5, while the shaded bands represent the corresponding 68 percent point-wise posterior probability bands. Compared to

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 <sup>[a]</sup>	1.00	0.66	0.16	0.79
Restrictions 1 & 5 <sup>[b]</sup>	0.00	0.84	0.01	0.84

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.

<sup>a</sup> Sign restrictions on IRFs as in Uhlig (2005).

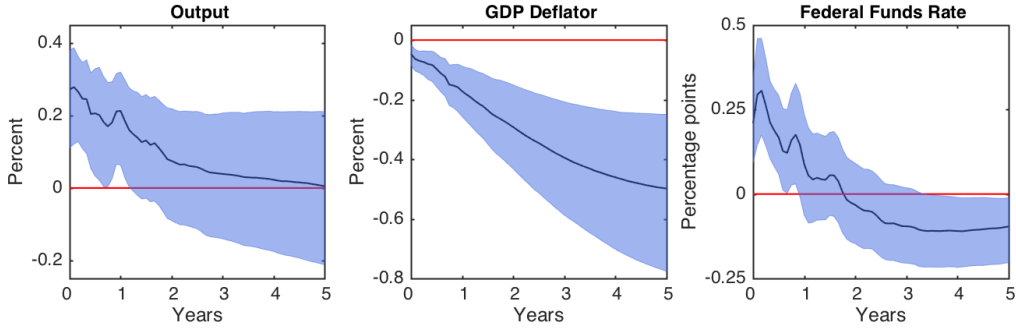
<sup>b</sup> Sign restrictions on IRFs as in Uhlig (2005) + zero restrictions on the systematic component of monetary policy described in Restriction 1.

Figure 3, the higher posterior probability of violating the sign restriction on  $\psi_y$  is associated with a more 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 the top panel. As expected, adding more restrictions makes the posterior estimates more precise.

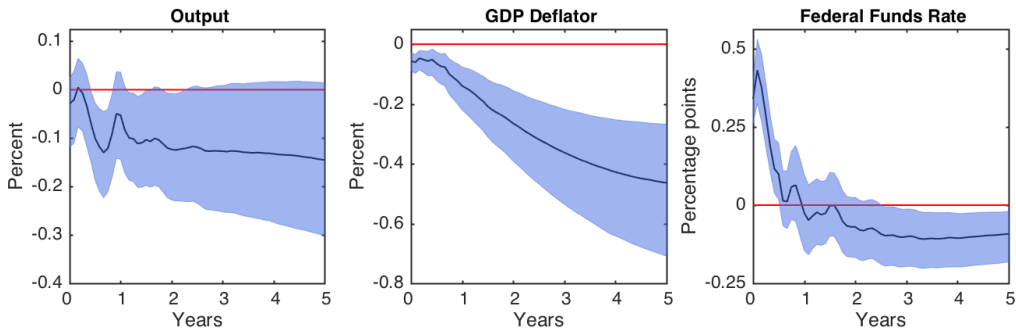
Panel (b) in Figure 4 plots the posterior median IRFs of selected endogenous variables to a contractionary shock to monetary policy under Restrictions 1, 2, and 5, that is, by combining Uhlig (2005) and our baseline identification, while the shaded bands represent the corresponding 68 percent point-wise posterior probability bands. Under this identification, the output response is negative and stays so over time. Hence, Table 3 and Panel (b) of Figure 4 show that our restrictions substantially shrink the set of models originally identified by Uhlig (2005) and that excluding models with counterfactual monetary policy equations—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 and thereby to recover the consensus.

The comparison of Uhlig (2005) to our baseline identification scheme shows that the restrictions on the systematic component of monetary policy, and not the zero restriction on the response of output to a monetary policy shock, are crucial to generating a drop in output following a contractionary monetary policy shock. Once restrictions are added to ensure that the systematic component of monetary policy is not counterfactual, output drops following a contractionary monetary policy shock.

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 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.

