Asymmetric Effects of Monetary Policy Easing and Tightening

Davide Debortoli
Mario Forni
Luca Gambetti
Luca Sala

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Davide Debortoli
Universitat Pompeu Fabra, CREi, BGSE and CEPR

Mario Forni
Università di Modena e Reggio Emilia, CEPR and RECent

Luca Gambetti
Universitat Autonoma de Barcelona, BGSE and Università di Torino

Luca Sala
Università Bocconi, IGIER and Baffi Carefin

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Abstract

Monetary policy easing and tightening have asymmetric effects: a policy easing has large effects on prices but small effects on real activity variables. The opposite is found for a policy tightening: large real effects but small effects on prices. Nonlinearities are estimated using a new and simple procedure based on linear Strutural Vector Autoregressions with exogenous variables (SVARX). We rationalize the result through the lens of a simple model with downward nominal wage rigidities.

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1 Introduction

There is a vast literature on the empirical effects of monetary policy shocks. A partial list of early contributions includes Bernanke and Blinder (1992), Bernanke and Gertler (1995), Bernanke and Mihov (1998) Christiano, Eichenbaum and Evans (1996, 1999), Cochrane (1994), Leeper, Sims and Zha (1996), Sims and Zha (2006) and Strongin (1995). Several advances have been made in recent years, especially in terms of shock identification, as for instance in the works of Romer and Romer (2004), Uhlig (2005), Arias, Caldara and Rubio-Ramírez (2016), Gertler and Karadi (2015), Miranda-Agrippino and Ricco (2017), Jarocinsky and Karadi (2020), Caldara and Herbst (2019). An important assumption, common to all of the above cited works, is model linearity: positive and negative shocks have the same effects in absolute value, there are no state dependencies, and the effects of shocks are proportional to the size of the shocks.

From a theoretical point of view, however, asymmetries or other type of non-linearities have been always considered a potential important feature of the transmission mechanism of monetary policy shock. The traditional asymmetry, put forward by Keynes (1936, Chapter 21), supports the view that monetary contractions have larger real effects than expansions. The explanation hinges on the presence of nominal rigidities in the labor market, preventing nominal wages to fall in response to contractionary demand shocks, thus giving rise to "involuntary" unemployment —i.e. at the prevailing wage rate labour supply exceeds labor demand. On the contrary, nominal wages are easily adjusted upwards in response to expansionary shocks, thus implying a modest response of output and other real variables. An illustration of this channel within modern general equilibrium models can be found in Kim and Ruge-Murcia (2009), Fagan and Messina (2009), Benigno and Ricci (2011), Abbritti and Fahr (2013), Schmitt-Grohe and Uribe (2016) and Benigno and Fornaro (2019), among others. The are also several potential sources of non-linearities. One example is the presence of price adjustment costs, as for instance illustrated in the menu costs models of Ball and Romer (1990), Ball and Mankiw (1994), Golosov and Lucas (2007), Midrigan (2011) and Alvarez, Le Bihan and Lippi (2016). In those models, large shocks may have relatively small real effects, since they induce most firms to change their prices, but smaller shocks may lead to substantial real effects, since their magnitude is not sufficient to trigger price adjustments.

Several empirical contributions have investigated and tested for the presence of nonlinearities in the transmission mechanisms of policy shocks. All in all the results are mixed. For instance, Cover (1992) and DeLong and Summers (1988) find evidence supporting the traditional asymmetry for the United States, and similar finding are obtained for several European countries in Karras (1996). Ravn and Sola (1996) find instead no evidence for asymmetries, once changes in policy regimes are taken into account. Weiss (1999) shows that the effects of money supply shocks on real GDP are larger when GDP growth is low, but does not find evidence of asymmetries between positive and negative shocks. More recently, Barnichon and Matthes (2018) and Angrist *et al.* (2018) find that monetary contractions have larger effects than expansions.

The present paper contributes to that debate by addressing the following question: are the effects of policy easing and tightening different? We use a new, simple empirical procedure to identify monetary policy shocks in a context of a nonlinear vector moving average representation. Non-linearities originate from the fact that the representation includes nonlinear functions of the monetary policy shock. The nonlinear moving average can be rewritten as a VAR with exogenous regressors (VARX). Estimation is conducted with a two-step procedure. In the first step, we identify the monetary policy shock according the identification scheme in Christiano, Eichenbaum and Evans (1996). In the second step, we estimate a VARX where a nonlinear function of the shock (e.g. the absolute value or a quadratic term) is treated as an exogenous observable regressor. To assess the validity of our empirical procedure, we perform Monte Carlo simulations using a reduced-form model. We also apply our methodology on artificial data generated from a nonlinear DSGE model, and show that the estimates resulting from our simple non-linear representation capture entirely the nonlinearities featured by the model.

The main result is that policy easing have large effects on prices but small effects on real economic activity variables, while policy tightening have large effects on economic activity but small effects on prices. We interpret the result through the lenses of a simple DSGE model with downward nominal wage rigidities.

Our approach bears a few similarities to the one recently proposed by Barnichon and Matthes (2018), who also postulate the existence of a non-linear moving average representation to assess the effects of monetary policy shocks. The main difference lies in the estimation method: Barnichon and Mattes approximate the impulse response functions through Gaussian basis functions and estimate the parameters of such functions *via* maximum likelihood; by contrast, our model is linear in the non-linear function of the monetary policy shock, so that we can use OLS estimation and do not need any assumption about the probability distribution of the shocks.

The remainder of the paper is organized as follows. Section 2 discuss the econometric approach. Section 3 presents the empirical evidence. Section 4 presents a model with downward nominal wage rigidities that is used for a Monte Carlo exercise, and Section 5 concludes.

2 Econometric approach

In the present section we introduce a nonlinear impulse-response function representation of the economy. We discuss how to identify the monetary policy shock, estimate the model and obtain nonlinear impulse response functions.

2.1 A nonlinear representation

We assume that the macroeconomic variables in the n-dimensional stationary vector x_t have the representation

$$x_t = \nu + \beta(L)g(u_{rt}) + \Gamma(L)u_t \tag{1}$$

where u_t is an n-dimensional vector of serially and mutually independent structural shocks, u_{rt} (an element of u_t) is the monetary policy shock, $\beta(L)$ is a vector of rational impulse-response functions in the lag operator L and $\Gamma(L)$ is an $n \times n$ matrix of rational impulse-response functions. $g(u_{rt})$ represents a nonlinear function of u_{rt}; for instance, $g(u_{rt}) = |u_{rt}|$ or $g(u_{rt}) = u_{rt}^2$.

Notice that serial and mutual independence of the shocks in u_t implies that u_{rt} is uncorrelated with the lags of $g(u_{rt})$ and x_t. However the contemporaneous correlation between u_{rt} and $g(u_{rt})$ is not necessarily zero.[1]

In the above representation $\Gamma_r(L)$, the column of $\Gamma(L)$ associated to u_{rt}, represents the effects of the linear term of the monetary policy shock, while $\beta(L)$ represents the effects of the nonlinear term. The total effect the monetary policy shock on the vector x_t is a combination

[1] For instance, if $g(u_{rt}) = |u_{rt}|$ (as assumed in the empirical part of the paper) we have a non-zero contemporaneous correlation if the probability distribution of u_{rt} is skewed, a possibility allowed by our hypotheses, as we do not place restrictions on the probability distribution of the structural shocks.

of the two terms. For instance when $g(u_{rt}) = |u_{rt}|$ the total effect will be $\Gamma_r(L)u_{rt} + \beta(L)|u_{rt}|$, i.e. $[\Gamma_r(L) + \beta(L)]u_{rt}$ for positive shocks and $[-\Gamma_r(L) + \beta(L)]u_{rt}$ for negative shocks.

We further assume that the impulse response functions can be parameterized as follows: $\beta(L) = A(L)^{-1}\tilde{\beta}(L)$ and $\Gamma(L) = A(L)^{-1}\Gamma_0$, where $A(L)$ is an $n \times n$ matrix of finite order polynomials in L such that $A(0) = I_n$, $\Gamma_0 = \Gamma(0)$ is a matrix of constants with the property that the elements on the main diagonal of Γ_0^{-1} are equal to one, and $\tilde{\beta}(L)$ is vector of polynomials in L. This parameterization is convenient since the model (1) can be written in the finite-order VARX form

$$A(L)x_t = \mu + \tilde{\beta}(L)g(u_{rt}) + \Gamma_0 u_t \tag{2}$$

where $\mu = A(1)\nu$, or equivalently

$$x_t = \mu + \tilde{A}(L)x_{t-1} + \tilde{\beta}(L)g(u_{rt}) + \Gamma_0 u_t$$

where $\tilde{A}(L) = I - A(L)$. From the above representation, the structural VARX representation is obtained by multiplying by Γ_0^{-1}, i.e.

$$Gx_t = \theta + G(L)x_{t-1} + \delta(L)g(u_{rt}) + u_t \tag{3}$$

where $G = \Gamma_0^{-1}$, $G(L) = G\tilde{A}(L)$, $\delta(L) = G\tilde{\beta}(L)$, and $\theta = G\mu$.

Below we discuss how to identify the monetary policy shock and estimate the impulse response functions using equation (3).

2.2 Identification

Let us come to the restrictions imposed to identify the monetary policy shock. First of all we assume that the macroeconomic variables of interest can be partitioned as $x_t = (s_t'\ r_t\ f_t')'$, where s_t is a n_s-dimensional vector of "slow-moving" variables, i.e. variables, such as output, the unemployment rate and the inflation rate, which react with a delay to the monetary policy shock; r_t is the federal funds rate; f_t is a n_f-dimensional vector of "fast-moving" variables, variables which immediately react to the shock.

We identify the monetary policy shock along the lines of Christiano, Eichenbaum and Evans (1996). More specifically we assume that (i) the monetary policy shock is orthogonal to the slow moving variables in s_t, and (ii) the interest rate r_t does not react on impact to the fast moving variables in f_t. These restriction can be implemented by imposing that G

(and therefore Γ_0) is lower triangular. The policy shock u_{rt} is the r-th shock in the vector u_t, with $r = n_s + 1$. Furthermore, we assume (iii) that the interest rate reacts to the nonlinear term only through the slow-moving variables; in other words, we assume that $\delta_r(L) = 0$. The assumed policy rule is therefore

$$r_t = \theta_r - \sum_{j=1}^{n_s} G_{rj} x_{it} + G_r(L) x_{t-1} + u_{rt}. \tag{4}$$

where θ_r is r-th entry of θ, G_{rj} is the (r, j) entry of G by and $G_r(L)$ is the r-th row of $G(L)$. Notice that only the slow-moving variables enter the equation contemporaneously. This is the same monetary policy rule as in Christiano, Eichenbaum and Evans (1996).

