ISSN 1518-3548

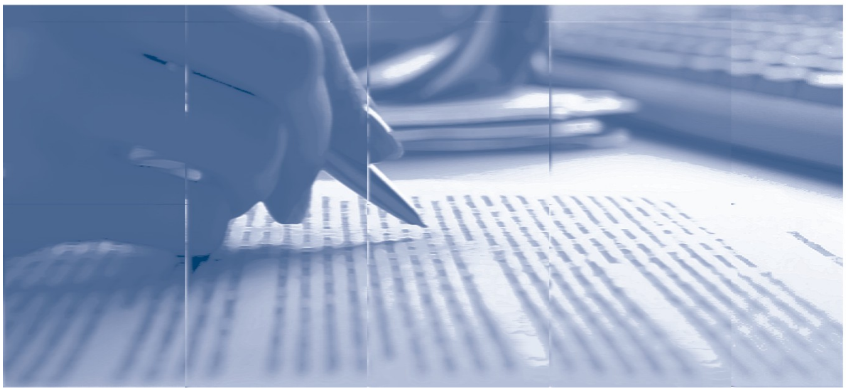
BANCO CENTRAL DO BRASIL

"Still" an Agnostic Procedure to Identify Monetary Policy Shocks with Sign Restrictions

Bruno Perdigão

June 2019

Working Papers



494

ISSN 1518-3548
CGC 00.038.166/0001-05

Working Paper Series	Brasília	n. 494	June	2019	p. 1-33

Working Paper Series

Edited by Research Department (Depep) – E-mail: workingpaper@bcb.gov.br

Editor: Francisco Marcos Rodrigues Figueiredo – E-mail: francisco-marcos.figueiredo@bcb.gov.br

Co-editor: José Valentim Machado Vicente – E-mail: jose.valentim@bcb.gov.br

Head of Research Department: André Minella – E-mail: andre.minella@bcb.gov.br

The Banco Central do Brasil Working Papers are all evaluated in double blind referee process.

Reproduction is permitted only if source is stated as follows: Working Paper n. 494.

Authorized by Carlos Viana de Carvalho, Deputy Governor for Economic Policy.

General Control of Publications

Banco Central do Brasil

Comun/Divip

SBS – Quadra 3 – Bloco B – Edifício-Sede – 2º subsolo

Caixa Postal 8.670

70074-900 Brasília – DF – Brazil

Phones: +55 (61) 3414-3710 and 3414-3565

Fax: +55 (61) 3414-1898

E-mail: identidadevisual.comun@bcb.gov.br

The views expressed in this work are those of the authors and do not necessarily reflect those of the Banco Central or its members.

Although these Working Papers often represent preliminary work, citation of source is required when used or reproduced.

As opiniões expressas neste trabalho são exclusivamente do(s) autor(es) e não refletem, necessariamente, a visão do Banco Central do Brasil.

Ainda que este artigo represente trabalho preliminar, é requerida a citação da fonte, mesmo quando reproduzido parcialmente.

Citizen Service Division

Banco Central do Brasil

Deati/Diate

SBS – Quadra 3 – Bloco B – Edifício-Sede – 2º subsolo

70074-900 Brasília – DF – Brazil

Toll Free: 0800 9792345

Fax: +55 (61) 3414-2553

Internet: http//www.bcb.gov.br/?CONTACTUS

Non-technical Summary

What is the effect of monetary policy on the economy? This question has been addressed empirically at least in the last 30 years with a large variety of econometric techniques. But results are far from conclusive and some of them point to effects with different directions than theory suggests, even for key macroeconomic variables, such as inflation and output. The reason for the lack of convergence in effects for such an old question lies in the difficulty of estimating causal effects in macroeconomics. Since most macro variables are endogenously determined in dynamic systems, identifying the effects of a variation in the desired variable (the monetary policy rate, for example) requires the introduction of identification assumptions the data are typically silent about.

In this paper I use prominent models as a laboratory to analyze the performance of different identification strategies and propose the introduction of new model consistent assumptions to identify monetary policy effects. Specifically, I propose to add as an assumption the inability of monetary policy to have real effects ten years after a change in the policy rate, besides standard restrictions on how interest rates and inflation should react to monetary policy. I present evidence that these assumptions help the identification of causal monetary policy effects in two prominent macroeconomic models: the canonical three-equation new keynesian model and the Smets and Wouters (2007) model. That is, from the models' perspective, I show the introduction of these assumptions approximates the identified monetary policy effects to its true effects. In a simple empirical application, I also show it might be important to recover short-term real effects of monetary policy.

Sumário Não Técnico

Qual o efeito da política monetária na economia? Essa questão tem sido abordada empiricamente nos últimos 30 anos com diferentes técnicas econométricas. Mas os resultados estão longe de serem conclusivos e, alguns deles, apontam para efeitos em direções opostas ao que a teoria preconiza, até para variáveis macroeconômicas usuais, como inflação e produto. A explicação para esse fenômeno está relacionada à dificuldade de estimar efeitos causais em economia, particularmente em variáveis macroeconômicas. Como as variáveis macroeconômicas são endogenamente determinadas em sistemas dinâmicos, a identificação de efeitos causais de determinada variável (a taxa básica de juros, por exemplo), exige a introdução de hipóteses de identificação, sobre as quais os dados disponíveis são geralmente pouco informativos.

Neste artigo, utilizo modelos proeminentes como laboratório para analisar a performance de diferentes estratégias de identificação e proponho a introdução de novas hipóteses, consistentes com os modelos, para identificação dos efeitos causais de política monetária. Especificamente, como nova hipótese de identificação, proponho a incapacidade da política monetária em produzir efeitos reais dez anos após a variação da taxa básica de juros, além das hipóteses usuais sobre como as taxas de juros e a inflação devem reagir à política monetária. Apresento evidências de que essas hipóteses auxiliam na identificação de efeitos causais de política monetária em dois modelos macroeconômicos canônicos: o modelo novo-keynesiano básico de três equações e o modelo de Smets and Wouters (2007). Isto é, sob o ponto de vista dos modelos, mostro que a introdução das hipóteses propostas aproxima o efeito identificado de política monetária de seu efeito real. Em um exercício empírico simples, também mostro que essas hipóteses podem ser importantes para identificar efeitos reais de curto prazo da política monetária.

“Still” an Agnostic Procedure to Identify Monetary Policy Shocks with Sign Restrictions

Bruno Perdigao*

Abstract

In this paper I use prominent models as a laboratory to analyze the performance of different identification strategies and propose the introduction of new model consistent restrictions to identify monetary policy shocks in SVARs. In particular, besides standard sign restrictions on interest rates and inflation, the inability of monetary policy to have real effects ten years after the shock is proposed as an additional identification restriction. Evidence is presented of the model consistency of this neutrality restriction both for the canonical three-equation new keynesian model and the Smets and Wouters (2007) model. In a simple empirical application, I show that this restriction may be important to recover real effects of monetary policy.

Keywords: Monetary shock, identification, SVAR, sign restrictions

JEL codes: C32, E52

The Working Papers should not be reported as representing the views of the Banco Central do Brasil. The views expressed in the papers are those of the author(s) and do not necessarily reflect those of the Banco Central do Brasil.

*Departamento Economico, Banco Central do Brasil. Email: bruno.perdigao@bcb.gov.br.

1 Introduction

What is the effect of monetary policy on the economy? This question has been addressed empirically at least in the last 30 years, most often using structural vector autoregression (SVAR) techniques. But results are far from conclusive and some of them point to responses with different directions than theory suggests, even for key macroeconomic variables, such as inflation and output.[1] The reason for the lack of convergence in responses for such an old question lies in the difficulty of estimating causal effects in macroeconomics. Since most macro variables are endogenously determined in dynamic systems, identifying the effects of an exogenous variation in the desired variable (the monetary policy rate, for example) requires the introduction of identification restrictions the data are typically silent about.

Since the data are most often not informative about the imposed restrictions, a validation exercise would be to test these restrictions against a class of models considered adherent to the data by the macro community. In this case, the reasonableness of the proposed restrictions will depend on the group of models that comply with them. The larger this class of models, the more robust are considered the restrictions. But how do traditionally used SVAR identification techniques perform in these controlled environments? The most common approach, Cholesky identification, does not hold in new keynesian models, so it can imply severely biased impulse response functions (IRF) when the shock of interest is identified with this procedure (Carlstrom et al., 2009; Castelnuovo, 2013). Even for other approaches, the identification of all parameters in a SVAR may require an amount of exclusion restrictions not compatible with a large class of models. On the other hand, agnostic techniques that rely on the imposition of fewer restrictions than required to assure point identification[2], such as Canova and Nicoló (2002) and Uhlig (2005) sign restrictions approach, may represent insufficient structure to identify the shock of interest (Paustian, 2007; Castelnuovo, 2012; Wolf, 2017).

In this paper I use prominent models as a laboratory to analyze the performance of different identification strategies and propose the introduction of new restrictions to identify monetary policy shocks in SVARs. In particular, besides standard sign restrictions used in the literature (i.e., restrictions on interest rates and inflation responses) a novel set of equality restrictions are proposed: the inability of monetary policy to have real effects ten years after the monetary shock. When only sign restrictions are imposed, the identification of monetary policy shocks is confounded by combinations of demand and supply shocks, as shown by Wolf (2017). Since these confounding shocks are usually very persistent, the introduction of neutrality restrictions in the medium run does a good job at eliminating them, approximating the identified IRFs to its true effects.

While the introduction of neutrality restrictions shrink the identified set of IRFs, mitigating the problem that sign restrictions alone are considered "too loose" to properly identify the desired effect, it keeps the agnostic spirit of the set identification approach adopted in Uhlig (2005), in the sense that it constitutes a small set of restrictions with large theoretical background. This paper's challenge with these restrictions is to improve the identification of monetary policy shocks without imposing much

[1] Recent surveys of the literature include Ramey (2016) and Nakamura and Steinsson (2017).

[2] In the context of identification of shocks in SVARs, we consider point identification the case in which the imposed restrictions allow the existence of a one-to-one relationship between the SVAR and its associated VAR representation. We call set identification the case in which this relationship is many-to-one.

structure, so it can be adherent to a large class of models. With this minimalist approach, it avoids "throwing the baby out with bathwater", that is, imposing unreliable structure in the data so it can forcefully produce precise estimates. As a downside, it loses precision in estimations.