## 5 Robustness

In the previous section we showed that while set-identification is appealing because results are robust to a wide range of models, the identified set of models might be very large and include models 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, the GDP deflator and the fed funds rate.<sup>20</sup>

## 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 to the endogenous variables in the model. 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 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 in 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.<sup>21</sup>

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

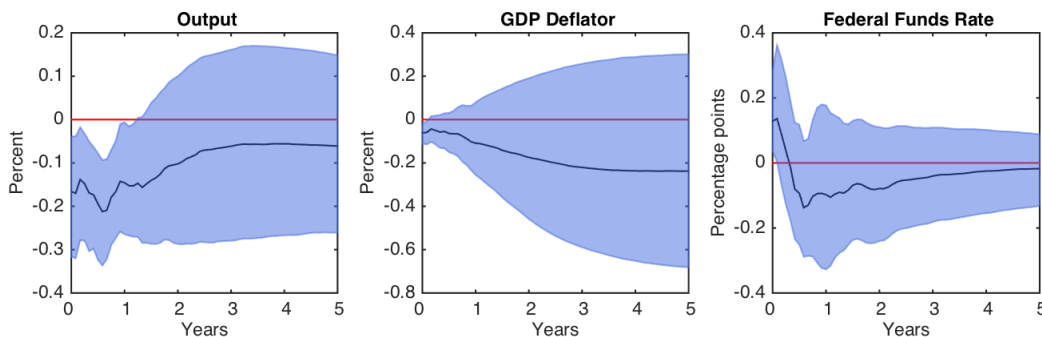
Figure [5](#) reports the responses of output, prices, and the fed funds rate to a contractionary monetary shock identified under the baseline identification augmented with Restriction [6](#). The

<sup>20</sup>The responses of other endogenous variables—unless otherwise noted—are similar to those described in Section [3](#) and are available on request.

<sup>21</sup>The SVAR specifications used in this subsection include a constant, for consistency with [Sims and Zha \(2006b\)](#).

median responses and 68 percent point-wise posterior probability bands are similar to those reported in Figure 1.

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.

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 non-negative, i.e.,  $\psi_{LR,m} > 0$ .*

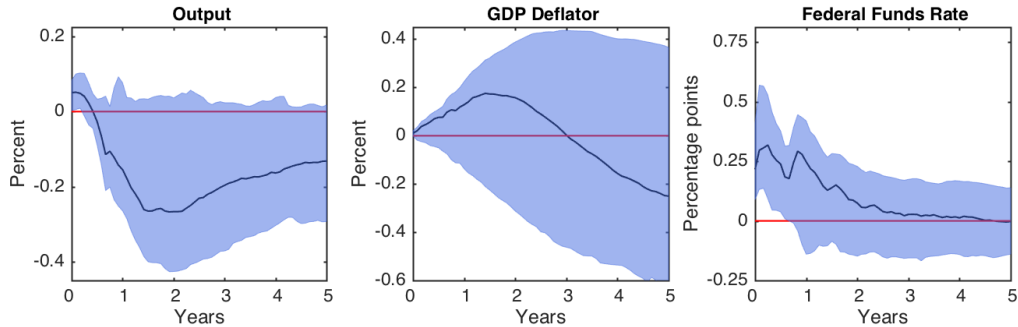
In the second specification we impose sign restrictions on the long-run coefficients on output, prices, and money. The idea is that—even in a model where monetary policy does not react contemporaneously to output and prices—it is plausible to assume that the long-run reaction of the fed funds rate to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

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

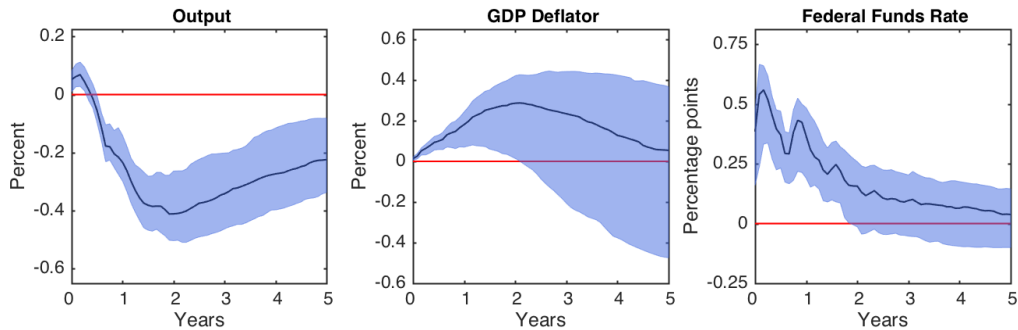
Figure 6 depicts the IRFs. As shown in Panel (a), under the alternative identification augmented with Restriction 7, the median responses of output, prices, and the fed funds rate to a contractionary monetary shock are similar to those reported in Figure 2, while the 68 percent point-wise posterior probability 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, the model features a more pronounced and precisely estimated price puzzle. The positive response of prices to a contractionary monetary shock accounts for the persistent tightening in the monetary policy stance despite the decline in output.