The policy rule above is sufficient to identify the monetary policy shock. Its impulse response functions, however, will depend also on our assumption on the first n_s entries of $\delta(0)$. Imposing (iv) $\delta_i(0) = 0$, $i = 1, \ldots, n_s$, would be in line with the idea that the slow moving variables do not react to the interest rate on impact.[2] On the other hand, if we do not impose (iv), we can leave it for testing. In the empirical application below we do not impose (iv) in the baseline specification: the restriction is never rejected. We impose (iv) in one of the robustness exercises.

2.3 Estimation

The model is estimated in two steps. In the first one the policy rule is estimated by OLS and an estimate of u_{rt}, denoted $\hat{u}_{rt}$, is obtained. Consistency is ensured by the fact that u_{rt} is orthogonal to lagged x's and s_t, because of the assumptions of equation (1) and assumption (i).[3] Once $\hat{u}_{rt}$ is available the function $g(\hat{u}_{rt})$ can computed.

In the second step, the other parameters in equation (3) can be estimated by OLS using $g(\hat{u}_{rt})$ as regressor. More formally, we estimate

$$x_{1t} = \theta_1 + G_1(L) x_{t-1} + \delta_1(L) g(u_{rt}) + u_{1t}, \tag{5}$$

[2] Notice also that (iv) guarantees contemporaneous sample orthogonality of u_{rt} and u_{it}, $i = 1, \ldots, n_s$, which otherwise does not necessary hold.

[3] Equivalently, we could estimate u_{rt} as the Cholesky shock corresponding to r_t in a standard structural recursive VAR for x_t. The resulting estimate of u_{rt} would be identical but the associate impulse response functions would not be consistent since the regressor $g(u_{rt})$ is neglected.

whereas for $j = 2, \ldots, n$, $j \neq r$, we estimate

$$x_{it} = \theta_j - \sum_{j=1}^{i-1} G_{ij} x_{jt} + G_i(L) x_{t-1} + \delta_i(L) g(u_{rt}) + u_{it}. \qquad (6)$$

With an estimate of the parameters of model (3) at hand, an estimate of $A(L)$, $\tilde{\beta}(L)$ and Γ_0 can be obtained as $\tilde{\beta}(L) = G^{-1}\delta(L)$, $A(L) = G^{-1}G(L)$ and $\Gamma_0 = G^{-1}$. Thus an estimate of $\beta(L)$, $\Gamma_r(L)$ and the total effect of monetary policy shock is obtained.

Regarding variance decomposition, one might be tempted to use standard formulas and sum the contribution to total variance of u_{rt} and $g(u_{rt})$. This procedure however is incorrect, since u_{rt} and $g(u_{rt})$ are not orthogonal in general. A simple way to overcome this problem is to compute, for each horizon, the prediction error due to u_{rt}, including the nonlinear term, and divide its sample variance by the sample variance of the total prediction error.

2.4 Inference

In the second step of the above estimation procedure $g(\hat{u}_{rt})$ is a generated regressor. Standard confidence bands do not take into account that u_{rt} is affected by an estimation error. Suitable confidence bands can be obtained via the following bootstrap procedure.

First, draw with replacement T integers $i(t)$, $t = 1, \ldots, T$, uniformly distributed between $2p+1$ and T, and construct the artificial sequences of shocks $u_t^1 = \hat{u}_{i(t)}$ and $g(u_{rt}^1) = g(\hat{u}_{r,i(t)})$, $t = 1, \ldots, T$. Repeat the procedure J times to get the sequences u_t^j and $g(u_{rt}^j)$, $j = 1, \ldots, J$.

Second, compute x_t^j, $j = 1, \ldots, J$, according to equation (3). Precisely, set the initial conditions $x_t^j = x_{t+2p}$, $g(v_t^j) = g(\hat{v}_{t+2p})$, $t = -p+1, \ldots, 0$ for all j.[4] Then compute recursively

$$x_t^j = \hat{G}^{-1}\hat{\theta} + \hat{G}^{-1}\hat{G}(L) x_{t-1}^j + \hat{G}^{-1}\hat{\delta}(L) g(u_{rt}^j) + \hat{G}^{-1} u_t^j$$

for $t = 1, \ldots, T$.

Finally, repeat the estimation procedure explained above for any one of the artificial data sets $x_1^j, \ldots, x_T^j$, $j = 1, \ldots, J$ (being careful to use in the second stage the estimates of the nonlinear term $g(u_{rt}^j)$ obtained in the first stage), to get the relevant impulse response functions. Finally compute the confidence band as usual, by taking appropriate pointwise percentiles.

Notice that model (3) above reduces to a VAR in the special case $\delta(L) = 0$. Hence the standard recursive monetary policy structural VAR model is nested into our model. We can

[4] We are forced to use $x_{p+1}, \ldots, x_{2p}$ and $g(\hat{u}_{r,p+1}), \ldots, g(\hat{u}_{r,2p})$ as the initial conditions since we do not have estimates for $\hat{u}_{r1}, \ldots, \hat{u}_{rp}$.

therefore test for the existence of nonlinear effects by running standard tests for the null hypothesis $\delta(L) = 0$ against the alternative $\delta(L) \neq 0$.

2.5 Simulations

We assess our econometric procedure by means of a Monte Carlo simulations. We focus on the following simple model

$$\begin{pmatrix} 1-0.2L & 0 \\ 0 & 1-0.6L \end{pmatrix} \begin{pmatrix} x_{1t} \\ x_{2t} \end{pmatrix} = \begin{pmatrix} 0.1L \\ 0.4L \end{pmatrix} |u_{rt}| + \begin{pmatrix} 1 & 0 & -0.3L \\ 0 & 1 & 0.4L \end{pmatrix} \begin{pmatrix} u_{1t} \\ u_{2t} \\ u_{rt} \end{pmatrix} \tag{7}$$

where x_{1t} and x_{2t} can be interpreted as inflation and the unemployment rate. Moreover we assume that the policy variable x_{3t} is set according to the rule

$$(1 - 0.5L)x_{3t} = 1.5x_{1t} + 0.5x_{2t} + u_{rt}$$

where $u_t \sim N(0, I)$. We generate $J = 500$ different samples of length $T = 200$. We apply our econometric procedure to each dataset. Figure 1 plots the results. The solid line represent the median; the dark gray area the percentile interval 16-84; the light gray area the percentile interval 5-95; the dashed lines are the theoretical impulse response functions. Panel (a) displays the responses to the linear term u_{rt} (left column) and the nonlinear term $|u_{rt}|$ (right column) separately for the two variables, x_{1t} and x_{2t}. Panel (b) displays the overall response of the two variables. The median responses and the theoretical ones overlap in all the cases suggesting that the empirical procedure is capable to recover the correct dynamics.

In a second simulation, we set the coefficients associated to $|u_{rt}|$ equal to zero leaving unchanged the remaining coefficients. The goal is to understand whether the procedure is able to correctly estimate the dynamics when the nonlinear term plays no role. Again we use $J = 500$ and $T = 200$. Figure 2 plots the results. Panel (a) plots the effects of the two terms, the linear and nonlinear one. The effects of the nonlinear term are correctly estimated to be zero. The total effects in this case, see panel (b), are fully symmetric.

We repeat the simulation with an identical specification but assuming an asymmetric distribution for the shocks. More specifically, we assume $u_{it} \sim \chi^2_2$, $i = 1, 2, 3$. The results are displayed in Figure 3, Panel (a). The results are identical, the model correctly estimates the effects, linear and nonlinear, of the monetary policy shock. All in all, the simulation suggest that our econometric approach seems to be very successful in correctly estimating the nonlinear representation.

We run a third simulation to understand the effects of mispecificated standard VAR models when the shock is identified neglecting the existence of a non linear term. We generate data from model (7) and then we identify the monetary policy shock using a standard VAR with a Cholesky decomposition. Notice that the restrictions implied by the decomposition hold in the model, the policy shock has no contemporaneous effects of x_{1t} and x_{2t}. In one simulation we assume normality, in the other we assume an asymmetric distribution as before. Panel (b) of Figure 3 plots the results. The impulse response in the left column are those obtained assuming normality. The mean across realizations overlap with the theoretical impulse response functions. Again the responses are obtained using a Cholesky identification scheme with the interest rate ordered third and the monetary policy shock being the third one. Notice that the variables are actually generated by four shocks since also the absolute value of the monetary policy shock affects the variables. However given that the identification restrictions are correct and the absolute value of the shock is orthogonal to the shock because of normality, the estimated impulse response functions are correct. In this identification the absolute value is simply part of the remaining unidentified structural shocks. Notice however that the conclusions about the effects of the shock would be substantially different from those obtained in the nonlinear model. Things change when the shocks are drawn from an asymmetric distribution. Indeed the estimated impulse response functions are biased, the point estimates being different from their theoretical counterpart. The reason is that, under an asymmetric distribution, the monetary policy shock and its absolute value are correlated, so that the VAR estimates are biased owing to the omitted variable effect.

2.6 Possible extensions and applications

The above method can be used to verify whether large shocks are relatively less effective than small shock in stimulating real activity. This of course requires a different choice for the function $g(u_{rt})$.

In addition, the method can be directly applied to the case of the function $g(\cdot)$ depending on the shock of interest and lagged x's. For instance, we can specify such function as the interaction term $u_{rt}x_{i,t-1}$, where x_{it} is either the unemployment rate or GDP growth, in order to study the dependence of the effects of monetary policy on the state of the economy. Of course, in place of $x_{i,t-1}$ we can specify a dummy variable indicating whether $x_{i,t-1}$ is below or above a pre-specified threshold.

The method can also be applied to a public spending shock, or a tax shock, provided that such shock can be found consistently by mean of linear techniques, i.e. by means of a linear policy rule similar to the one of equation (4). This is the case of a public spending shock identified as in Blanchard and Perotti (2002) or a 'foresight' spending shock defined as in Forni and Gambetti (2016). By using the interaction term $u_{jt}x_{i,t-1}$, where u_{jt} is the fiscal shock, we can verify whether fiscal policy is more effective during recessions, as suggested in Auerbach and Gorodnicenko (2013). This is the topic of ongoing research.