This paper's first contribution is to show the introduction of model consistent neutrality restrictions improves identification substantially. As measures of identification performance, the identified IRF bounds together with the underlying model IRF and the fraction of real variables negative responses following a contractionary monetary shock are presented, both widely used in this literature (Fry and Pagan, 2011; Canova and Paustian, 2011). For almost all real variables and IRF horizons, the identified set of IRFs is substantially tightened with the introduction of neutrality restrictions. It also comprises the underlying model responses or at least become very close to it. I also show that identified real variables responses following a contractionary shock are strictly negative few periods after the shock, so an empirical macroeconomist employing the proposed identification strategy in this controlled environment would undoubtedly find real effects of monetary policy. For comparison, the identification performance when only sign restrictions are used to identify monetary shocks is presented, an identification setup closer to Uhlig (2005) agnostic procedure. This comparison makes clear that the good performance of the identification proposal is entirely due to the inclusion of medium-run neutrality restrictions, since monetary shocks are poorly identified when only sign restrictions are imposed, even when the data generating process (DGP) is given by a model in which only monetary policy shocks satisfy these sign restrictions.

Second, the Smets and Wouters (2007) model is used as the underlying DGP to compare the performance of this paper's identification approach with recent identification strategies proposed by Arias et al. (2016a) and Wolf (2017) to identify monetary policy shocks. Both of these papers employ theoretically reasonable restrictions in a set identification SVAR context, what makes them perfectly comparable to the proposed identification setup. For the specific DGP used in this comparison, I argue this paper's approach is more model consistent and effective them theirs. Finally, I show in a simple empirical application the introduction of monetary neutrality restrictions in ten years is sufficient to recover real effects of monetary policy, a result in contrast with Uhlig's previous findings.

In the next section, this paper is related to others in the literature. Then, I closely follow Wolf (2017) in describing the problem with Uhlig's "sign restriction only" approach to identify monetary policy shocks. Based on empirical and theoretical papers, it is also argued why the neutrality restrictions make sense. The section is closed with a clear example of how important the additional restriction may be in a standard textbook new-keynesian model. I repeat the exercise for a more reasonable DGP in Section 4, the Smets and Wouters (2007) model, and compare the performance of the proposed restrictions with recent model-consistent restrictions suggested by Arias et al. (2016a) and Wolf (2017). The fifth section presents a simple empirical application based on a VAR estimated with US data that shows the ten-year horizon neutrality restrictions may be important to identify real effects of monetary policy. The last section concludes.

2 Related literature

The use of SVAR to identify monetary policy shocks is observed since the 80's. Early methods of identification include short-run (Sims, 1980) and long-run restrictions (Blanchard and Quah, 1988). Evolution in data availability and computation capacity over the years made possible the introduction of new and modern methods, such as Uhlig (2005) sign restriction approach and high frequency identification (Gürkaynak et al., 2005; Gertler and Karadi, 2015). Recent techniques include the possibility of mixing sign and zero restrictions (Arias et al., 2016b), the introduction of elaborated priors on functions of model parameters (e.g: IRFs)(Andrle and Plasil, 2016), the identification of VARs with instrumental variables (Stock and Watson, 2012; Mertens and Ravn, 2013) and the robust computation of lower and upper bounds of IRFs through optimization procedures (Giacomini and Kitagawa, 2015).

The empirical macro literature that made use of these techniques is large in scope. The causal effects of almost all thinkable aggregate disturbances have been studied, including monetary shocks (Bernanke et al., 2005; Coibion, 2012), productivity shocks (Chari et al., 2008; Peersman and Straub, 2009), government spending shocks (Mountford and Uhlig, 2009), government taxation shocks (Mountford and Uhlig, 2009; Mertens and Ravn, 2013), oil price shocks (Kilian and Murphy, 2012), etc. Despite the great effort to answer these classical questions, a great variety of results can be found due to the difficulty in identifying causal effects in macroeconomics.

For this reason, a subgroup of this SVAR literature aims to validate these identification techniques in controlled environments. Some authors have showed the performance of recursive identification and sign restrictions in cases where the DGP is given by a specified model. Carlstrom et al. (2009) documented the harsh implications a recursive approach may have on the responses of monetary shocks when the DGP is given by a standard new-kewnesian model. Castelnuovo (2013) showed the Choleky identification underestimates the effects of monetary policy on financial variables in a medium scale new-kewnesian model with financial frictions. Even when the DGP satisfies the imposed restrictions, the truncation of the number of lags in a VAR can distort results when long-run restrictions are imposed, as Chari et al. (2008) point out in the discussion of the response of hours to productivity shocks in a business-cycle model. In the context of identifying monetary policy shocks with sign restrictions, Paustian (2007), Castelnuovo (2012) and Wolf (2017) point to the fact that Uhlig (2005) inequality restrictions on inflation and interest rate are not enough to recover real effects of monetary policy, even when the DGP is given by a model in which only monetary policy shocks satisfy the imposed restrictions. In this case, Paustian (2007) documented that identification of multiple shocks and higher values for the variance of the shock of interest improve identification. However, Wolf (2017) emphasized that even implausibly large variances of the shock of interest can't rule out the existence of confounding shocks in most common cases.

Another branch of this literature suggested the use of sign restrictions to choose between competing models that predict divergent causal effects of a specific shock on a variable of interest. The exercise works as follows: i) depart from a broad class of models with different frictions and uncertainty regarding parameter estimates; ii) derive the signs of variables responses to this shock that are robust to all possible models; iii) use these robust restrictions to partially identify a VAR with sign restrictions, leaving the variable of interest unrestricted. Dedola and Neri (2007) used this approach to identify how productivity shocks affect hours worked. They used a broad class of models that encompassed Real Business-Cycle (RBC) models and models with nominal rigidities, as well as different parameterizations for them, to derive the robust sign responses. The estimated VAR with US data and identified through these sign restrictions predicted hours are more likely to rise following a productivity shock, an evidence in favor of RBC models. In a similar exercise, Canova and Paustian (2011) proposed this approach to investigate the compatibility of real data with wage and price rigidities, since different degrees of these frictions may result in divergent responses of wages to a monetary shock. The authors defended the importance of this method since the model likelihood may be flat for different degrees of these nominal rigidities, what undermines the use of traditional likelihood-ratio tests.

This paper connects to those that argue for the introduction of model consistent restrictions as a way to improve identification. In this regard, Arias et al. (2016a) proposed the use of sign and zero restrictions on the monetary equation of the SVAR, what constitutes a novel approach to identification. Specifically, they impose that monetary policy contemporaneous reaction to inflation and output must be positive and also that monetary policy doesn't react to total and nonborrowed reserves on impact.[3] Arias et al. (2016a) claim model consistency of their approach, since most new keynesian models include a Taylor rule with these features. With these new restrictions, the authors find that contractionary monetary shocks are most likely to have negative effects on output, in contrast with Uhlig's previous findings. In the same spirit, Wolf (2017) departs from Uhlig's approach to draw candidate impulse vectors, but proposes, in addition to sign restrictions on interest rates and inflation, the exclusion of candidate draws that have implausibly large effects on output.

This paper is similar to those two, in the sense of trying to bring to SVAR identification new model consistent restrictions. In Section 4, the model consistency of this paper's approach is compared with those of Wolf (2017) and Arias et al. (2016a). I argue through comparisons based on the Smets and Wouters (2007) model the proposed restrictions are more likely to shrink the identified set of impulse responses in the direction of the effects caused by true monetary policy shocks. For that, I claim the proposed approach is more effective then theirs. To our knowledge, this paper is the first to analyze in a controlled environment how the combination of equality and inequality restrictions can improve identification. Much has been done with sign restrictions alone to test weather Uhlig's seminal sign restrictions recover the true effects of monetary policy (Paustian, 2007; Castelnuovo, 2012; Wolf, 2017). But none of these papers have shown how the introduction of model consistent equality restrictions can improve identification.

3 Overview of main identification issues with sign restrictions and importance of the ten-year monetary neutrality restrictions

This section briefly presents Uhlig's sign restriction approach to compute IRFs and point the possible identification problems with the identified set of impulse responses, closely following Wolf (2017). I

[3] Although they introduce new sign and zero restrictions, their principal conclusions are driven mostly from their sign restrictions.

introduce and motivate why the additional ten-year neutrality restrictions make sense and help identify monetary policy shocks. Then, it is shown the implications of these additional restrictions when the DGP is given by a canonical three-equation new-keynesian model, taken from Galí (2015) textbook.

3.1 Uhlig's "pure sign restriction" approach

To identify the shock of interest, I depart from the infinite SVAR representation of the model generated data:

$$A^{-1}y_t = B + \sum_{j=1}^{\infty} B_j y_{t-j} + \epsilon_t, \tag{1}$$

where y_t is a $n \times 1$ vector of observed macroeconomic variables and ϵ_t is a mean zero vector of structural disturbances. I assume these shocks are not correlated with each other and impose unit variance as a normalization condition, $E(\epsilon_t \epsilon_t') = I_n$. As is standard in simultaneous equations models, the contemporaneous impact matrix, A, is not identified. For that reason, empirical macroeconomists usually try to recover structural content from this model departing from the associated VAR form of (1), given by:

$$y_t = C + \sum_{j=1}^{\infty} C_j y_{t-j} + u_t, \tag{2}$$

where $u_t = A\epsilon_t$ and $E(u_t u_t') = A(A)' \equiv \Sigma$. The theoretical appeal of the infinite VAR representation lies in the fact that it may be rationalized as a reduced form associated with a DSGE model if some conditions are satisfied, as shown by Fernández-Villaverde et al. (2007).[4] In the exercises that follows, these conditions are satisfied, so we are able to map the structural parameters of the DSGE model solution in the VAR representation.

Given the VAR representation, if we are interested in the effects of a particular shock, only one column of A has to be identified. Supposing we are interested only in the effects of monetary policy shocks, Uhlig's "pure sign restriction approach" to calculate IRFs works as follows. Consider A the true SVAR contemporaneous impact matrix and its individual columns as $[a_1, a_2, ..., a_n]$. Uhlig (2005) shows that, for any matrix $\tilde{A}$ that satisfies $\tilde{A}\tilde{A}' = \Sigma$ (the Cholesky decomposition of Σ, for example), a is a column of A if and only if there is an n-dimensional vector α of unit length, so that a can be characterized as $a = \tilde{A}\alpha$ (*proposition A.1 of Uhlig (2005)*). Hence, his "pure sign restriction approach" consists of repeating the following steps:

1. *Draw a random vector $\bar{\alpha}$ from the unit sphere.*

2. *Compute $\bar{a} = \tilde{A}\bar{\alpha}$ and the IRFs associated with $\bar{a}$.*

3. *Keep only those IRFs that satisfy the sign restrictions.*

[4]Specifically, the number of observed variables and the number of orthogonal shocks in the model must be the same. Also, some conditions regarding the stability of a particular combination of the matrices representing the state-space solution of the model are necessary. We call these the *invertibility conditions*. In this case, the existence of an infinite VAR representation is conditional on the history of observed variables being perfectly informative about the current state variables.