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

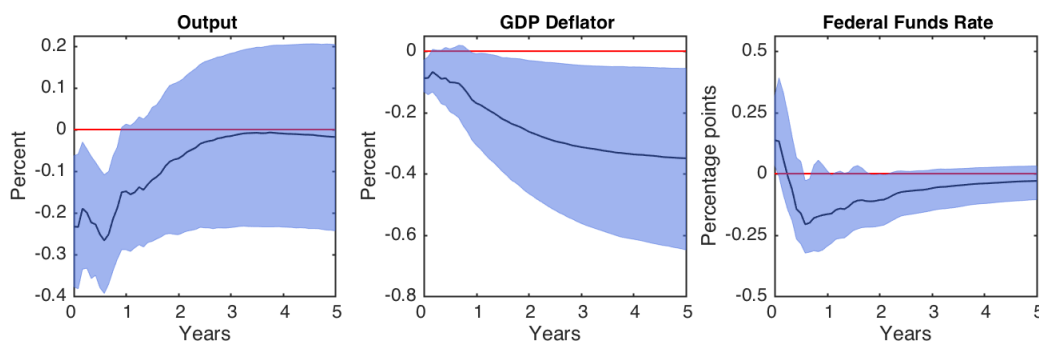
Clearly, Figures 5 and 6 confirm that our finding that output drops following a contractionary monetary policy shock is robust to more stringent characterizations of the systematic component of monetary policy that impose sign restrictions on the long-run coefficients of output, prices, and money.



## 5.2 Zero Restriction on $\psi_{p_c}$

Our baseline and alternative identification schemes follow [Christiano, Eichenbaum, and Evans \(1996\)](#) and [Leeper and Zha \(2003\)](#) by allowing the fed funds rate to respond to contemporaneous movements in commodity prices and by not imposing any restriction on  $\psi_{p_c}$ . 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  $\psi_{p_c} = 0$ .

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



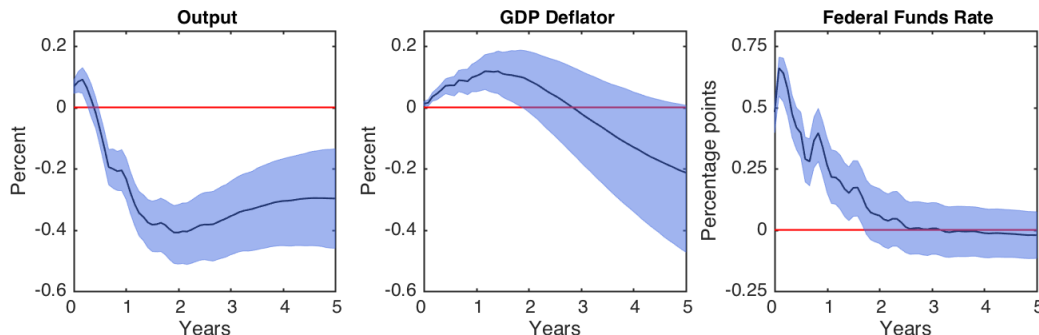
NOTE: The solid lines depict median responses of the specified variable to a contractionary monetary policy shock of size 1 standard deviation under the baseline identification augmented with the restriction  $\psi_{p_c} = 0$ ; the shaded bands represent the 68 percent point-wise posterior probability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

Figure 7 plots the IRFs to a contractionary monetary shock when we add the restriction  $\psi_{p_c} = 0$  to our baseline identification scheme. The additional restriction leads to a slightly more pronounced drop in output and in prices, to a significant decline in the commodity price index (not shown), 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 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 and more hump-shaped, returning to its pre-shock level within five years. The response of prices shows a more pronounced price puzzle than in Figure 2, while the decline in commodity prices (not shown) is stronger and more significant. 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.