3 Evidence

In this Section we present our empirical application. We use US quarterly data from 1961-Q2 to 2008-Q3, to avoid the zero lower bound period. In a robustness exercise we use the whole sample 1961-Q2 to 2019-Q3. As anticipated above, we set $g(u_{rt}) = |u_{rt}|$, so that we can distinguish the effects of negative and positive shocks.

3.1 Model specification

We consider six different model specifications. The specifications are the following:

(S1) Δ log of GDP deflator ($\times$100), the unemployment rate, the federal funds rate.

(S2) Δ log of GDP deflator, log of per-capita real GDP, federal funds rate.

(S3) Δ log of GDP deflator, Δ log of wage, unemployment, log of per-capita real GDP, federal funds rate.

(S4) Δ log of GDP deflator, unemployment, federal funds rate, the spread BAA Moody's Corporate Bond Yeld minus 10-year Treasury Bond Yield.

(S5) Δ log of GDP deflator, unemployment, log of per-capita real GDP, federal funds rate, BAA-10Y.

(S6) Δ log of GDP deflator, Δ log of wage, unemployment, federal funds rate, BAA-10Y.

In all specifications we use the AIC criterion, which points to 6 lags for all specifications. In a robustness exercise we use 4 lags.[5]

We test the reliability of the identified shock using the orthogonality test proposed in Forni and Gambetti (2014). The test is an F-test of the null that the coefficients of the lags of the explanatory variables listed in the first column of Table 1 are equal to zero. The null hypothesis is therefore that the shock is not predictable. Table 1 reports the p-value for the six specifications. The null is rejected for S1, S2 and S3. Especially the principal components and the spread seem to have high predictive power. The three specifications should not be used. On the contrary, the shock estimated using specifications S4, S5 and S6, which include the risk-premium, is never predicted.

3.2 Results

We start off our analysis by testing for linearity. We use a likelihood ratio test to test the null of a linear VAR versus the alternative represented by the model discussed in the previous section. For all of the specifications we reject the null at the 1% significance level suggesting that nonlinearities play a role.

We next discuss the estimated dynamics. We start discussing the results for S4, which is taken as the baseline specification. Figure 4 plots the estimated impulse response functions of the nonlinear model. The first column reports the effects of a policy easing which reduces the federal funds rate by 100 basis points on impact. The second column reports the effects of a policy tightening which increases the federal funds rate by 100 basis points on impact. The third column reports the effects of a contractionary policy shock in the linear model, the model without the nonlinear component. Solid lines are the point estimates and the gray area represents the 68% confidence bands.

The effects in the linear model are in line with a large body of empirical literature. Prices reduce slowly to a small extent (there is no evidence of price puzzle) and unemployment significantly increases.

In the nonlinear model an interesting result emerge. A policy easing has a large and significant effect on prices (about 2% after 2 years and 4% after 8 years) and small and non-significant effects on unemployment. A policy easing is effective in stimulating prices but not

[5] A standard LR test rejects both the BIC dynamic specification and the null of 4 lags against the AIC dynamic specification with probability value less than 0.001.

the real economy. A policy tightening, on the contrary, produces the opposite result; the effect on prices is not significant, whereas the effect on unemployment is large and significant. The tightening is effective on the real side of the economy but is ineffective to lower the price level. The result depends on the response of the two variables to the nonlinear term. The response of prices to the absolute value of the shock is positive, whereas that of unemployment is negative. This magnifies the response of unemployment to a contractionary shock and that of prices to an expansionary shock.

The situation depicted by our finding is complicated for policy authorities. It is very easy to boost inflation but very costly to reduce it. It is very easy to generate recessions but hard to stimulate the economy.

Figure 5 reports the impulse response functions obtained using S5. The results are very similar and the main conclusion confirmed. Prices significantly increase after an expansionary shock but do not reduce significantly after a contractionary shock. The opposite holds true for real activity variables: GDP falls and unemployment increases significantly following a tightening but do not move significantly after a policy easing.

Finally we repeat the estimation including nominal wages in the model (specification S6). Figure 6 reports the estimated impulse response functions. The response of wages closely track that of prices: wages significantly increase after a policy easing but do not reduce significantly following a contraction.

Table 2 shows variance decomposition, computed as explained in Subsection 2.4. Results are similar across specifications. In the non-linear models the effects of monetary policy are larger than in the linear one, especially for prices: in the linear specification, the effects on prices are negligible, whereas in the non-linear ones are sizable, albeit in S6 they are somewhat smaller than in the other specifications.

3.3 Robustness checks

We perform three robustness exercises. In the first one, we impose restriction (iv) discussed in Subsection 2.2, i.e. we impose zero impact effects of $|u_{rt}|$ on the slow moving variables in the baseline specification S4. Results are shown in figure 7. The basic result is similar to the one of figure 4 where the restriction is not imposed.

In the second exercise we estimate model S4 with just 4 lags. Results are reported in figure 8. With this dynamic specification asymmetry of positive and negative shocks is reduced, but is still there.

In the last exercise, we use the whole data set, including the zero lower bound period. We consider again specification S4, but use the 3-month Treasury Bill rate in place of the federal funds rate. Results are strongly asymmetric (indeed, the point estimate of unemployment increases, albeit not significantly, after an expansionary shock).

4 A model with downward nominal wage rigidities

This section illustrates a simple theoretical model with downward nominal wage rigidities that gives rise to asymmetric effects of monetary policy shocks. This model is used for two main purposes: first, to interpret the evidence discussed in the previous section; second, to assess, by means of a Monte Carlo Simulation, whether our empirical method is able capture the nonlinearities featured by the theoretical model.

4.1 Preferences, Technology and Monetary Policy

The economy is populated by a large number of identical households with preferences described by the objective function $\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \frac{C_t^{1-\sigma}}{1-\sigma}$, where C_t denotes consumption and $\beta \in (0,1)$ is the subjective discount factor. The household budget constraint is given by

$$P_t C_t + B_t = W_t N_t + r_{t-1} B_{t-1}, \tag{8}$$

where P_t denotes the price level, B_t denote nominal one-period riskless bonds, and r_t is the gross nominal interest rate between period t and $t+1$.

Each household supplies inelastically one unit of labor $\bar{N} = 1$. However, the labor market features downward nominal wage rigidities, so that $W_t \geq \phi W_{t-1}$, where $\phi \leq 1$ is a parameter measuring the severity of the rigidity. Whenever the latter constraint is binding, only a fraction $N_t \leq \bar{N} = 1$ of households is employed, and the remaining $1 - N_t$ households remain unemployed. In other words, the presence of downward nominal wage rigidities may give rise to "involuntary" unemployment.

Output of the single good (Y_t) is produced by perfectly competitive firms using labor as the only input according to the linear technology $Y_t = \exp\{a_t\} N_t$, where a_t denotes total factor productivity, which is assumed to follow the exogenous random-walk process $a_t = a_{t-1} + u_{at}$, with $u_{at} \sim N\left(-\sigma_a^2/2, \sigma_a^2\right)$. Firms' profit maximization implies that real wages $W_t/P_t = 1$

in every period. Also, it follows that the "natural" level of output (i.e. the level of output prevailing when the economy operates at full employment) is given by $Y_t^n \equiv \exp\{a_t\}$.

Monetary policy is conducted according to a Taylor-type interest rate rule

$$r_t = \bar{R}\Pi_t^{\phi_\pi} \exp\{m_t\} \tag{9}$$

where $\bar{R}$ is the steady-state interest rate, $\phi_\pi > 1$ is a parameter measuring the central bank's response to inflation, and m_t is a monetary policy shocks, following the AR(1) process $m_t = \rho_m m_{t-1} + u_{rt}$, where $u_{rt} \sim N\left(-\sigma_r^2/2, \sigma_r^2\right)$.

4.2 Equilibrium

The competitive equilibrium of this economy is fully characterized by the following two equations, summarizing the relationship between output and inflation:

$$1 = \Pi_t^{\phi_\pi} \exp\{m_t\}\mathbb{E}_t \left\{ \left(\frac{Y_{t+1}}{Y_t}\right)^{-\sigma} \Pi_{t+1}^{-1} \right\} \tag{10}$$

$$\left(Y_t/\exp\{a_t\} - 1\right)\left(\exp\{u_{at}\} - \phi\Pi_t^{-1}\right) = 0 \tag{11}$$

Equation (10) is an aggregate demand (AD) relationship, and is obtained combining the consumption Euler equation from the household's optimal consumption/savings decision with the monetary policy rule (9) and the market clearing condition $Y_t = C_t$. Equation (11) describes instead an aggregate supply (AS) relationship, and is obtained combining the production function, the household's labor supply subject to the downward nominal wage rigidity, and the firms labor demand implying that the real wage $W_t/P_t = \exp\{a_t\}$.

Figure 10 provides a graphical illustration of the main mechanism of the model. It plots the aggregate demand (AD) and aggregate supply (AS) curves, for a given level of expected output and inflation. Note that the presence of downward wage rigidities introduce a "kink" in the aggregate supply relationship, and for this reason the real effects of monetary policy shocks are asymmetric. Suppose for instance that the economy is initially in a situation where technology is at its steady state level, the economy is at full-employment, i.e. $Y_t^n = \exp a_t = 1$, and (gross) inflation $\Pi = 1$ so that the downward wage rigidity is not binding (point A in the graph). Starting from that situation, an expansionary monetary shock stimulates aggregate demand (i.e. the AD shifts to the right, to point B) putting upward pressures on nominal wages and prices, meaning that the downward wage rigidity is not binding (i.e. the economy lies in the vertical portion of the AS curve). Thus, the only effect of the monetary shock is an increase in inflation, with no effect on output. On the contrary, a contractionary monetary shock that reduces aggregate demand (the AD shifts to the left) makes the downward wage rigidity binding (i.e. the economy moves to the horizontal part of the AS curve), which implies a reduction in output, with no effect on inflation (point C). Instead, the effects of expansionary and contractionary shocks would be symmetric while output remains below its level. Thus, when looking at the average effects of monetary shocks between periods with full-employment and periods with "involuntary" unemployment, contractionary shocks have stronger effects that expansionary ones.