To impose the monetary neutrality restrictions, Arias et al. (2016b) algorithm to mix equality and inequality restrictions is used. It basically adds a previous step to Uhlig's "pure sign restriction approach" in which the vector $\bar{\alpha}$ is draw conditional on the imposed equality restrictions. Then, I calculate the impulse response functions and keep those that satisfy the sign restrictions.

A problem with this approach is that, even if there is a single shock that satisfies the imposed restrictions, identification may be confounded by linear combinations of other structural disturbances. Uhlig (2005) recognizes this issue, and Wolf (2017) shows this is indeed the problem behind the conclusions of some empirical papers that made use of sign restrictions (Uhlig, 2005; Dedola and Neri, 2007). To clearly see this point, note that the "pure sign restriction approach" implies the existence of an orthonormal matrix Q that satisfies:

$$A = \tilde{A}Q \Rightarrow AQ' = \tilde{A}. \tag{3}$$

Thus, a candidate $\bar{a}$, given by a draw $\bar{\alpha}$ from the unit sphere, can be represented as:

$$\bar{a} = \tilde{A}\bar{\alpha} = AQ'\bar{\alpha} = A\bar{q} = a_1\bar{q}_1 + a_2\bar{q}_2 + ... + a_n\bar{q}_n, \tag{4}$$

where $\bar{q}_i$ is the element i of the unit length vector $Q'\alpha$. That is, $\bar{a}$ is a linear combination of the true columns of A, with weights given by the vector $\bar{q}$. Hence, Uhlig's "pure sign restriction approach" delivers a set of linear combinations of structural shocks that satisfy the sign restrictions.

In the following sections, it is shown the introduction of monetary policy neutrality restrictions can remove combinations of structural disturbances that confound the identification of monetary policy shocks when only sign restrictions on interest rates and inflation are imposed.

3.2 Monetary neutrality restrictions in the medium run

Besides standard sign restrictions on inflation and interest rates, this paper proposes monetary policy should have no real effects ten years after the shock. This time horizon is labeled as medium run in this paper. The reason why these restrictions help the identification of monetary shocks is because it eliminates combinations of persistent supply and demand shocks that confound the identification of monetary disturbances when only sign restrictions are imposed. Thus, the ten-year neutrality restrictions shrink the identified set of impulse responses in the direction of true monetary policy effects.

How reasonable are these restrictions? In practice, central banks are getting increasingly concerned about monetary policy transparency and predictability. Ben Bernanke, for example, left this message clear in a 2007 speech:

"*The fact that the public is uncertain about and must learn about the economy provides a reason for the central bank to strive for predictability and transparency*".

Greater predictability and transparency might mean that, given a monetary shock, central bank authorities will strive to conduct the economy rapidly to its equilibrium path, thus reducing the persistence of the shock. Since the longevity of real effects of monetary policy are correlated to the shock persistence, the neutrality restrictions seem compatible with central banks intention to enhance predictability of policy decisions.

The hypothesis of monetary policy neutrality in ten years is also consistent with a large group of empirical papers that employ different methods to identify the effects of monetary policy shocks. The neutrality restrictions are consistent, for example, with Romer and Romer (2004) narrative method to identify monetary shocks, with Gertler and Karadi (2015) high frequency identification in VAR's and Evans and Marshall (2009), Boivin et al. (2009) and Uhlig and Ahmadi (2015) identification of monetary shocks in FAVARs. Boivin et al. (2009) test the absence of relative sectoral price changes ten years after a monetary contractionary shock (what could induce a medium-run monetary non-neutrality) and find that the hypothesis of monetary neutrality in ten years is not rejected at a 10% significance level.

The proposed neutrality restrictions also have a large theoretical background. Models with very different ways to incorporate nominal rigidities feature monetary neutrality ten years after the shock. Examples include time-dependent price setting models (e.g. Smets and Wouters (2007)), menu costs models (e.g. Golosov and Lucas (2007)) and models with rationally inattentive firms (e.g. Maćkowiak and Wiederholt (2009)). In fact, I am not aware of a model with nominal rigidities in which the proposed restrictions don't hold at least approximately. For this reason, it is believed the neutrality restrictions don't impose relevant additional structure on the underlying DGP, what makes us feel comfortable with not departing from the agnostic proposal of the set identification literature. It is important to note, however, the length of time for monetary policy to reach neutrality varies significantly among these models. In state-dependent price models, for example, monetary effects are usually "faster" than time-dependent price models. For this reason, it is imposed that sign restrictions are binding only until one quarter after the shock. Table 1 presents the restrictions that will be used throughout this paper. Time periods are defined quarterly. The central column shows the standard sign restrictions on interest rates and inflation used to identify a monetary contractionary shock. I call this set of restrictions the "sign restrictions only" approach. The right column adds the proposed neutrality restrictions, where z_t represents a vector of real macroeconomic variables.

Table 1: Agnostic restrictions on impulse response functions

Variables	**Sign restrictions only**	**Sign and zero restrictions**
i_{t+h}	≥ 0	≥ 0
π_{t+h}	≤ 0	≤ 0
$\boldsymbol{z_{t+40}}$	**?**	$\boldsymbol{= 0}$

Notes: for the restrictions on inflation and interest rates I set $h = 0, 1$. The vector z_t represents real wages, consumption, hours worked, output and investment when the DGP is given by the Smets and Wouters (2007) model (Section 4) and only output when the DGP is given by the three-equation model.

3.3 Three-equation model example

The exercises that follow make use of the techniques presented before. Specifically, I depart from the VAR equation (1) and try to recover the effects of monetary policy shocks with sign and zero restrictions, assuming the true contemporaneous impact matrix, A, is unknown. This exercise simulates the procedures carried through by an empirical macroeconomist with real data. To focus exclusively on identification issues and avoid parameter estimation uncertainty, this subsection and Section 4 use true VAR parameters of the underlying models.[5] I also employ a sufficient number of lags in the VAR to avoid lag truncation bias.

To have a first glimpse on the impact of the medium-run neutrality restrictions on the identification of monetary shocks, the canonical three-equation model of Galí (2015) is consider as the underlying DGP:

$$y_t = E_t(y_{t+1}) - \sigma^{-1}(i_t - E_t(\pi_{t+1}) - r^*) + e_{d,t}, \tag{5}$$

$$\pi_t = \beta E_t(\pi_{t+1}) + \kappa y_t + e_{s,t}, \tag{6}$$

$$i_t = r^* + \phi_\pi \pi_t + \phi_y y_t + e_{i,t}, \tag{7}$$

where: $e_{j,t} = \rho_j e_{j,t-1} + \epsilon_{j,t}$, $j \in \{d, s, i\}$. In this stylized model, the IRF dynamics come from the shocks persistence, since there are no state variables besides the autoregressive shocks. The calibrated parameter values are presented in Table A.1 in Appendix A.

Notice that only monetary policy shocks can drive interest rates and inflation in opposite directions. This feature is, indeed, present in a large group of new-keynesian models. Hence, it may appear at first glance that sign restrictions alone are sufficient to identify monetary policy shocks. Figure 1 presents the IRFs of a standard deviation monetary shock when identification is given by sign restrictions alone. Since enough restrictions are not imposed to pin down a unique contemporaneous impact matrix A (i.e., a unique model associated with the VAR), IRF bounds computed for different matrices A that satisfy the imposed restrictions are reported. As emphasized in Fry and Pagan (2011), these bounds represent model uncertainty. For computing them, I run Uhlig's "pure sign restrictions" algorithm until 10,000 accepted draws that satisfy the sign restrictions are recovered. The identified bounds of IRFs are presented with dashed red lines, the corresponding median is painted in black and the true model IRFs are presented in dashed blue lines. The identified IRFs are consistent with Uhlig (2005) original findings: the sign of the output response is inconclusive[6] and its median is positive. This is not a novel finding in the literature, as shown by Paustian (2007), Castelnuovo (2012) and Wolf (2017). However, when the neutrality restriction on output is added to the sign restrictions, the IRF bounds became strictly negative, as presented in Figure 2.[7] Not only the upper and lower bounds of IRFs have the correct sign, but the bounds interval is tight, providing valuable information about the output response magnitude. Thus, for both measures of shock identification performance

[5]Since there are no identification issues regarding the estimation of VAR parameters, the same results would have been obtained simulating an arbitrarily large sample from the model, estimating VAR parameters and imposing the equality and inequality restrictions to recover the effects of monetary policy shocks.

[6]Since I am not estimating any parameters, the term "statistically zero" would be inappropriate.

[7]This time I use Arias et al. (2016b) algorithm to mix equality and inequality restrictions until 10,000 draws are accepted.

usually employed (i.e., the fraction of responses with correct sign and the tightness of IRF bounds), an empirical macroeconomist who introduces the neutrality restriction will improve the identification of monetary policy shocks in a VAR.

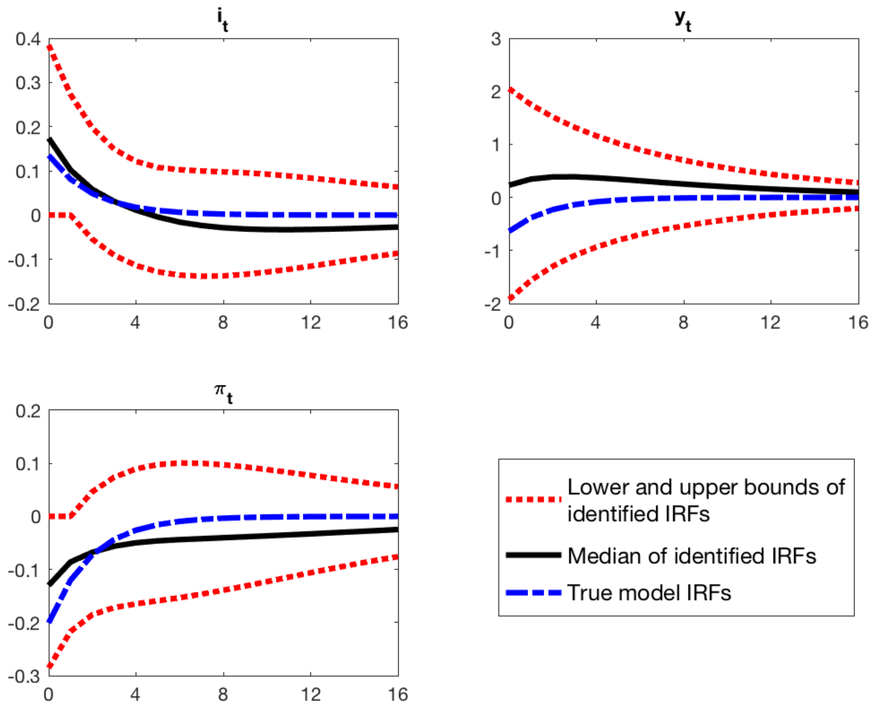


Figure 1: IRFs of a σ_i contractionary monetary policy shock identified with only sign restrictions (three-equation model)

The reason behind this finding lies in the persistence of the underlying shocks. In this regard, the lower persistence of monetary shocks vis-a-vis other shocks is essential for the performance of the proposed approach, since the neutrality restriction excludes confounding combination of persistent demand and supply shocks that satisfy the sign restrictions. This picture gets clear when Uhlig's "pure sign restriction" algorithm is run using the true matrix of contemporaneous effects (A) instead of the Cholesky decomposition matrix ($\tilde{A}$). In this case, I am computing IRFs of a linear combination of true model shocks and keeping those that satisfy the sign restrictions. Through an inspection of the weights in this linear combination of structural shocks (i.e., the weight vector $\bar{q}$ in equation (4)), it is possible to check the confounding elements behind the monetary shock identification.[8] For identified IRFs (i.e: IRFs that satisfy imposed restrictions), Figure 3 presents the output responses on impact (x axis) and the weights associated with each structural disturbance (y axis), both for the "sign restrictions only" case (left panel) and the sign and zero restriction case (right panel). The vertical line represents the true model effect. As we can see, the true IRF of output on impact is obtained for both cases when the monetary policy shock weight is close to one and other weights are close to zero. Figure 3 also shows clearly that the improvement in identification performance due to the introduction of a ten-year neutrality restriction really reflects better identification of monetary shocks and not some

[8] Wolf (2017) originally proposed this investigation. I follow his approach and present a similar figure. To smooth the original weights, the weights are filtered with a HP filter.