### 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 models with potentially implausible 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  $\psi_y$  and  $\psi_p$  can only take values between 0 and 4. The posterior median for  $\psi_y$  is 0.97, and the 68 percent probability interval ranges from about 0.3 to 2.1. The posterior median for  $\psi_p$  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  $\psi_m$  can only take values between 0 and 4. The posterior median of  $\psi_m$  is 0.6, and the 68 percent probability interval ranges

TABLE 4: Contemporaneous Coefficients in the Monetary Policy Equations

(a) <i>Baseline Identification</i>					
Coefficient	$\psi_y$	$\psi_p$	$\psi_{pe}$	$\psi_{ptr}$	$\psi_{nbr}$
	0.91	1.70	0.00	0.00	0.00
	[0.27; 2.12]	[0.53; 3.12]	[-0.24; 0.25]		
(b) <i>Alternative Identification</i>					
Coefficient	$\psi_y$	$\psi_p$	$\psi_{pe}$	$\psi_m$	
	0.00	0.00	0.00	0.67	
			[-0.50; 0.47]	[0.18; 1.84]	

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 16<sup>th</sup> and 84<sup>th</sup> percentiles of the posterior distributions are reported in brackets. See the main text for details.

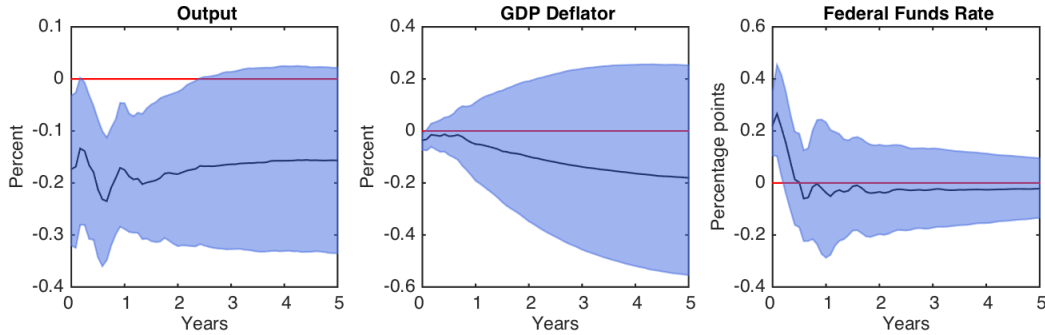
from 0.2 to 1.8, fairly similar to those reported in Table 1.

Figure 9 plots the IRFs to a contractionary monetary shock under the augmented baseline identification.<sup>22</sup> 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 10 plots the IRFs to a contractionary monetary shock under the augmented alternative identification. Not surprisingly, similar posterior estimates for  $\psi_m$  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  $\psi_m$ .

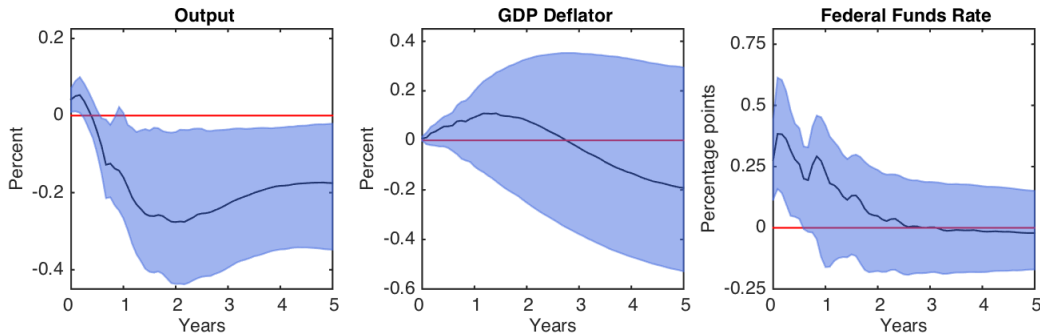
<sup>22</sup>Results are robust to imposing an upper bound of 2 on  $\psi_y$ , and an upper bound of 3—also in combination with a lower bound of 1—on  $\psi_p$ .

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: 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.