In order to provide a quantitative example of the described asymmetries, we adopt a quarterly calibration of the model, where the discount factor $\beta = 0.99$, the intertemporal elasticity of substitution $\sigma = 1$, the downward wage rigidity parameter $\phi = 1$, the monetary policy coefficient $\phi_\pi = 1.5$. Regarding the two shock processes, in line with existing empirical estimates (see e.g. Smets and Wouters, 2007), we set the autocorrelation of the monetary shock $\rho_m = 0.5$ and the standard deviations $\sigma_r = 0.25$ percent, while the standard deviation of (permanent) innovations to technology is $\sigma_a = 0.45$. The model is solved and simulated using a (non-linear) global projection method, where the expectation term in the aggregate demand (10) is approximated with a Chebyshev polynomial on a coarse grid for the monetary policy shock (see Appendix for more details).

Figure 11 displays the impulse responses (in logs) of output and (annualized) inflation to a 25 basis point monetary shock. The top panel shows the responses assuming that the economy is initially at the steady state and there is no technology shock (i.e. with $u_{at} = 0$ $\forall t$). As explained earlier, a contractionary monetary shock (solid line) leads to a reduction in output, but has no effect on inflation. On the contrary, an expansionary shock (dashed line) leads to a rise in inflation, without affecting output. The bottom panel shows the average impulse response across 1000 realizations of the technology shock, and shows that the effects on output of contractionary monetary shocks are (in absolute value) about twice as large as for expansionary shocks.

4.3 Assessing the empirical representation

We first perform a Monte Carlo simulation with the main goal of assessing whether the non-linear representation of the economy that we have postulated is capable of capturing and approximating the type of nonlinearities present in the theoretical model arising from downward rigidities.

Before presenting the simulation its has to be noted that model (1) can be rewritten by making explicit u_{rt} as

$$x_t = \nu + \Gamma_r(L)u_{rt} + \beta(L)g(u_{rt}) + \tilde{\Gamma}(L)\tilde{u}_t \tag{12}$$

where $\tilde{u}_t$ is the $n-1$-dimensional vector of non-policy shocks and $\tilde{\Gamma}(L)$ the associated matrix of impulse response functions. Using a parametrization similar to the one used before the implied VARX representation can be found:

$$A(L)x_t = \mu + \tilde{\Gamma}_r(L)u_{rt} + \tilde{\beta}(L)g(u_{rt}) + \tilde{\Gamma}_0\tilde{u}_t \tag{13}$$

where now $\tilde{\Gamma}_0$ has dimension $n \times (n-1)$ matrix.

The simulation works as follows. We generate 1000 realization of output and inflation using the theoretical model discussed above. For each pair of realizations of output and inflation we estimate (13) by OLS using the corresponding realization of the shock, say u^j_{rt} together with $|u^j_{rt}|$, as regressors. Then we average the 1000 impulse response functions. Notice that here, we do not attempt to identify the policy shock, we take directly its true realization, along with its absolute value, as the regressors of (13). This is because in the model the impact effect of the monetary policy shock is nonzero. Hence the simulation does not aim at evaluating the identification procedure; rather, it is designed to understand whether the nonlinear representation (1) is a good approximation of the nonlinear dynamics of the model.

The bottom row of Figure 11 shows the mean impulse response functions. The responses are almost identical to the theoretical ones. The nonlinear representation is capable of capturing very accurately the asymmetry in the effects of the monetary policy shock present in the model.

5 Conclusions

We have found that monetary policy shock, identified as in Christiano et al. (1996, 1999), have asymmetric effect: a policy easing has large effects on prices but small effects on real activity, whereas a policy tightening has large real effects but small effects on prices. We have shown that this finding is in line with a simple DSGE model with downward nominal wage rigidity.

Our result has been obtained by a simple two-stage procedure: first, the monetary policy shock has been estimated as the residual of a standard Taylor-type policy rule; second, a nonlinear function of the shock (i.e. its absolute value) has been used as an additional regressor for the other variables in the system. The impulse-response functions have been obtained by combining the coefficients estimated in the two steps. The validity of the procedure has been assessed by a simulation exercise.

The above method can be applied to the case of impulse response functions depending on lagged x's, capturing the state of the economy. In this way we could verify whether fiscal policy is more effective during recessions.

References

[1] Abbritti, M., and S. Fahr (2013), Downward Wage Rgidities and Business Cycle Asymmetries, Elsevier, 60(7), 871-886.

[2] Alvarez, F., Le Bihan,H., and F. Lippi (2016), The Real Effects of Monetary Shocks in Sticky Price Models: A Sufficient Statistic Approach, American Economic Review, 106(10), 2817-2851.

[3] Angrist, J.D., Jordà, O. and G.M. Kuersteiner (2018), Semiparametric Estimates of Monetary Policy Effects: String Theory Revisited, Journal of Business & Economic Statistics, 36(3), 371-387.

[4] Arias, J.E., D. Caldara and J.F Rubio-Ramírez (2019), The Systematic Component of Monetary Policy in SVARs: An Agnostic Identification Procedure, Journal of Monetary Economics, Elsevier, 101(C), 1-13.

[5] Auerbach A.J. and Y. Gorodnichenko (2012). Measuring the Output Responses to Fiscal Policy, American Economic Journal: Economic Policy 4, pp. 1-27.

[6] Ball, L., and D. Romer (1990), Real Rigidities and the Non-Neutrality of Money, The Review of Economic Studies, 57(2), 183-203.

[7] Ball, L., and N.G. Mankiw (1994), A sticky-price manifesto, Carnegie-Rochester Conference Series on Public Policy, Elsevier, 41(1), 127-151, December.

[8] Barnichon, R., and C. Matthes (2018), Functional Approximation of Impulse Responses, Journal of Monetary Economics, Elsevier, 99(C), 41-55.

[9] Benigno, P., and L. A. Ricci (2011), The Inflation-Output Trade-Off with Downward Wage Rigidities. American Economic Review, 101 (4): 1436-66.

[10] Benigno, G., and L. Fornaro (2019), The Keynesian Growth Approach to Macroeconomic Policy and Productivity, Liberty Street Economics 20190401, Federal Reserve Bank of New York.

[11] Bernanke, B.S., and A. Blinder (1992), The Federal Funds Rate and the Channels of Monetary Transmission, American Economic Review, 82, 901-921.

[12] Bernanke, B.S., M. Gertler, (1995), Inside the Black Box: The Credit Channel of Monetary Policy Transmission, Journal of Economic Perspectives, Vol. 9, No. 4, pages 27 - 48.

[13] Bernanke, B.S., I. Mihov (1998), Measuring Monetary Policy, The Quarterly Journal of Economics, Oxford University Press, vol. 113(3), pages 869-902.

[14] Blanchard, O.J. and R. Perotti (2002). An Empirical Characterization of the Dynamic Effects of Changes in Government Spending and Taxes on Output. The Quarterly Journal of Economics: 1329-1368.

[15] Caldara, D., and E. Herbst (2019), Monetary Policy, Real Activity, and Credit Spreads: Evidence from Bayesian Proxy SVARs, American Economic Journal: Macroeconomics, 11 (1): 157-92.

[16] Christiano, L., M. Eichenbaum, and C. Evans (1996), The Effects of Monetary Policy Shocks: Evidence from the Flow of Funds, The Review of Economics and Statistics, MIT Press, vol. 78(1), 16-34.

[17] Christiano, L., M. Eichenbaum, and C. Evans (1999), Monetary Policy Shocks: What Have We Learned and to What End?, in: J.B Taylor and M. Woodford (eds.), Handbook of Macroeconomics, 1, Elsevier: North Holland, 65-148.

[18] Cochrane, J.H. (1994), Permanent and Transitory Components of GNP and Stock Prices, Quarterly Journal of Economics, 109, 241-265.

[19] Cover, J.P. (1992), Asymmetric Effects of Positive and Negative Money-Supply Shocks, Quarterly Journal of Economics, November 1992, 107(4), pp. 1261-82.

[20] DeLong, J.B., and L.H. Summers (1988), How Does Macroeconomic Policy Affect Output?, Brookings Papers on Economic Activity, 1988, (2), pp. 433-94.

[21] Fagan, G. and J. Messina (2009), Downward wage rigidity and optimal steady-state inflation, Working Paper Series 1048, European Central Bank.

[22] Forni, M., and L. Gambetti (2014), Sufficient information in structural VARs, Journal of Monetary Economics, Elsevier, vol. 66(C), pages 124-136.

[23] Forni, M. and L. Gambetti (2016), Government spending shocks in open economy VARs, Journal of International Economics, Elsevier, vol. 99(C), pages 68-84.

[24] Gertler, M., and P. Karadi (2015), Monetary Policy Surprises, Credit Costs, and Economic Activity, American Economic Journal: Macroeconomics, 2015, 7(1): 44-76.

[25] Golosov, M., and R.E. Lucas Jr. (2007), Menu Costs and Phillips Curves, Journal of Political Economy, University of Chicago Press, 115, 171-199.

[26] Jarocinski, M., and P. Karadi (2020), Deconstructing Monetary Policy Surprises - The Role of Information Shocks, American Economic Journal: Macroeconomics, 12(2), 1-43.

[27] Karras, Georgios (1996), Are the Output Effects of Monetary Policy Asymmetric? Evidence from a Sample of European Countries, Oxford Bulletin of Economics and Statistics, May 1996, 58(2), pp. 267-78.

[28] Keynes, J.M. (1936), The General Theory of Employment, Interest, and Money, Palgrave Macmillan.

[29] Kim, J. and F.J. Ruge-Murcia (2009), How much inflation is necessary to grease the wheels?, Journal of Monetary Economics, 56(3), 365-377.

[30] Leeper, E.M., C.A. Sims and T. Zha (1996), What Does Monetary Policy Do? Brookings Papers on Economic Activity, 2, 1-63.

[31] Midrigan, V. (2011) Menu Costs, Multiproduct Firms, and Aggregate Fluctuations, Econometrica, 79(4), 1139-1180.

[32] Miranda-Agrippino and Ricco (2017), The Transmission of Monetary Policy Shocks, Bank of England, Staff Working Paper n. 657.

[33] Ravn, M.O., and M. Sola (1996), A Reconsideration of the Empirical Evidence on the Asymmetric Effects of Money Supply Shocks: Positive vs. Negative or Big vs. Small?, Unpublished manuscript, University of Aarhus, Denmark, March 1996.

[34] Romer, C., and D. Romer (2004), A New Measure of Monetary Shocks: Derivation and Implications, American Economic Review, American Economic Association, vol. 94(4), pages 1055-1084, September.