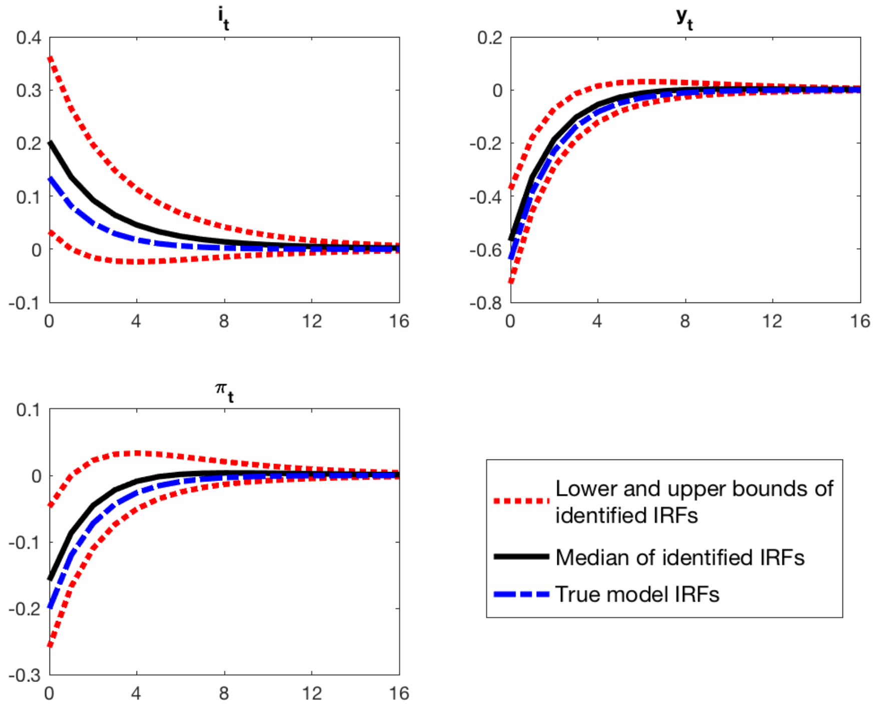


Figure 2: IRFs of a σ_i contractionary monetary policy shock identified with sign restrictions and monetary neutrality restrictions (three-equation model)

spurious combinations of other structural disturbances. Hence, it is argued the proposed neutrality restriction shrinks the identified set of impulse responses toward the true monetary policy effects.

4 Smets and Wouters (2007) model

In this section, previous section exercises are repeated, but for a more complex DGP, the Smets and Wouters (2007) model. The identification performance of sign and neutrality restrictions is also compared with recent identification strategies proposed by Arias et al. (2016a) and Wolf (2017). It is argued the proposed restrictions are more model consistent and more effective at recovering true monetary policy shocks.

The Smets and Wouters (2007) model represents a theoretically rich environment, since it embodies different new keynesian model features, such as habit formation in consumption, investment adjustment costs, variable capital utilization and price and wage rigidities. All of these ingredients contribute for the existence of reasonable hump-shaped impulse responses of seven different disturbances: government expenditure shocks, monetary policy shocks, risk premium shocks, investment shocks, mark-up shocks of wages and prices and total factor productivity shocks. This elaborated structure, with microfounded mechanisms, makes the model a proper environment for policy analysis. For these reasons, the Smets and Wouters (2007) model is the benchmark DGP used in this paper.

The dashed blue lines in Figures 4 and 5 show the true effects of a standard deviation contractionary monetary shock for the Smets and Wouters (2007) model. Results are based on the posterior mode estimated by the authors. I present the responses of all the observable variables used to estimate

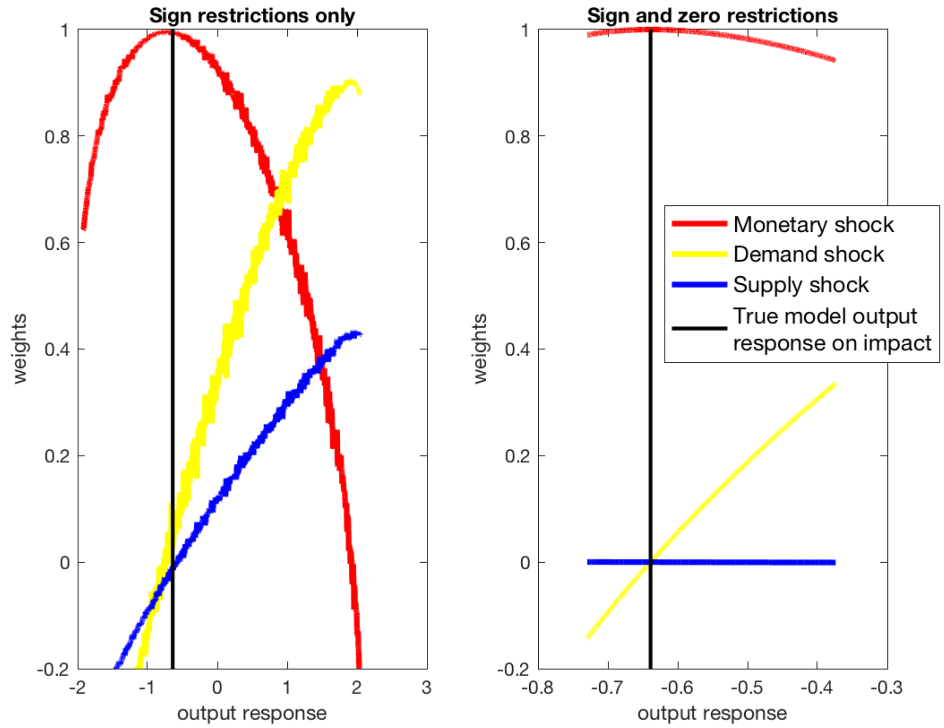


Figure 3: Structural shocks weights versus output impact responses for identified IRFs (three-equation model)

the model: interest rates (i), real output (y), inflation (π), hours worked (lab), real wages (w), real consumption (c) and real investment (inv). As expected, the real variables present a hump-shaped negative response. Figure 4 also presents the identified impulse response bounds when only sign restrictions are imposed until one quarter after the shock. We can see the sign restrictions are not enough to deliver either the correct direction or reasonable bounds of real variables responses to a monetary shock, not even approximately.

As in the last section, when the additional neutrality restrictions that monetary policy doesn't have real effects ten years after the shock are imposed, identification improves substantially, as shown in Figure 5.[9] In comparison with Figure 4, we can notice the range of admissible responses is severely reduced. Despite the possibility of positive values for all real variables responses in the initial periods following the shock, the median is negative with a hump-shaped format. For almost all real variables, the underlying model IRFs are inside the identified bounds or at least very close to the lower bounds.[10] Thus, as a first measure of identification performance, we can see the range of identified IRFs provides valuable information regarding monetary policy effects. Also, we can notice the median is always slightly underestimated, so it can be interpreted, at least for this DGP, as a lower bound for monetary policy effects.

[9] For the SW (2007) model, monetary neutrality is imposed for all observed real variables: output, consumption, investment, hours worked and wages.

[10] The only exception is the investment response, since small weights given to the investment-specific shock have large effects on this variable. The reason why the underlying model IRFs lie bellow the identified lower bounds in some cases is due to small weights given to confounding shocks that push IRFs to a monetary shock in the opposite direction of its true effects.

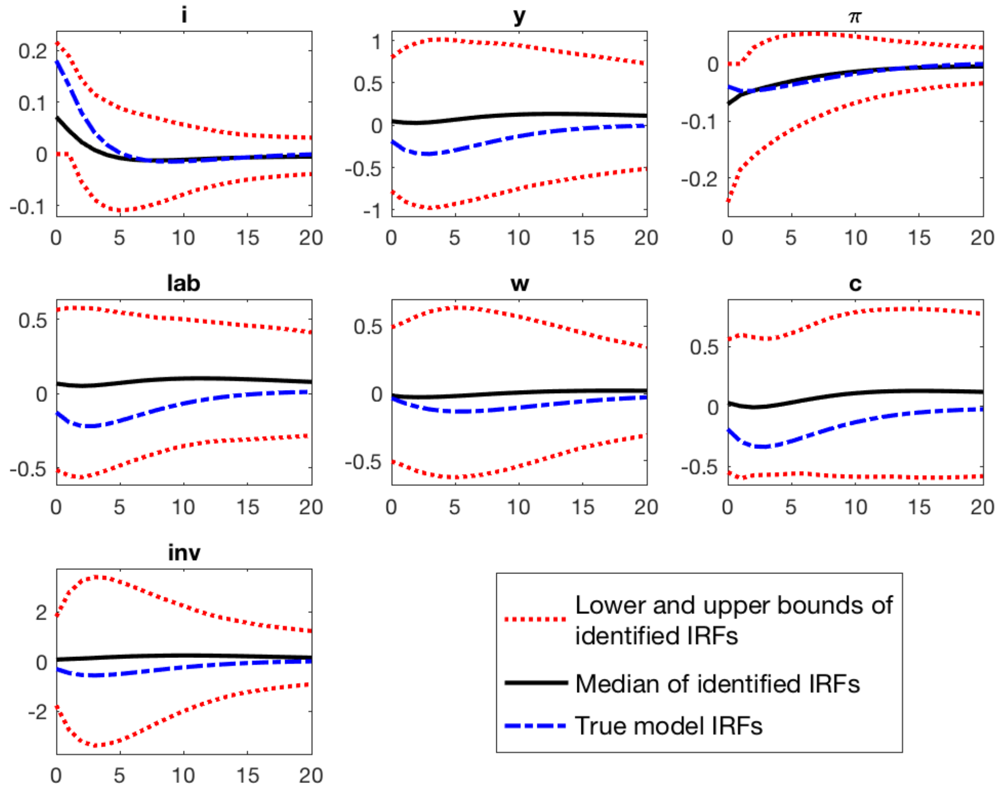


Figure 4: IRFs of a σ_i contractionary monetary policy shock identified with only sign restrictions - SW(2007) model