#### 5.4 Monetary Policy Equation in First Differences

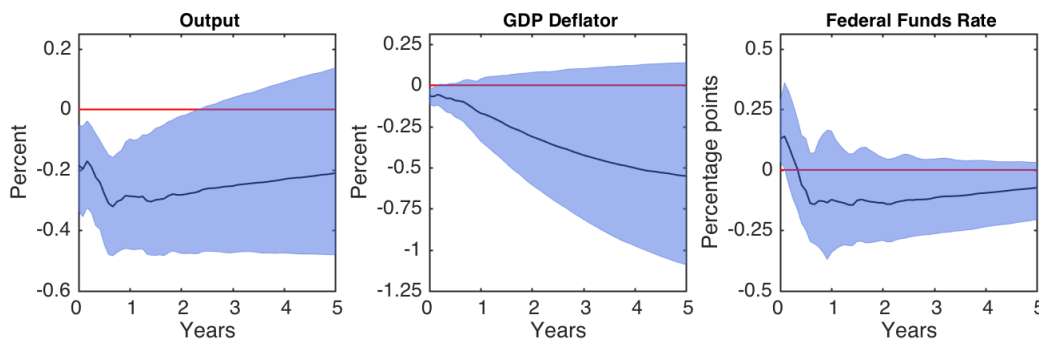
Finally, in our baseline identification scheme, the fed funds rate responds to the level of output and prices. But researchers, especially those working with DSGE models, often consider Taylor-type monetary policy equations in which the funds rate responds to inflation and some measures of economic activity, 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 model 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.<sup>23</sup>

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

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

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



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 model estimated in first differences; the shaded bands represent the 68 percent point-wise probability bands.

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 more hump-shaped than in the baseline specification, 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.

## 6 Conclusion

This paper characterizes the effects of monetary policy shocks in the United States using a set-identified SVAR. Key to our approach is that we identify monetary policy shocks by imposing the

<sup>23</sup>This specification includes a constant.

minimal number of restrictions needed to generate a systematic component of monetary policy that encompasses the vast literature on monetary policy rules. We consistently find that monetary policy shocks induce an economic and statistically significant decline in output. Moreover, under our baseline identification, our responses for output, prices, and the fed funds rate closely resemble those from [Smets and Wouters \(2007\)](#). We also document the importance of imposing plausible restrictions on the systematic component of monetary policy by showing that set-identified models with a counterfactual systematic component imply a lack of response of output to monetary shocks.

Our analysis shows that while set identification is appealing because it does not require inference to be based on very specific—and often questionable—exclusion restrictions, it is subject to the danger of including implausible models. Our results suggest that carefully imposing restrictions on the structural coefficients, as also advocated by [Baumeister and Hamilton \(2015\)](#), rather than on impulse responses, as typically done in the literature, might be more sensible and might mitigate this drawback of set-identified SVARs. Obviously, the issue of how to conduct set identification in SVARs is not limited to the identification of monetary policy shocks, and the approach described in this paper can be applied to a variety of problems.

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## 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 model 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 A.1 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 fed funds rate not react contemporaneously to output and prices. As shown in the second row of Table A.1, the probability of drawing a negative  $\psi_m$  when we combine Restrictions 3 and 9 is 0.18, about the same as in the first row.

What are the consequences for the IRFs? Figure A.1 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.

TABLE A.1: Probability of Violating Restrictions Imposed by the Alternative Identification