[35] Schmitt-Grohe, S., and M. Uribe (2016), Downward Nominal Wage Rigidity, Currency Pegs, and Involuntary Unemployment, Journal of Political Economy 124, October 2016, 1466-1514.

[36] Sims, C. A., and T. Zha, (2006). Does monetary policy generate recessions?, Macroeconomic Dynamics, 10(02), pp. 231-272.

[37] Smets, F., and R. Wouters (2007), Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach, American Economic Review, 97(3), 586-606.

[38] Strongin, S. (1995), The Identification of Monetary Policy Disturbances: Explaining the Liquidity Puzzle, Journal of Monetary Economics, 35, 463-498.

[39] Uhlig, H. (2005), What are the Effects of Monetary Policy on Output? Results from an Agnostic Identification Procedure, Journal of Monetary Economics, 52, 381-419.

Appendix: Solution of the Model

Solving the model amounts to solve the following system

$$1 = \beta \bar{R} \Pi_t^{\phi_\pi} \tilde{Y}_t^{\sigma} \exp\{m_t\} \mathbb{E}_t \left\{ \exp\{-\sigma u_{a,t+1}\} \tilde{Y}_{t+1}^{-\sigma} \Pi_{t+1}^{-1} \right\} \tag{14}$$

$$\left(\tilde{Y}_t - 1\right) \left(\exp\{u_{at}\} - \Pi_t^{-1}\right) = 0 \tag{15}$$

where $\tilde{Y}_t \equiv Y_t / \exp\{a_t\}$ is detrended output. To solve the model, we approximate the expectation term on the RHS of the aggregate demand through a Chebyshev polynomial on a coarse grid for the monetary shocks, i.e. we approximate the function

$$X(m_t) \equiv \mathbb{E}_t \left\{ \exp\{-\sigma u_{a,t+1}\} \left(\tilde{Y}_{t+1}\right)^{-\sigma} \Pi_{t+1}^{-1} \right\}.$$

Note that, since the technology innovation u_{at} is assumed to be *i.i.d.*, it does not affect future expectations and thus it does not constitute an argument of the function $X(\cdot)$. The advantage of this procedure is that the expectation function $X(\cdot)$ is a smooth function of the monetary shock, while the policy functions of inflation and output are not, due to the "kink" related to downard wage rigidities.

For a given guess of the function $X(m_t)$, the solution of the model can be obtained analytically as

$$\begin{aligned} &\tilde{y}_t = 0,\ \pi_t = -\frac{1}{\phi_\pi}\left[x_t + m_t + (\bar{r} - \rho)\right] && \text{if } m_t \leq \phi_\pi u_{at} - x_t - (\bar{r} - \rho) \\ &\tilde{y}_t = -\frac{1}{\sigma}\left[x_t + m_t - \phi_\pi u_{at} + (\bar{r} - \rho)\right],\ \pi_t = -u_{at} && \text{if } m_t > \phi_\pi u_{at} - x_t - (\bar{r} - \rho) \end{aligned}$$

where lower-case variables denote the log of upper case variables, which can be used to calculate $\tilde{y}_{t+1}$ and π_{t+1} for all realizations of future shocks. The initial guess constitutes an equilibrium if it satisfies

$$X(m_t) = \mathbb{E}_t \left[\exp\{-\sigma\left(u_{a,t+1} + \tilde{y}_{t+1}\right) - \pi_{t+1}\}\right].$$

Tables

	S1	S2	S3	S4	S5	S6
6 PC	0.00	0.00	0.02	0.12	0.13	0.64
8 PC	0.00	0.00	0.04	0.22	0.18	0.85
TB3M	0.04	0.04	0.06	0.59	0.62	0.71
GS10	0.00	0.01	0.00	0.68	0.67	0.53
AAA Yield	0.00	0.01	0.00	0.21	0.21	0.10
BAA Yield	0.13	0.38	0.17	0.52	0.52	0.32
BAA-AAA	0.00	0.00	0.00	0.17	0.18	0.13
BAA-GS10	0.00	0.00	0.00	1.00	1.00	1.00
VXO	0.89	0.92	0.99	0.98	0.98	0.90
S&P500	0.13	0.36	0.34	0.54	0.60	0.51
CPI inflation	0.11	0.51	0.43	0.38	0.34	0.46
Unemployment rate	0.55	1.00	1.00	1.00	1.00	1.00
Hours Worked	0.54	0.89	0.93	0.75	0.76	0.70
JLN Macro 3m	0.09	0.27	0.64	0.38	0.41	0.77
E1Y	0.13	0.08	0.26	0.08	0.08	0.31
Real Loans	0.93	0.56	0.47	0.33	0.38	0.31
Wage	0.99	0.76	1.00	0.77	1.00	0.68

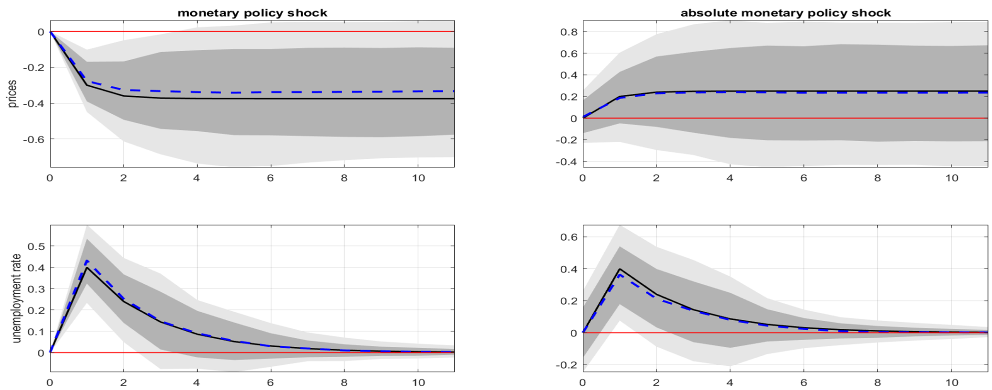
Table 1: Orthogonality test (Forni and Gambetti, 2014). F test for the overall significance of the regression of the estimated monetary policy shock onto the first 4 lags of the indicated variables, p-values. In the first two rows we regress the estimated shock onto the first 6 and 8 principal components of a large data set including macroeconomic US quarterly data. In the remaining rows we use one variable at a time as the regressor.

	k=0	k=4	k=8	k=16	k=40	k=0	k=4	k=8	k=16	k=40
			S4 Linear					S4 Non-Linear		
Prices	0.0	0.2	0.1	1.5	8.7	6.9	20.1	29.4	40.3	60.2
Unemployment rate	0.0	3.3	13.9	15.7	15.7	2.2	2.3	19.5	43.2	52.2
Federal Funds Rate	76.6	29.2	28.2	32.4	22.0	81.4	38.5	40.9	44.1	57.4
spread BAA-GS10	2.0	2.6	8.1	10.1	10.4	3.6	7.5	17.4	21.6	24.5
			S5 Linear					S5 Non-Linear		
Prices	0.0	0.4	0.3	2.1	11.3	6.4	21.4	31.5	44.8	63.6
Wage	0.0	1.0	1.6	5.8	15.9	0.0	4.9	13.8	26.8	55.4
Unemployment rate	0.0	2.8	14.6	18.9	18.6	1.1	3.5	23.4	44.5	53.6
Federal Funds Rate	77.2	30.6	31.2	34.8	23.9	81.3	38.2	42.0	45.0	58.5
spread BAA-GS10	2.0	2.2	8.1	11.0	11.4	3.9	8.6	18.6	22.2	23.7
			S6 Linear					S6 Non-Linear		
Prices	0.0	0.4	0.5	0.9	5.8	1.6	6.8	9.1	12.0	34.8
Per Capita GDP	0.0	7.3	19.3	13.7	9.7	0.1	10.2	29.9	28.1	37.1
Unemployment rate	0.0	2.2	14.6	16.2	14.5	0.2	8.8	27.1	32.0	38.0
Federal Funds Rate	72.4	34.2	30.4	30.2	22.8	73.2	44.7	45.3	44.8	41.4
spread BAA-GS10	3.3	1.8	6.0	6.3	7.8	7.8	14.5	21.7	20.3	22.1

Table 2: Variance decomposition in the linear and the nonlinear models, specifications S4, S5 and S6.

Figures

Panel (a)



Panel (b)

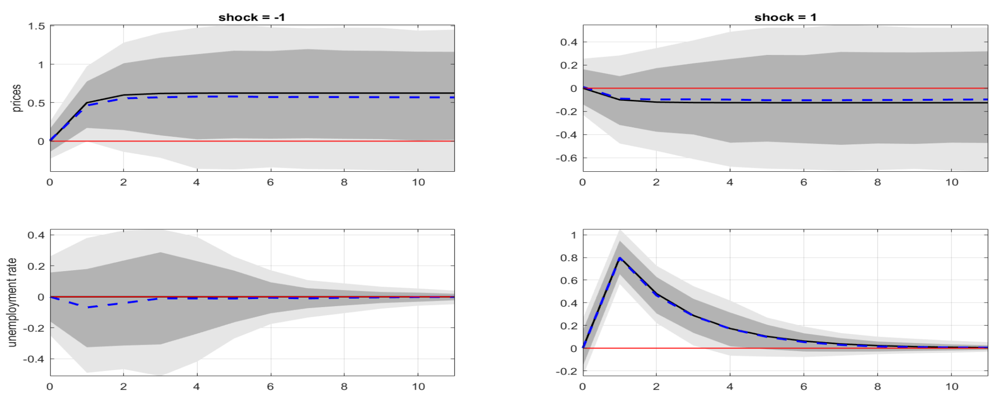
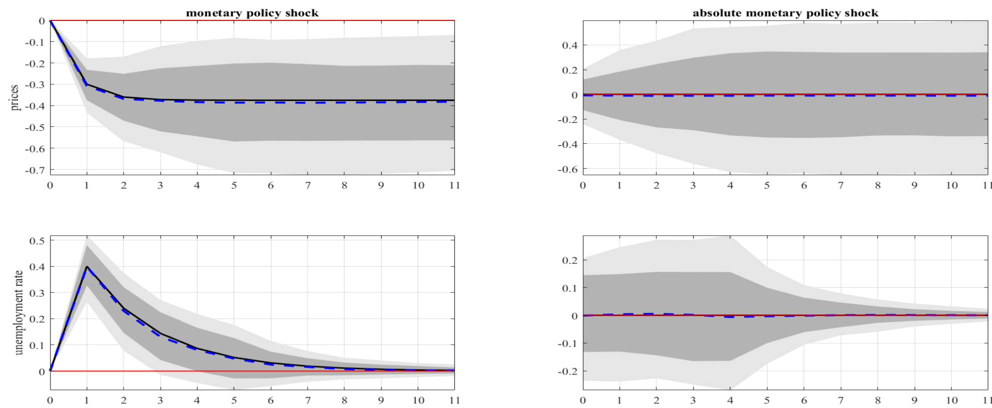


Figure 1: Simulation 1. 500 random samples of length $T = 200$ generated with model (7). The solid line represent the median; the dark gray area the percentile interval 16-84; the light gray area the percentile interval 5-95; the dashed lines are the theoretical impulse response functions. Panel (a) displays the responses to the linear term u_{rt} (left column) and the nonlinear term $|u_{rt}|$ (right column) separately for prices (first row) and the unemployment rate (second row). Panel (b) displays the overall response of the two variables to expansionary shocks (left column) and contractionary shocks (right column).