Only the identified bounds and the median IRFs were shown in Figures 4 and 5, hence it is important to present other features regarding the distribution of IRFs in these intervals. The close proximity between the lower bounds and the median for real variables responses gives a first hint that most identified responses are negative. As a second measure of identification performance, Tables 2 and 3 show the proportion of negative responses for all real variables in different horizons after the monetary shock for the identification with only sign restrictions and the identification that adds monetary neutrality restrictions, respectively. As we can see, the former identification approach performs poorly, with almost all combinations of variables and IRF horizons below 50% of negative responses. The introduction of neutrality restrictions improves identification substantially. All IRFs proportion of negative responses are higher than 90% four quarters after the shock. This percentage increases with the IRF horizon, reaching strictly negatives responses for almost all real variables.[11] In this sense, an empirical macroeconomist employing this identification strategy for this DGP would undoubtedly recover negative effects of a contractionary monetary policy shock, in contrast with the case when only sign restrictions are imposed, as in Uhlig (2005).

Again, the reason behind the sharp identification improvement with the introduction of neutrality restrictions lies in the exclusion of combinations of persistent structural disturbances that confound the identification of monetary shocks when only sign restrictions are imposed. In Figure 6, shock

[11]Results are robust to imposing the neutrality restrictions in different time horizons, as shown in Tables B.1 to B.4 in Appendix B.

weights versus output responses on impact for identified IRFs are reported, exactly as was done for Figure 3. Following Wolf (2017), all the disturbances but monetary shocks are split between positive demand and positive supply shocks according to their sign impacts on output and inflation.[12] The weights presented were averaged in these categories. Overall, the introduction of neutrality restrictions reduces the range of admissible impact responses for all real variables (mostly for positive values) and considerably increases the weight of monetary disturbances in the accepted draws of the algorithm.

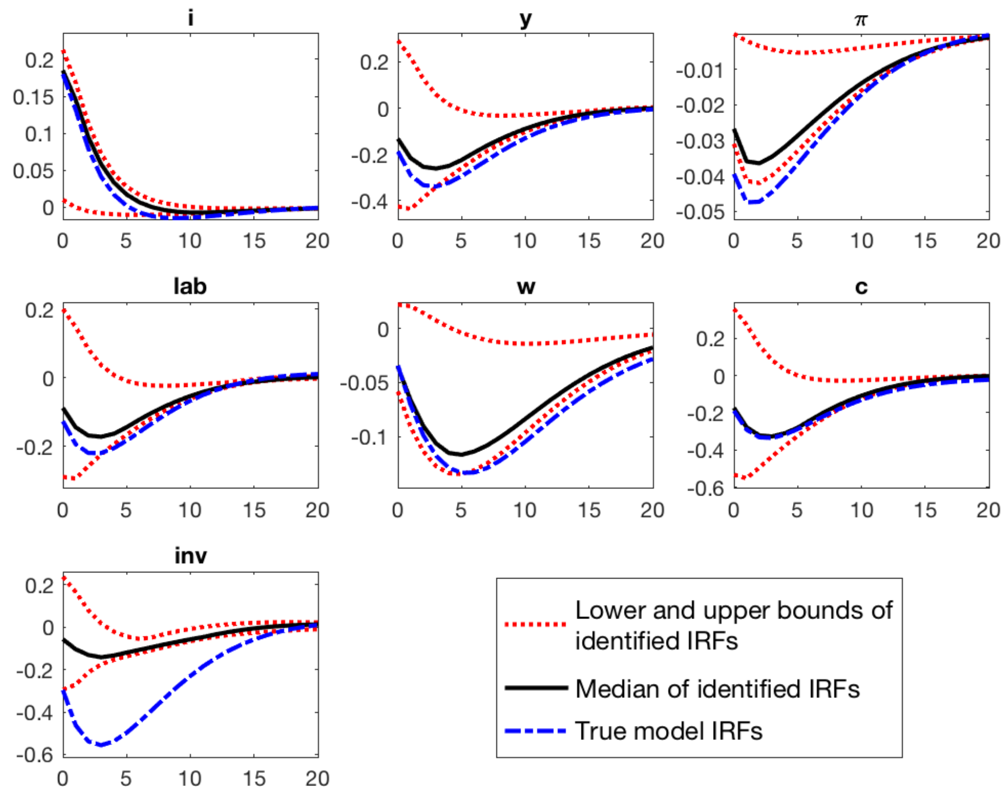


Figure 5: IRFs of a σ_i contractionary monetary policy shock identified with sign and zero restrictions - SW(2007) model

How do these results compare with Arias et al. (2016a) and Wolf (2017) proposed identification restrictions when the DGP is given by the Smets and Wouters (2007) model? Tables 4 and 5 replicate the previous results incorporating in the "sign restriction only" approach some restrictions proposed by these authors, respectively. Arias et al. (2016a) most important restrictions for their results concern the parameters of the equation that describes the monetary policy rule in the SVAR. In particular, they impose the interest rate responds positively to contemporaneous movements in inflation and output.[13] That is, taking the SVAR representation in equation (1) as example, they impose the entries of the A matrix associated with output and inflation in the monetary rule equation must be negative.[14] The

[12] Demand shocks: investment-specific shock, risk premium shock, government expenditure shock. Supply shocks: total factor productivity shock, wage mark-up shock, price mark-up shock.

[13] They also impose interest rates are not affected contemporaneously by total and nonborrowed reserves, but these restriction are not the ones driving down output after a contractionary monetary shock in their empirical exercise.

[14] Moving contemporaneous output and inflation to the right side of this equation, we can see these restrictions imply the interest rate is a positive function of these variables.

authors claim model consistency of their restrictions, since most new keynesian models incorporate Taylor rules with these features. However, as Wolf (2017) points out, the signs on the monetary rule parameters associated with output and inflation in the SVAR are sensible to the monetary rule specification and to the definition of output gap used in this equation. In the Smets and Wouters (2007) model, for example, their restrictions don't hold for the estimated parameter mode, even if we define the variables in the VAR precisely the same way as in the model. Even if we remove from the Taylor rule specification the deviation of the output growth from its potential level, a novel term in the SW (2007) policy specification, Arias et al. (2016a) restrictions on contemporaneous SVAR parameters won't be verified in the SW (2007) model.[15] This feature explains the poor performance of results when Arias et al. (2016a) restrictions on structural parameters are incorporated. In this case, the proportion of negative responses resembles those of the "sign restrictions only" specification, with almost all pairs of real variables and IRF horizons presenting positive responses after a contractionary monetary policy shock.

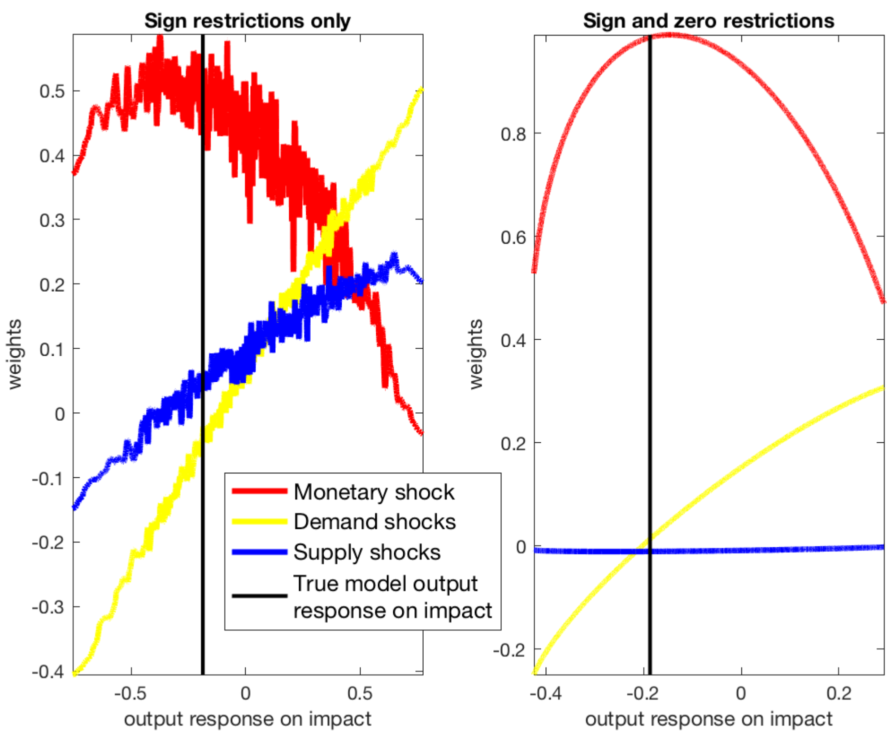


Figure 6: Accepted impulse weights of identified monetary shocks - SW(2007) model

Besides standard sign restrictions on interest rates and inflation, Wolf (2017) proposes a restriction to rule out implausibly large responses of output to a monetary shock. Specifically, he imposes the absolute value of (output response)/(quarterly interest rate response) to be lower than 1.2 on impact. While this restriction seems compatible with a large group of empirical papers that estimate the effects of monetary policy shocks, it is not enough to recover strictly negative real variables responses following a contractionary monetary shock when the DGP is given by the Smets and Wouters (2007)

[15] For this exercise, the model was not reestimated. The original parameters mode was considered.

model, as shown in Table 5.[16] Despite the slightly improvement in relation to the "sign restriction only" approach, we notice that all pairs of variables and IRF horizons show proportions of negative responses below 70%.