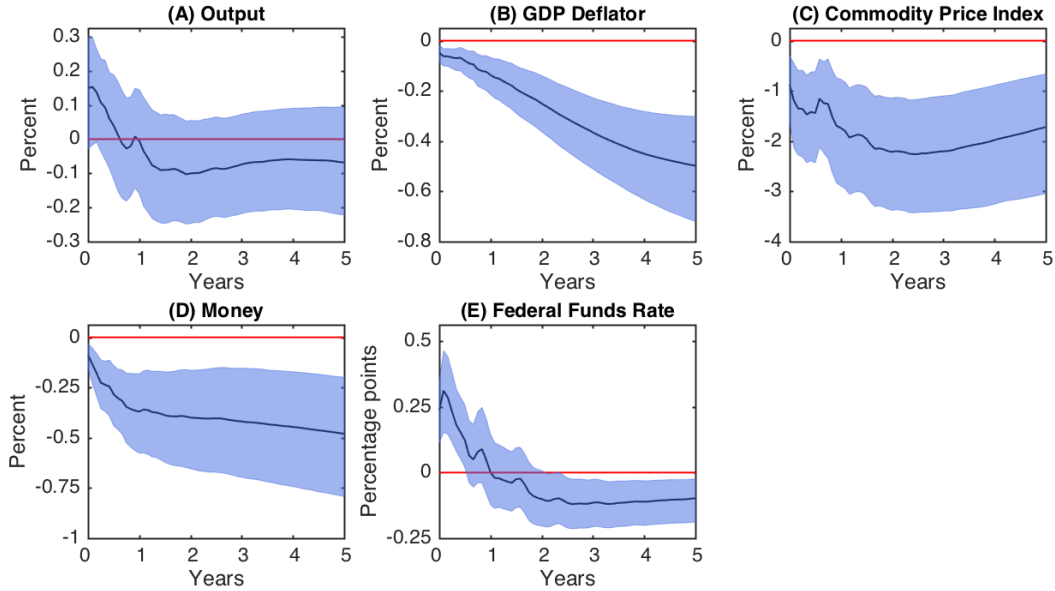
Probability	$P(\psi_y \neq 0 \cup \psi_p \neq 0)$	$P(\psi_m < 0)$
Restriction 9 <sup>[a]</sup>	1.00	0.16
Restrictions 3 & 9 <sup>[b]</sup>	0.00	0.18

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.

<sup>a</sup> Sign restrictions on impulse responses based on Uhlig (2005).

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

FIGURE A.1: 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.

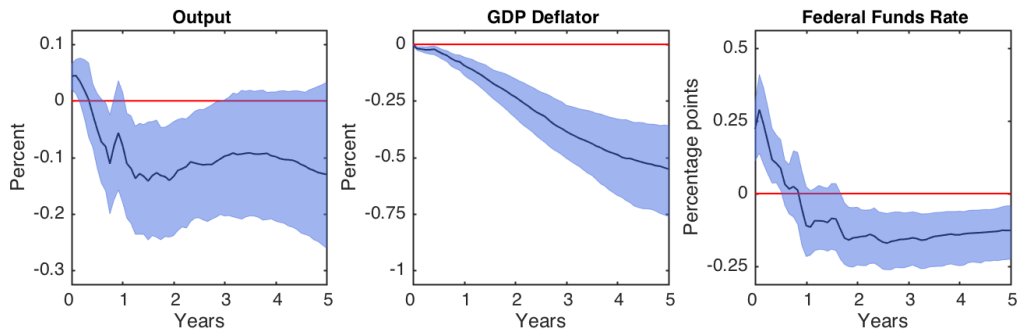
Panel (a) in Figure A.2 plots the impulse responses associated with Restrictions 3 and 9.<sup>24</sup> Under this identification, the response of output is negative and similar to the response reported in Figure 2. Hence, combining the zero restrictions on the contemporaneous response of the fed funds 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 A.1 confirms this result by presenting the results derived by combining Restrictions 3, 4, and 9: imposing an additional sign restriction on the 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

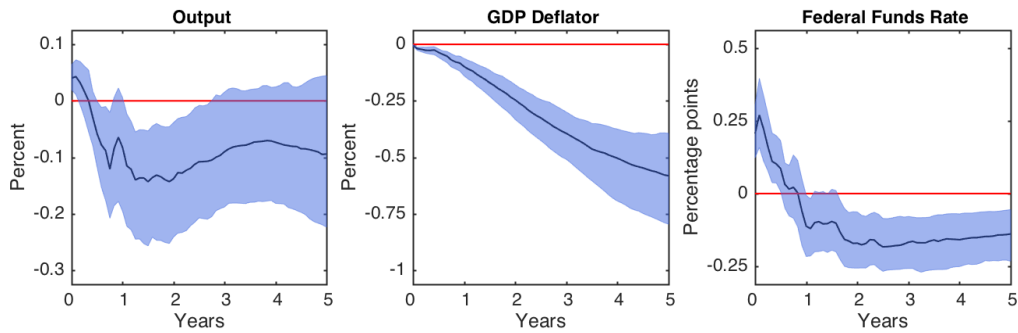
<sup>24</sup>We do not report the impulse responses of commodity prices and money, as they are similar to those plotted in Figure A.1. These responses are available upon request.

alternative identification.

FIGURE A.2: 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 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 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.