Panel (a)



Panel (b)

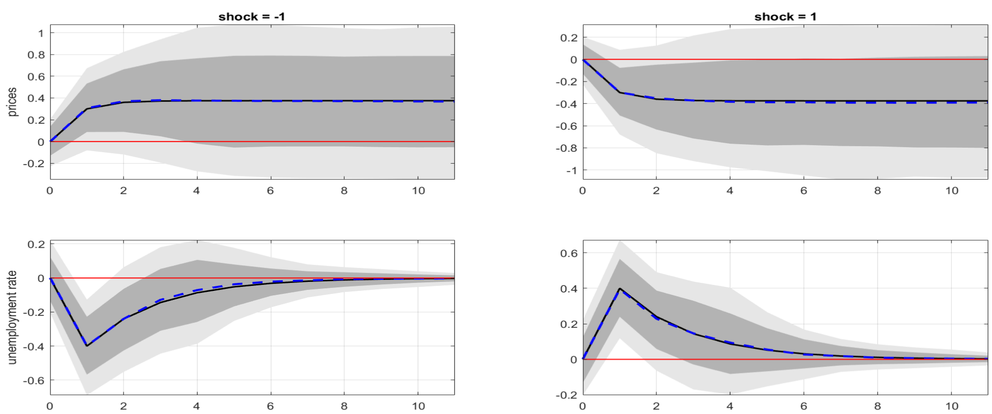
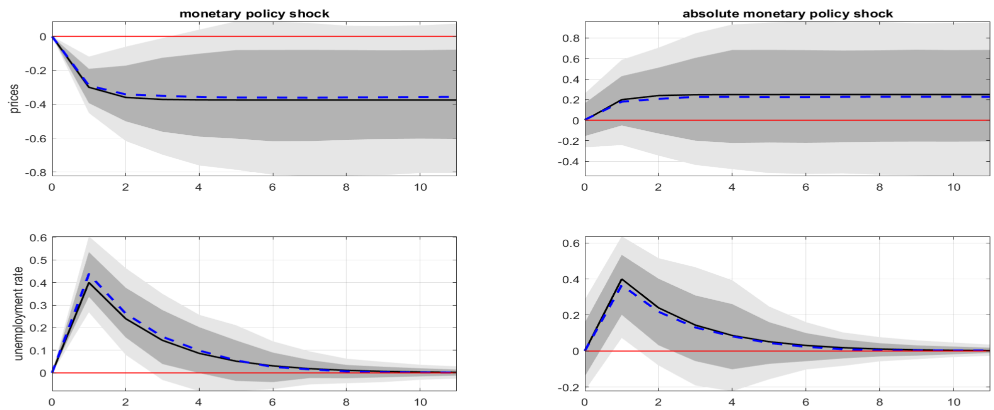


Figure 2: Simulation 2. 500 random samples of length $T = 200$ generated with model (7), with the coefficient of $|u_{rt}|$ set to 0. The solid line represent the median; the dark gray area the percentile interval 16-84; the light gray area the percentile interval 5-95; the dashed lines are the theoretical impulse response functions. Panel (a) displays the responses to the linear term u_{rt} (left column) and the nonlinear term $|u_{rt}|$ (right column) separately for prices (first row) and the unemployment rate (second row). Panel (b) displays the overall response of the two variables to expansionary shocks (left column) and contractionary shocks (right column).

Panel (a)



Panel (b)

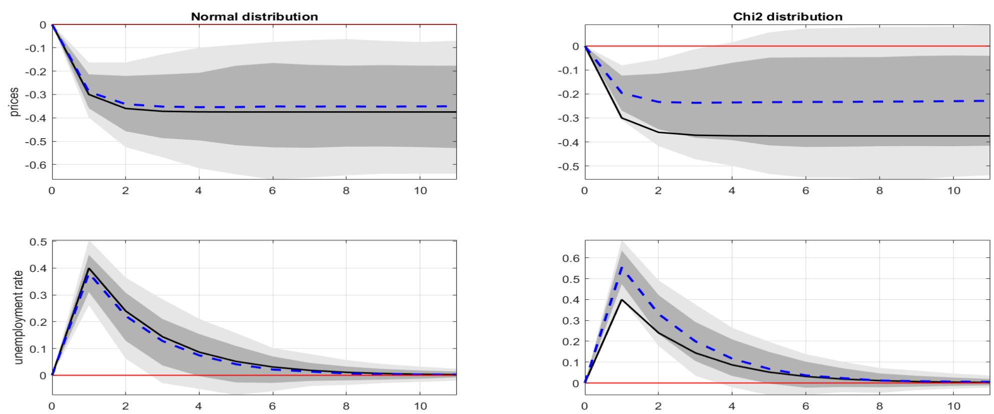


Figure 3: Simulation 3. 500 random samples of length $T = 200$ generated with model (7), but $u_{it} \sim \chi^2_2$, $i = 1, 2, 3$. The solid line represent the median; the dark gray area the percentile interval 16-84; the light gray area the percentile interval 5-95; the dashed lines are the theoretical impulse response functions. Panel (a) displays the responses to the linear term u_{rt} (left column) and the nonlinear term $|u_{rt}|$ (right column) separately for the two variables. x_{1t} and x_{2t}. Panel (b) displays the results obtained for the impulse response function of u_{rt} when estimating a standard linear VAR model. In the left column the shocks are normally disributed; in the right column $u_{it} \sim \chi^2_2$, $i = 1, 2, 3$.

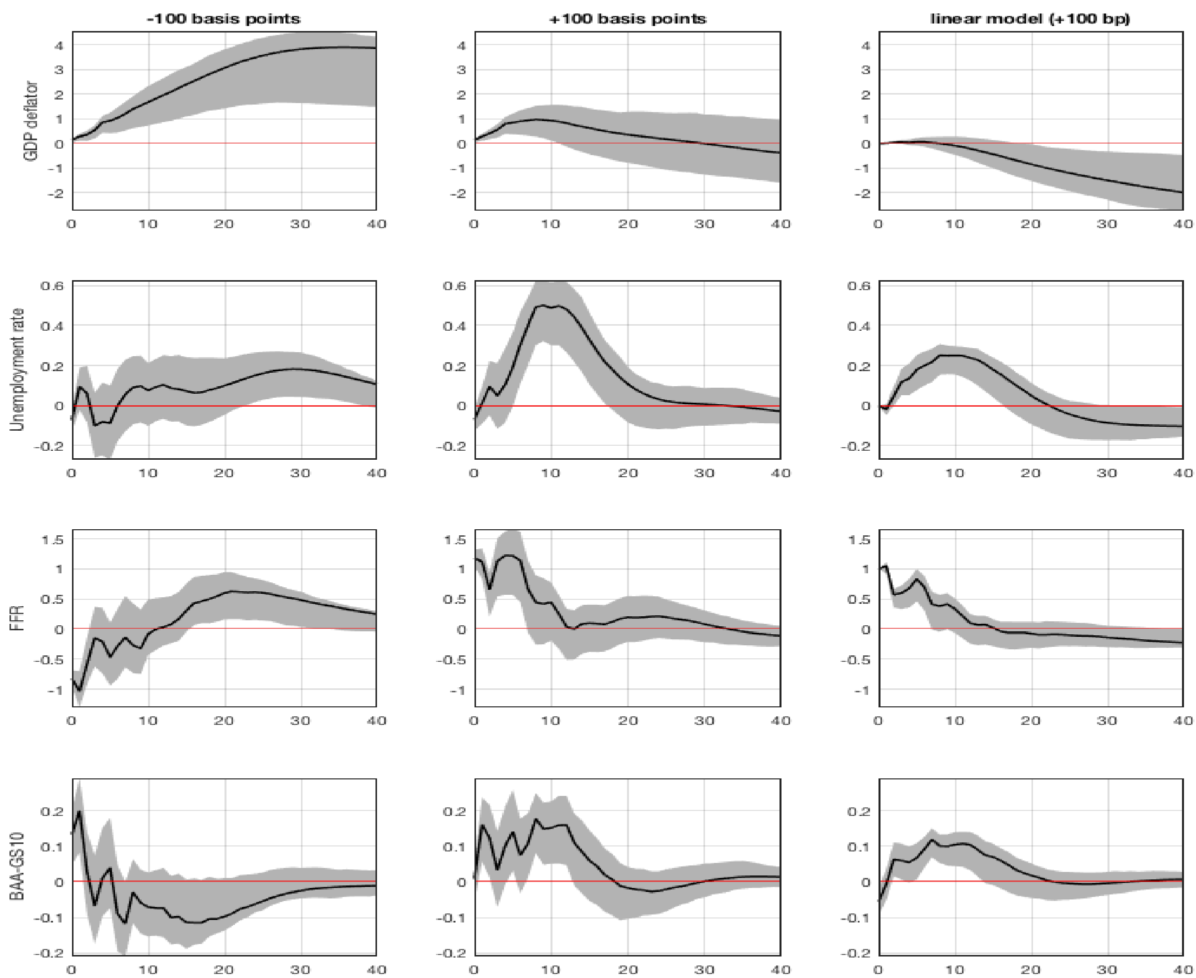


Figure 4: Estimated impulse response functions, specification S4, 6 lags (AIC). The first column reports the effects of a policy easing which reduces the federal funds rate by 100 basis points on impact. The second column reports the effects of a policy tightening which increases the federal funds rate by 100 basis points on impact. The third column reports the effects of a contractionary policy shock in the corresponding linear model. Solid lines are the point estimates and the gray area represents the 68% confidence bands.