Table 2: Proportion of negative responses for different IRF horizons - **sign restrictions only**

Variables	h = 0	h = 2	h = 4	h = 6	h = 8	h =10	h =12
y	44%	47%	45%	41%	38%	36%	34%
lab	38%	42%	39%	35%	30%	28%	27%
w	53%	54%	53%	52%	50%	48%	47%
c	45%	51%	48%	42%	37%	35%	34%
inv	45%	46%	45%	43%	41%	39%	37%

Table 3: Proportion of negative responses for different IRF horizons - **sign and zero restrictions**

Variables	h = 0	h = 2	h = 4	h = 6	h = 8	h =10	h =12
y	65%	84%	97%	100%	100%	100%	100%
lab	65%	84%	98%	100%	100%	100%	100%
w	82%	94%	100%	100%	100%	100%	100%
c	66%	84%	96%	100%	100%	100%	100%
inv	59%	82%	100%	100%	100%	100%	91%

Table 4: Proportion of negative responses for different IRF horizons - **Arias et al. (2016a)**

Variables	h = 0	h = 2	h = 4	h = 6	h = 8	h =10	h =12
y	42%	46%	45%	42%	40%	38%	37%
lab	30%	36%	35%	32%	29%	27%	27%
w	50%	51%	50%	49%	48%	47%	47%
c	41%	49%	48%	43%	39%	37%	36%
inv	43%	44%	44%	43%	42%	40%	39%

The performance of this paper's identification approach vis-a-vis those of Arias et al. (2016a) and Wolf (2017) can also be compared through an analysis of disturbance weights in the accepted draws of Uhlig (2005) and Arias et al. (2016b) algorithms. Table 6 presents the mean shock weights for identified IRFs with different identification strategies. It can be noticed the identification with

[16]An important disclaimer has to be made here. In his paper, Wolf (2017) shows the model consistency of his approach using a non-invertible three variable VAR representation of the Smets and Wouters (2007) model. For what I have tested, his specification looks worse here than in his paper mostly because I am dealing with the full VAR (7 - variable) representation of the model. Also, a small part of this divergence is probably due to some slight difference in the parameters used to calibrate the model.

Table 5: Proportion of negative responses for different IRF horizons - Wolf (2017)

Variables	**h = 0**	**h = 2**	**h = 4**	**h = 6**	**h = 8**	**h =10**	**h =12**
y	50%	63%	58%	51%	44%	40%	38%
lab	40%	49%	47%	41%	35%	31%	29%
w	56%	60%	61%	59%	58%	56%	54%
c	44%	58%	56%	48%	43%	39%	37%
inv	51%	53%	52%	50%	47%	44%	42%

Table 6: Mean identified shock weights for different identification strategies

Identification setup	$\boldsymbol{\epsilon_r}$	$\boldsymbol{\epsilon_a}$	$\boldsymbol{\epsilon_p}$	$\boldsymbol{\epsilon_b}$	$\boldsymbol{\epsilon_g}$	$\boldsymbol{\epsilon_I}$	$\boldsymbol{\epsilon_w}$
Sign restrictions only	0.40	-0.06	-0.21	0.17	0.05	0.05	-0.15
Wolf (2017)	0.50	-0.09	-0.19	0.21	0.02	0.02	-0.15
Arias et al (2016)	0.36	-0.11	-0.24	0.21	0.06	0.07	-0.14
Sign and zero restrictions	**0.82**	**-0.00**	**0.02**	**0.03**	**0.00**	**0.11**	**0.00**

Table 7: Mean absolute IRFs after 40 quarters (in percent) for different identification strategies

Identification setup	**i**	**y**	$\boldsymbol{\pi}$	**lab**	**w**	**c**	**inv**
True model	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.01**	**0.01**
Sign restrictions only	0.01	0.12	0.01	0.06	0.05	0.16	0.16
Wolf (2017)	0.01	0.11	0.01	0.06	0.04	0.15	0.16
Arias et al (2016)	0.01	0.11	0.01	0.06	0.04	0.15	0.16
Sign and zero restrictions	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**

monetary neutrality restrictions gives substantially higher weight to the monetary shock and less weight to other disturbances. As can be seen, Wolf (2017) fares better than the "sign restriction only" approach, but worse than this paper proposal, while Arias et al. (2016a) performs even worse than the former for the DGP used in this paper.[17] In this sense, the identified set of IRFs with the addition of neutrality restrictions is closer to the true effects of monetary shocks than competing identification strategies.

Finally, to reinforce that the proposed approach improves identification through the exclusion of persistent confounding combinations of shocks other than monetary, Tables 7 and 8 present two distinct measures of shock persistence for different identification setups and the SW (2007) model. Table 7 plots the mean absolute IRFs of all real variables 40 quarters after the shock. By design, this paper's proposal restricts to zero these responses. But notice the competing strategies accept as

[17]Here, we notice that the strange results for the investment IRF comes from the 0.11 mean weight given to the investment-specific shock. Although this value does not seem so large, the investment-specific shock has a large positive effect on investment, what explains the findings for the investment response.

Table 8: Mean half lives of identified monetary shocks (in time periods) for different identification strategies

Identification setup	i	y	π	lab	w	c	inv
True model	**2**	**12**	**10**	**11**	**24**	**12**	**12**
Sign restrictions only	9	28	9	25	26	31	26
Wolf (2017)	5	36	10	26	25	32	27
Arias et al (2016)	9	28	8	25	26	31	26
Sign and zero restrictions	**3**	**9**	**12**	**9**	**21**	**9**	**9**

confounding monetary shocks combinations of highly persistent shocks. The range of these values are between 0.04 and 0.16 percent deviation from the steady state, in absolute terms, depending on the identification setup and the real variable analyzed. For each real variable, it represents roughly a third of the lowest values verified in the true model responses.[18]

Table 8 reports the mean half-lives of shocks, defined as the number of periods at which responses are higher then half their values on impact. Despite the pitfalls with this measure of shock persistence when the IRFs are not monotonically behaved, as is the case for the Smets and Wouters (2007) model, it presents another evidence that the competing identification strategies are confounded by combinations of persistent shocks. We can see the half-lives of all real variables responses are above 20 for other identification setups (sometimes above 30), in discrepancy with the half-lives observed in the model for all real variables but wages. In sum, for both measures of shock persistence, the identification with neutrality restrictions delivers the acceptance of less persistent shocks, in accordance to the effects observed for monetary shocks in the model.

I end this section pointing that the introduction of monetary policy neutrality in a ten-year horizon as an identification hypothesis, along standard sign restrictions on inflation and interest rates, substantially improves identification. It still does not perfectly recover the effects of monetary shocks: a fraction of identified real variables responses in the initial periods following a contractionary shock are still positive and the true model responses lie outside the identified bounds in some cases. But this approach improves identification "at a very low cost", since neutrality restrictions have strong theoretical background. Thus, I believe this strategy does not compromise the agnostic spirit of set identification literature. According to the two measures of shock identification performance, it also performs better than the competing identification setups of Arias et al. (2016a) and Wolf (2017). Hence, the proposed identification strategy provides valuable information for empirical macroeconomists who are evaluating the trade-off between imposing additional identification structure and enhancing estimated IRF's precision.

[18]In the model, the lowest point occurs at three quarters after the shock for output, consumption, investment and hours worked, and at 5 quarters after the shock for real wages. Note also that in all cases there isn't a persistent movement in the interest rate to justify these results.

5 Empirical application

This section provides a simple example with real data showing the monetary neutrality restrictions might be important to identify real effects of monetary policy. For consistency with previous sections, the quarterly data that Smets and Wouters (2007) used to estimate their model are employed. The data sample ranges from 1956Q1 to 2004Q4. Specifically, a three-variable VAR with four lags composed by the quarterly Fed Funds Rate, the log difference of GDP deflator and the real per capita GDP growth is estimated.[19] This VAR can be rationalized as a reduced form for the three-equation model or a non-invertible three-equation VAR representation of the Smets and Wouters (2007) model, as in Wolf (2017). This empirical exercise closely follows the exercises from previous sections, with two small differences. First, due to a limitation in the amount of data available, the empirical VAR contains only four lags. Second, VAR parameters are estimated, so parameter estimation uncertainty is reflected in IRF bounds. Identification strategies are implemented exactly the same way as before.

For comparison, IRFs to a standard deviation contractionary shock are identified using both identification setups specified before: the "sign restrictions only" approach and the approach incorporating the proposed neutrality restriction. The sign restrictions remain the same as in previous sections: following a contractionary monetary policy shock, the Fed Funds Rate rises and inflation decreases for two periods. Since the VAR includes real GDP per capita growth as real variable, the monetary neutrality restriction implies the cumulative sum of this variable must be zero 40 quarters after the shock. Additionally, to make sure the output response stays very close to zero from quarter 40 onward, I impose the restriction that its cumulative sum between quarters 40 and 80 must be zero.[20] It is important to note that this second restriction pins down a unique column of the contemporaneous impact matrix A of the SVAR. Thus, there is no longer model uncertainty regarding the estimation of IRFs to monetary policy shocks, allowing inference to be conducted the usual way. In other words, for the identification setup that features neutrality restrictions, we are back in the standard VAR case where IRF bounds represent only parameter uncertainty. For the "sign restrictions only" approach, two sources of uncertainty of different nature accumulate in the computation of IRFs: the one related to parameter estimation and model uncertainty, since this setup doesn't impose enough restrictions to pin down a unique A contemporaneous impact matrix of the SVAR.

Inference is conducted the usual way for Bayesian estimated VARs. I assume a noninformative Jeffrey's prior for the coefficients (ϕ) and the variance-covariance matrix (Σ), i.e., $p(\phi, \Sigma) \propto |\Sigma|^{\frac{-(n+1)}{2}}$. Kadiyala and Karlsson (1997) deliver the posterior for (ϕ, Σ).[21] For the "sign restrictions only" identification setup, 10,000 parameter vectors are drawn from the posterior distribution. For each, I draw 100 candidate impulse responses with Uhlig's sign restrictions algorithm and keep the ones satisfying the sign restrictions.[22] For the identification setup that incorporates neutrality restrictions,

[19] I refer the reader to the Smets and Wouters (2007) data appendix for detailed information about the corresponding codes of these time series in the FRED database.

[20] Without this restriction, the median output response crosses the zero line 40 quarters after the shock and becomes positive onward, although not statistically significant. This feature was not present in previous sections. Results are invariant to changing the time length of this second restriction.

[21] For a sample of the size used in this exercise, this procedure is similar to drawing from the joint likelihood of (ϕ, Σ), despite a slight increase in the degrees of freedom.

[22] Close to 30% of the draws are accepted.