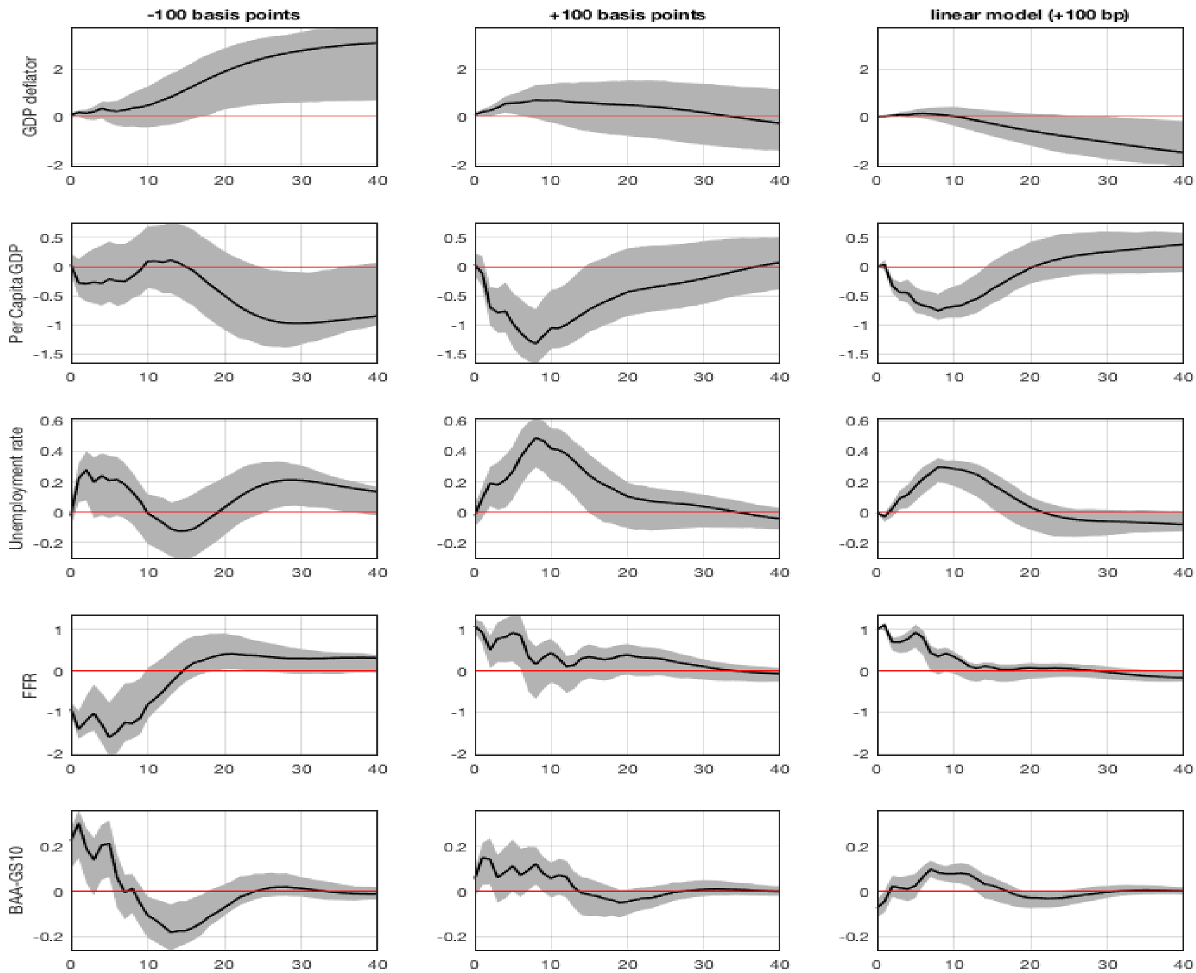


Figure 5: Estimated impulse response functions, specification S5, 6 lags (AIC). The first column reports the effects of a policy easing which reduces the federal funds rate by 100 basis points on impact. The second column reports the effects of a policy tightening which increases the federal funds rate by 100 basis points on impact. The third column reports the effects of a contractionary policy shock in the corresponding linear model. Solid lines are the point estimates and the gray area represents the 68% confidence bands.

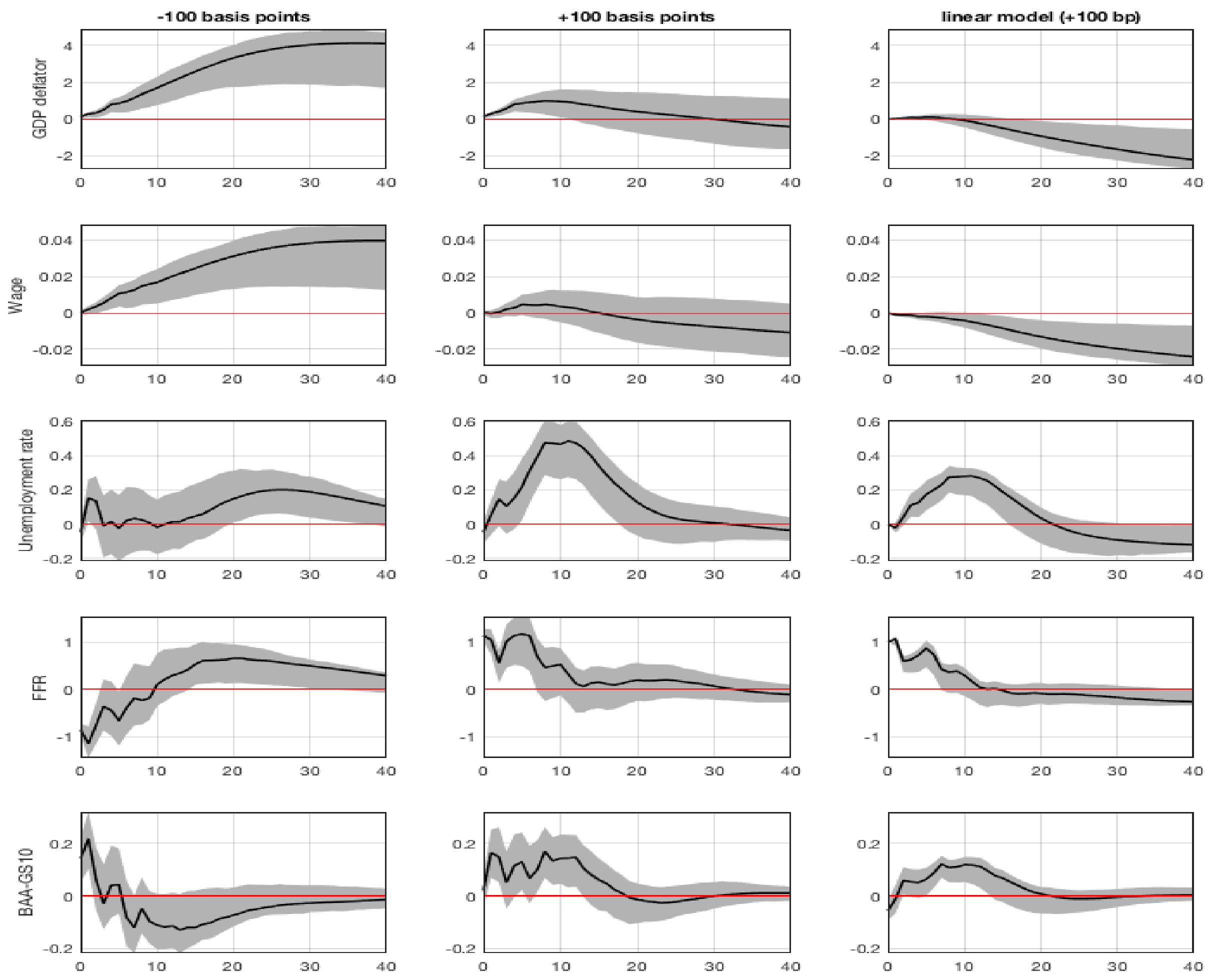


Figure 6: Estimated impulse response functions, specification S4, 6 lags (AIC). The first column reports the effects of a policy easing which reduces the federal funds rate by 100 basis points on impact. The second column reports the effects of a policy tightening which increases the federal funds rate by 100 basis points on impact. The third column reports the effects of a contractionary policy shock in the corresponding linear model. Solid lines are the point estimates and the gray area represents the 68% confidence bands.