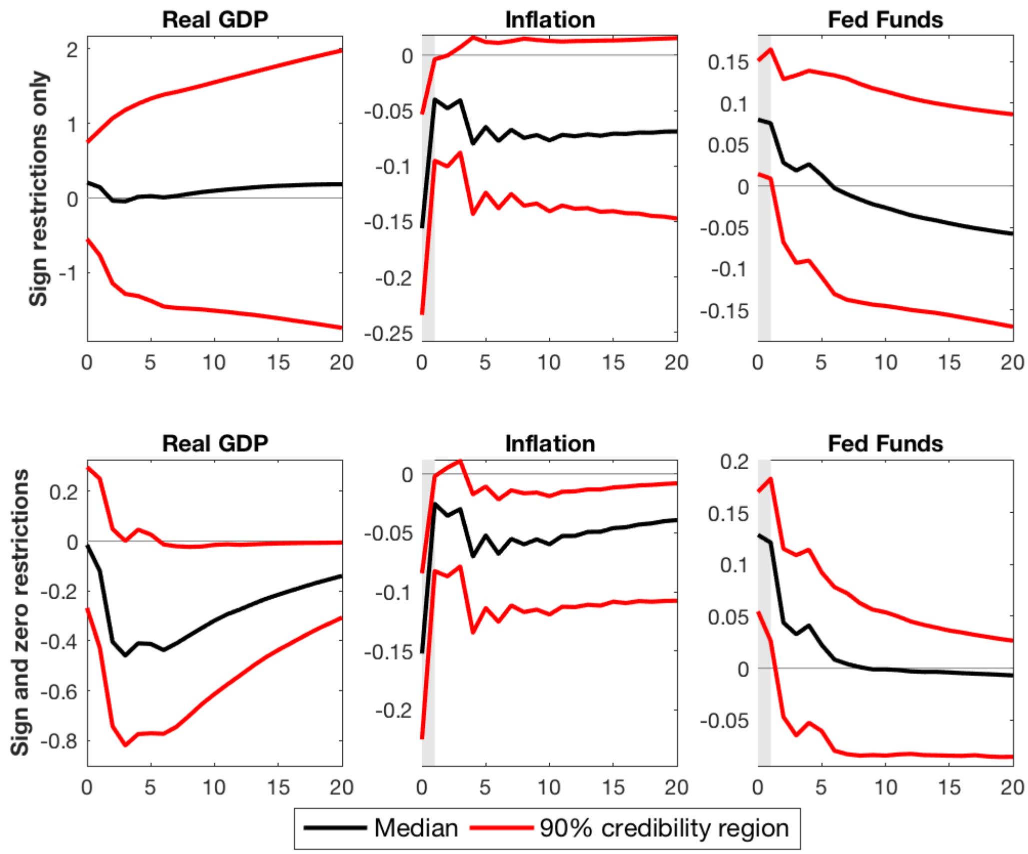


Figure 7: Identified IRFs of a σ_i contractionary monetary shock for the "sign restriction only" approach (first row) and the identification setup incorporating the neutrality restrictions (second row). Estimated three-variable VAR with US data. Sample: 1956Q1 - 2004Q4

Arias et al. (2016b) algorithm is used to mix equality and inequality restrictions. In this case, I draw 10,000 parameters from the posterior and compute IRF bounds as is standard in Bayesian VAR exercises.

Figure 7 presents the IRF of a standard deviation monetary shock for the "sign restriction only" approach (first row) and the identification setup incorporating the neutrality restrictions (second row). The median is painted in black and the red lines represent a 90% credibility region. By design, the Fed Funds Rate rises and inflation drops until one quarter after the shock. We clearly see for the "sign restriction only" case the direction of real output response is ambiguous and its median is positive, as in Uhlig (2005). When the neutrality restrictions are additionally imposed, the real output response becomes statistically negative at 10% level of significance five quarters after the shock, with its median lowest point reaching roughly -0.40 three to five periods after the shock, a pattern precisely in accordance with the Smets and Wouters (2007) model.

In Appendix C, some robustness exercises are implemented. First, the time horizon in which monetary neutrality is imposed is varied. Figure C.1 shows real output responses when monetary neutrality binds between seven and thirteen years.[23] All of them point to real effects of monetary policy when the additional neutrality restrictions are imposed. Figure C.2 repeats the same exercise

[23] To save space, the Fed Funds Rate and inflation responses are omitted.

done in Figure 7, but for a shorter sample that ranges from 1978Q1 to 2004Q4. This shorter sample might be more robust to structural breaks, since it is closer to the great moderation period. Again, it can be noticed the introduction of neutrality restrictions is sufficient to recover a statistically significant negative output response following a contractionary monetary shock.

6 Conclusion

Throughout this paper the introduction of a small set of model consistent restrictions to identify monetary shocks in a set identified SVAR framework is defended. Specifically, I propose to combine standard sign restrictions on interest rates and inflation IRFs with equality restrictions that prevent monetary policy from having real effects ten years after the shock. It is shown that this novel set of neutrality restrictions eliminate important confounding elements that are present when only sign restrictions are imposed. The algorithm introduced by Arias et al. (2016b) to mix equality and inequality restrictions is used to this end.

To assess the theoretical plausibility of my set of restrictions, I first check their identification performance in controlled environments, that is, when the DGP is given by prominent models used in the literature. As a first example, the neutrality restriction is shown to be sufficient to perfectly recover negative effects of a contractionary monetary policy shock when the DGP is given by the canonical three-equation model of Galí (2015). Then, the same exercise is conducted for a complex DGP, the Smets and Wouters (2007) model. It can be seen in this case that the approach substantially shrinks the identified set of impulse responses toward the true effects of monetary policy shocks. It is also noted that, for this DGP, the proposed identification setup is more effective to recover monetary policy effects than recent identification approaches driven by model consistent restrictions suggested by Arias et al. (2016a) and Wolf (2017).

Finally, as a simple empirical application, I estimate a VAR with US data and show the additional neutrality restrictions might help to identify real effects of monetary policy shocks. While other restrictions can be imposed with the same goal, this paper's minimalist approach keeps the agnostic spirit of the set identification literature, which aims to impose a limited number of restrictions backed by strong theoretical support.

References

Andrle, Michal and Michal Plasil, "System Priors for Econometric Time Series," *Working Paper* WP/16/231, International Monetary Fund, 2016.

Arias, Jonas E, Dario Caldara, and Juan F. Rubio-Ramírez, "The Systematic Component of Monetary Policy in SVARs: An Agnostic Identification Procedure," 2016, *1*131.

Arias, Jonas, Juan Rubio-Ramírez, and Daniel Waggoner, "Inference Based on SVARs Identified with Sign and Zero Restrictions : Theory and Applications," *Federal Reserve Bank of Atlanta*, 2016, (30).

Bernanke, Ben S., Jean Boivin, and Piotr Eliasz, "Measuring the Effects of Monetary Policy: A Factor-Augmented Vector Autoregressive (FAVAR) Approach," *Quarterly Journal of Economics*, 2005, (February), 387–422.

Blanchard, Olivier J and Danny Quah, "The dynamic effects of aggregate demand and supply disturbances," *National Bureau of Economic Research*, 1988.

Boivin, Jean, Marc P Giannoni, and Ilian Mihov, "Sticky Prices and Monetary Policy : Evidence from Disaggregated U . S . Data," *American Economic Review*, 2009, *No*. 12824, 350–384.

Canova, Fabio and Gianni De Nicoló, "Monetary disturbances matter for business fluctuations in the G-7," *Journal of Monetary Economics*, 2002, *4*9 (6), 1131–1159.

_ **and Matthias Paustian**, "Business cycle measurement with some theory," *Journal of Monetary Economics*, 2011, *5*8 (4), 345–361.

Carlstrom, Charles T., Timothy S. Fuerst, and Matthias Paustian, "Monetary policy shocks, Choleski identification, and DNK models," *Journal of Monetary Economics*, 2009, *5*6 (7), 1014–1021.

Castelnuovo, Efrem, "Monetary Policy Neutrality? Sign Restrictions Go to Monte Carlo," 2012, *2*012 (July), 1–32.

_ , "Monetary policy shocks and financial conditions: A Monte Carlo experiment," *Journal of International Money and Finance*, 2013, *3*2, 282–303.

Chari, Varadarajan V, Patrick J Kehoe, and Ellen R McGrattan, "Are structural VARs with long-run restrictions useful in developing business cycle theory?," *Journal of Monetary Economics*, 2008, *5*5 (8), 1337–1352.

Coibion, Olivier, "Are the effects of monetary policy shocks big or small?," *American Economic Journal: Macroeconomics*, 2012, *4* (2), 1–32.

Dedola, Luca and Stefano Neri, "What does a technology shock do? A VAR analysis with model-based sign restrictions," *Journal of Monetary Economics*, 2007, *5*4 (2), 512–549.

Evans, Charles L. and David A. Marshall, "Fundamental economic shocks and the macroeconomy," *Journal of Money, Credit and Banking*, 2009, *41* (8), 1515–1555.

Fernández-Villaverde, Jesús, Juan F Rubio-RAMÍREZ, Thomas J Sargent, and Mark W Watson, "ABCs (and Ds) of understanding VARs," *American Economic Review*, 2007, *97* (3), 1021–1026.

Fry, Renée and Adrian Pagan, "Sign Restrictions in Structural Vector Autoregressions: A Critical Review," *Journal of Economic Literature*, 2011, *49* (4), 938–960.

Galí, Jordi, *Monetary policy, inflation, and the business cycle: an introduction to the new Keynesian framework and its applications*, Princeton University Press, 2015.

Gertler, Mark and Peter Karadi, "Monetary Policy Surprises, Credit Costs and Economic Activity *," *American Economic Journal: Macroeconomics*, 2015, *7* (1), 7(1): 44–76.

Giacomini, Raffaella and Toru Kitagawa, "Robust inference about partially identified SVARs," 2015, (June), 1–47.

Golosov, Mikhail and Robert E Lucas, "Menu Costs and Phillips Curves," *Journal of Political Economy*, 2007, *115* (2), 171–199.

Gürkaynak, Refet S., Brian P. Sack, and Eric T. Swanson, "Do Actions Speak Louder Than Words? The Response of Asset Prices to Monetary Policy Actions and Statements," *International Journal of Central Banking*, 2005, *1* (1), 55–93.

Kadiyala, K and Sune Karlsson, "Numerical methods for estimation and inference in Bayesian VAR-models.," *Journal of Applied Econometrics*, 1997, *12* (December 1994), 99–132.

Kilian, Lutz and Daniel P Murphy, "Why agnostic sign restrictions are not enough: understanding the dynamics of oil market VAR models," *Journal of the European Economic Association*, 2012, *10* (5), 1166–1188.

Maćkowiak, Bartosz and Mirko Wiederholt, "Optimal sticky prices under rational inattention," *American Economic Review*, 2009, *99* (3), 769–803.

Mertens, Karel and Morten O. Ravn, "The Dynamic Effects of Personal and Corporate Income Tax Changes in the United States," *American Economic Review*, 2013, *103* (4), 1212–1247.

Mountford, Andrew and Harald Uhlig, "What are the effects of fiscal policy shocks?," *Journal of applied econometrics*, 2009, *24* (6), 960–992.

Nakamura, Emi and On Steinsson, "Identification in Macroeconomics," *Columbia University*, 2017.

Paustian, Matthias, "Assessing sign restrictions," *The BE Journal of Macroeconomics*, 2007, *7* (1), 23.

Peersman and Straub, "Technology Shocks and Robust Sign Restrictions in a Euro area SVAR," *International Economic Review*, 2009, *50* (3).

Ramey, Valerie A, "Macroeconomic shocks and their propagation," *Handbook of Macroeconomics*, 2016, *2*, 71–162.

Romer, Christina D and David H Romer, "A New Measure of Monetary Shocks: Derivation and Implications," *American Economic Review*, 2004, *94* (4), 1055–1084.

Sims, Christopher A, "Macroeconomics and reality," *Econometrica: Journal of the Econometric Society*, 1980, pp. 1–48.

Smets, Frank and Rafael Wouters, "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach," *American Economic Review*, 2007.

Stock, James H and Mark W Watson, "Disentangling the Channels of the 2007–09 Recession," *Brookings Papers on Economic Activity*, 2012, *2012* (1), 81–135.

Uhlig, Harald, "What are the effects of monetary policy on output? Results from an agnostic identification procedure," *Journal of Monetary Economics*, 2005, *52* (2), 381–419.

_ **and Pooyan Amir Ahmadi**, "Sign Restrictions in Bayesian FaVARs with an Application to Monetary Policy Shocks," *NBER Working Paper Series*, 2015.

Wolf, Christian K, "Masquerading Shocks in Sign-Restricted VARs," *Manuscript, Princeton University*, 2017.

APPENDIX

A Three-equation model

Table A.1: Calibrated parameters: three-equation model

Parameter	**Parameter interpretation**	**Value**
β	discount factor	0.99
σ	inverse of IES	1
φ	inverse Frisch elasticity	1
ϵ	demand elasticity	6
θ	Calvo parameter	0.66
ϕ_π	inflation coefficient (T. rule)	1.5
ϕ_y	output coefficient (T. rule)	0.1
ρ_s	cost-push shock persistence	0.8
ρ_d	demand shock persistence	0.9
ρ_r	monetary shock persistence	0.6
σ_r	std monetary shock	0.5
σ_s	std cost-push shock	0.5
σ_d	std demand shock	0.5

B Smets and Wouters (2007) model

Table B.1: Proportion of negative responses for different IRF horizons - **monetary neutrality in 8 years**

Variables	h = 0	h = 2	h = 4	h = 6	h = 8	h =10	h =12
y	64%	83%	95%	100%	100%	100%	100%
lab	63%	82%	95%	100%	100%	100%	100%
w	77%	90%	96%	100%	100%	100%	100%
c	65%	83%	94%	100%	100%	100%	100%
inv	56%	78%	100%	100%	100%	98%	85%

Table B.2: Proportion of negative responses for different IRF horizons - **monetary neutrality in 9 years**

Variables	h = 0	h = 2	h = 4	h = 6	h = 8	h =10	h =12
y	64%	84%	97%	100%	100%	100%	100%
lab	64%	83%	97%	100%	100%	100%	100%
w	80%	93%	98%	100%	100%	100%	100%
c	65%	83%	95%	100%	100%	100%	100%
inv	58%	80%	100%	100%	100%	100%	89%

Table B.3: Proportion of negative responses for different IRF horizons - **monetary neutrality in 11 years**

Variables	h = 0	h = 2	h = 4	h = 6	h = 8	h =10	h =12
y	65%	85%	98%	100%	100%	100%	100%
lab	65%	85%	98%	100%	100%	100%	100%
w	82%	94%	100%	100%	100%	100%	100%
c	66%	84%	96%	100%	100%	100%	100%
inv	60%	83%	100%	100%	100%	100%	92%

Table B.4: Proportion of negative responses for different IRF horizons - **monetary neutrality in 12 years**

Variables	**h = 0**	**h = 2**	**h = 4**	**h = 6**	**h = 8**	**h =10**	**h =12**
y	65%	85%	98%	100%	100%	100%	100%
lab	65%	85%	98%	100%	100%	100%	100%
w	82%	94%	100%	100%	100%	100%	100%
c	66%	84%	96%	100%	100%	100%	100%
inv	61%	84%	100%	100%	100%	100%	92%

Table B.5: Mean identified shock weights for sign and zero restrictions identification

Sign and zero restrictions	ϵ_r	ϵ_a	ϵ_p	ϵ_b	ϵ_g	ϵ_I	ϵ_w
Monetary neutrality in **8** years	0.81	-0.00	0.01	0.04	0.00	0.12	0.00
Monetary neutrality in **9** years	0.82	-0.00	0.02	0.04	0.00	0.11	0.00
Monetary neutrality in **11** years	0.82	-0.00	0.02	0.03	0.00	0.11	0.00
Monetary neutrality in **12** years	0.82	-0.00	0.02	0.03	0.00	0.11	0.00

C Empirical application with US data

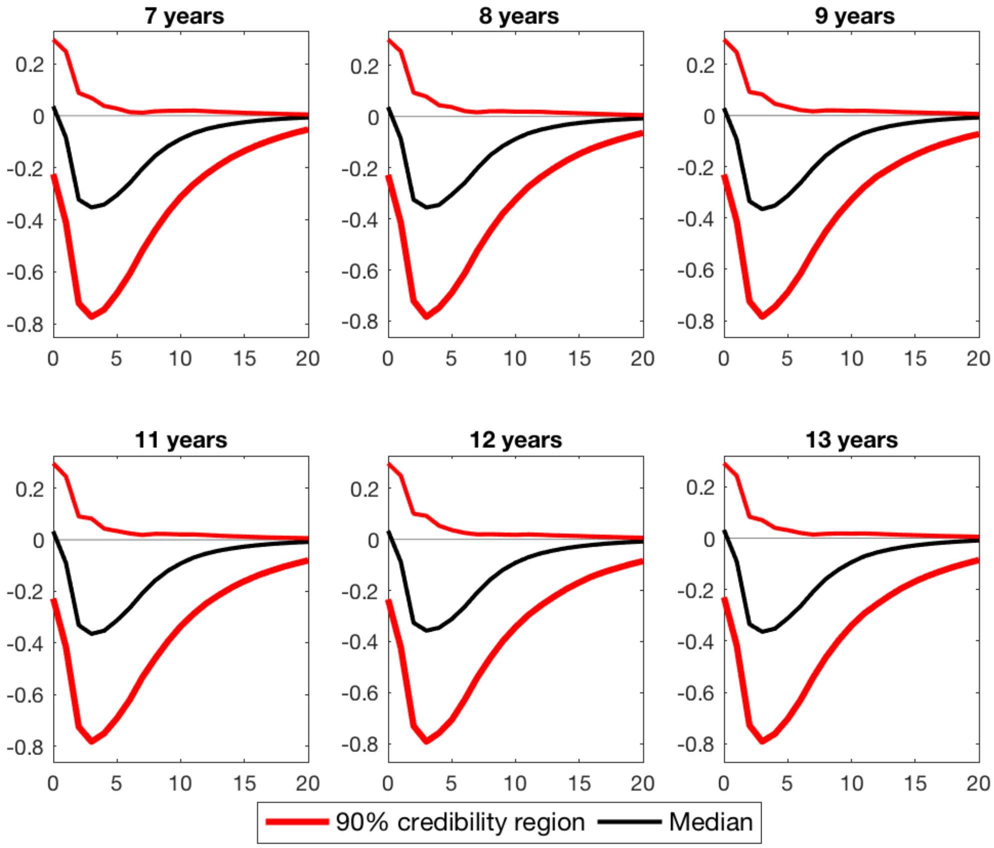


Figure C.1: Identified output responses of a σ_i contractionary monetary shock imposing the neutrality restrictions in different time lengths. Estimated three-variable VAR with US data. Sample: 1956Q1 - 2004Q4.

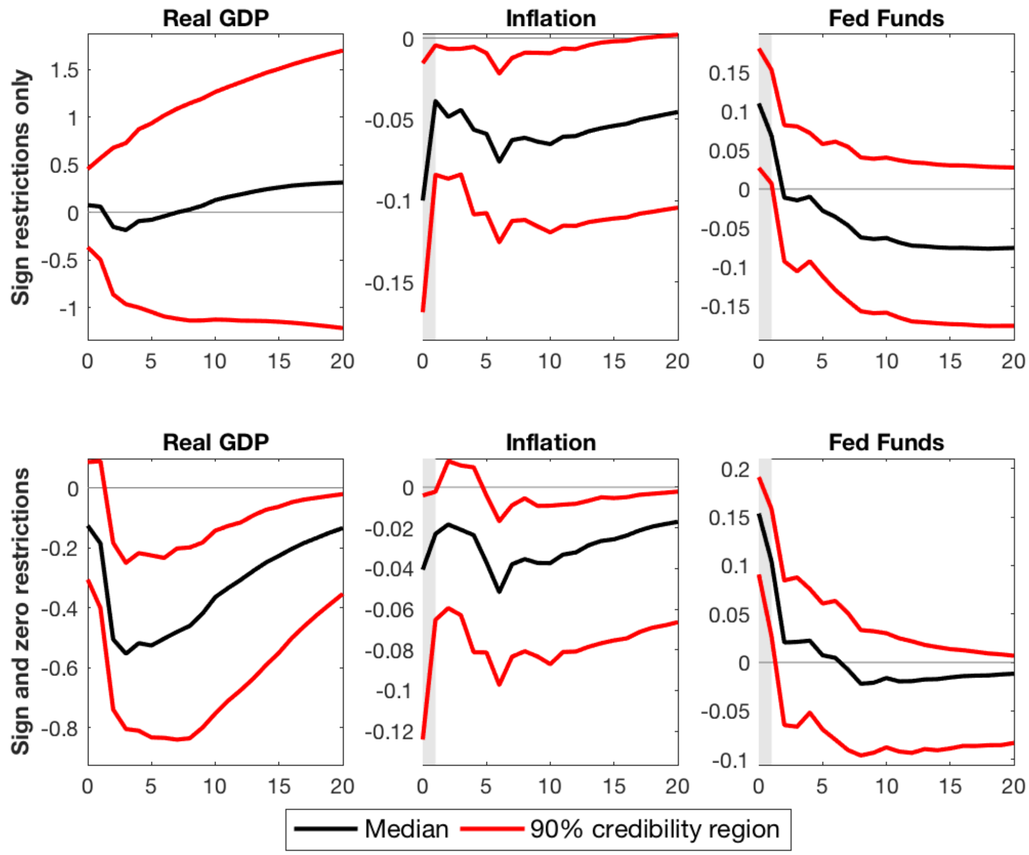


Figure C.2: Identified IRFs of a σ_i contractionary monetary shock for the "sign restriction only" approach (first row) and the identification setup incorporating the neutrality restrictions (second row). Estimated three-variable VAR with US data. Sample: 1978Q1 - 2004Q4.