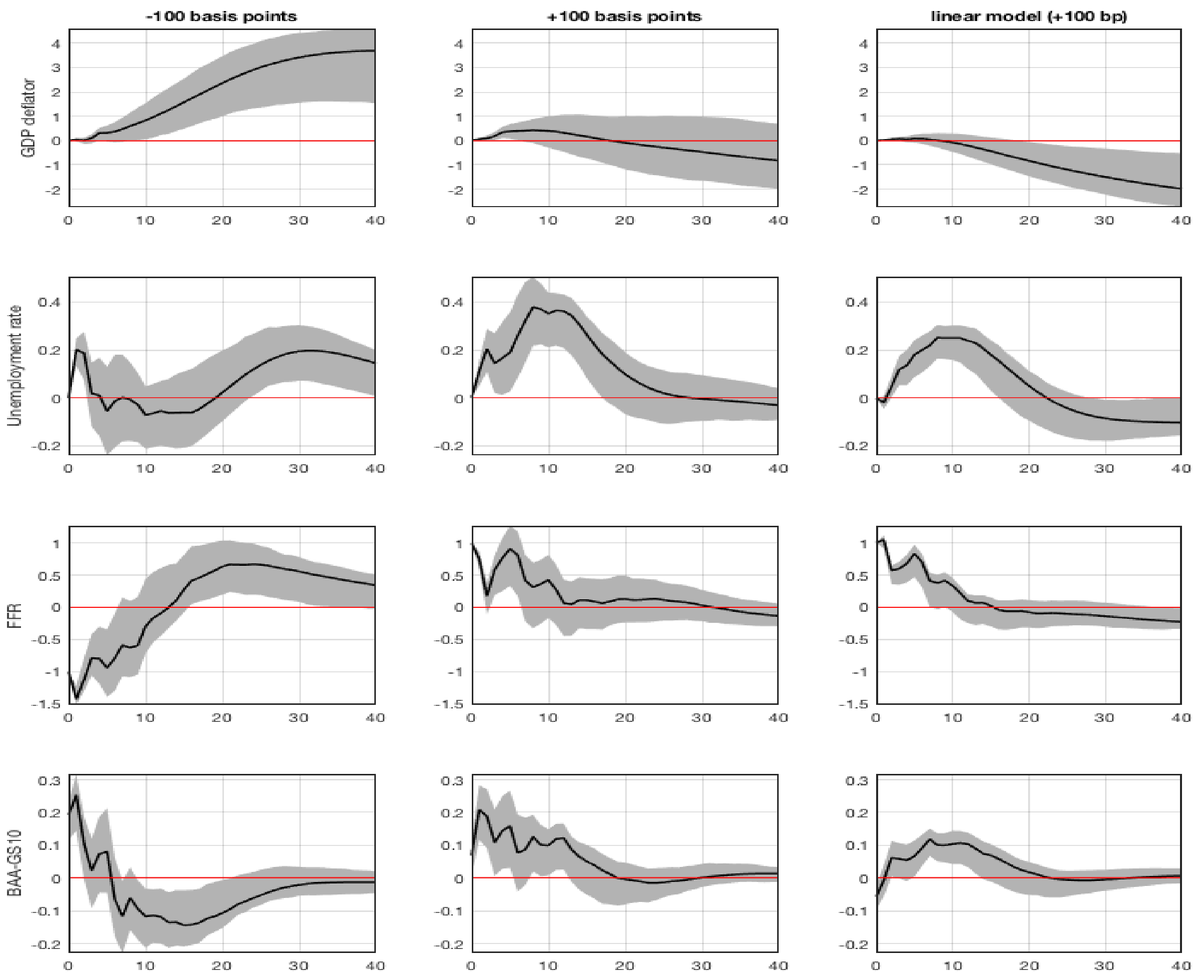


Figure 7: Estimated impulse response functions, specification S4, 6 lags (AIC), obtained by imposing restriction (iv), i.e. no impact effect of $|u_{rt}$ on prices and unemployment. The first column reports the effects of a policy easing which reduces the federal funds rate by 100 basis points on impact. The second column reports the effects of a policy tightening which increases the federal funds rate by 100 basis points on impact. The third column reports the effects of a contractionary policy shock in the corresponding linear model. Solid lines are the point estimates and the gray area represents the 68% confidence bands.

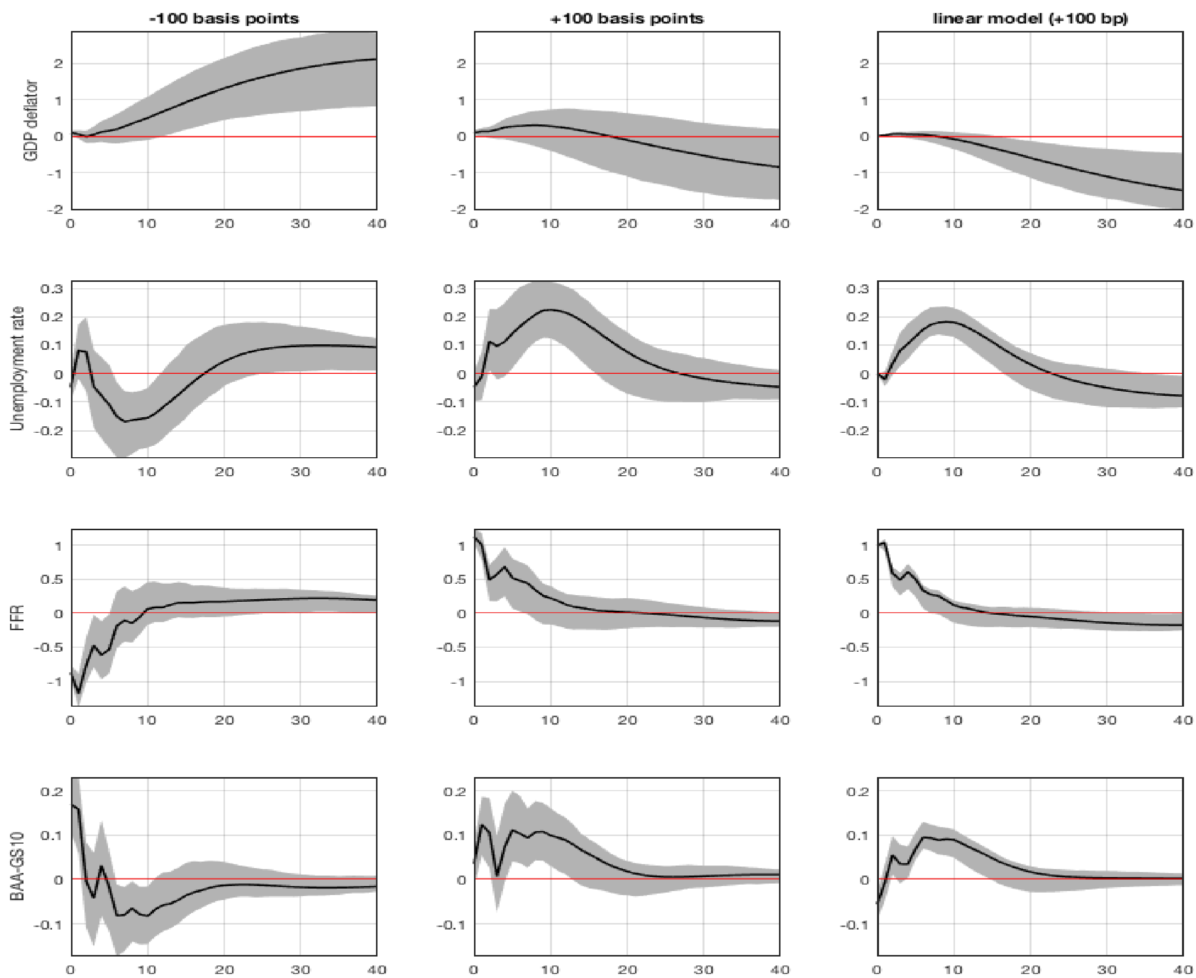


Figure 8: Estimated impulse response functions, specification S4, 4 lags. The first column reports the effects of a policy easing which reduces the federal funds rate by 100 basis points on impact. The second column reports the effects of a policy tightening which increases the federal funds rate by 100 basis points on impact. The third column reports the effects of a contractionary policy shock in the corresponding linear model. Solid lines are the point estimates and the gray area represents the 68% confidence bands.

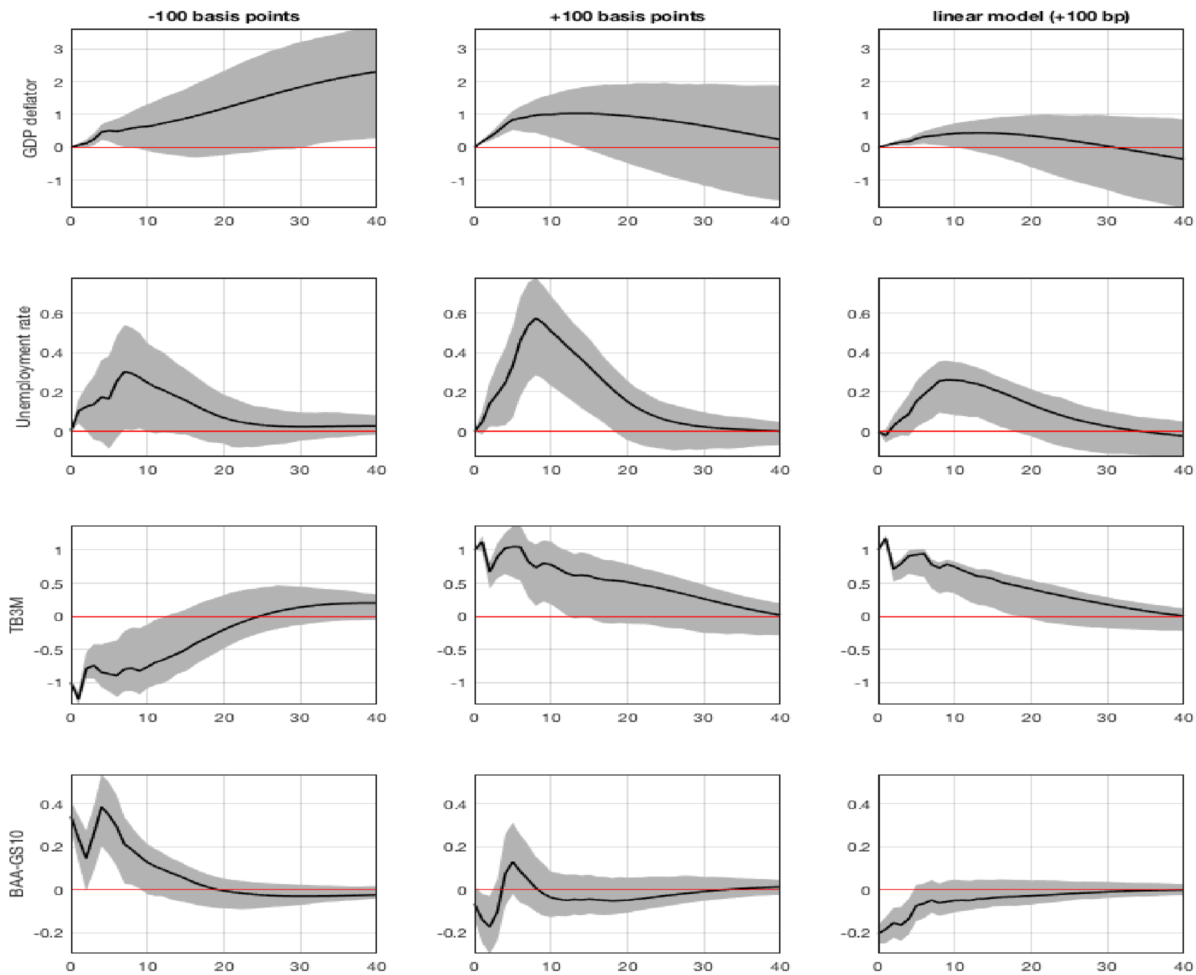


Figure 9: Estimated impulse response functions, specification S4, all sample, TB3M in place of FFR. The first column reports the effects of a policy easing which reduces the federal funds rate by 100 basis points on impact. The second column reports the effects of a policy tightening which increases the federal funds rate by 100 basis points on impact. The third column reports the effects of a contractionary policy shock in the corresponding linear model. Solid lines are the point estimates and the gray area represents the 68% confidence bands.

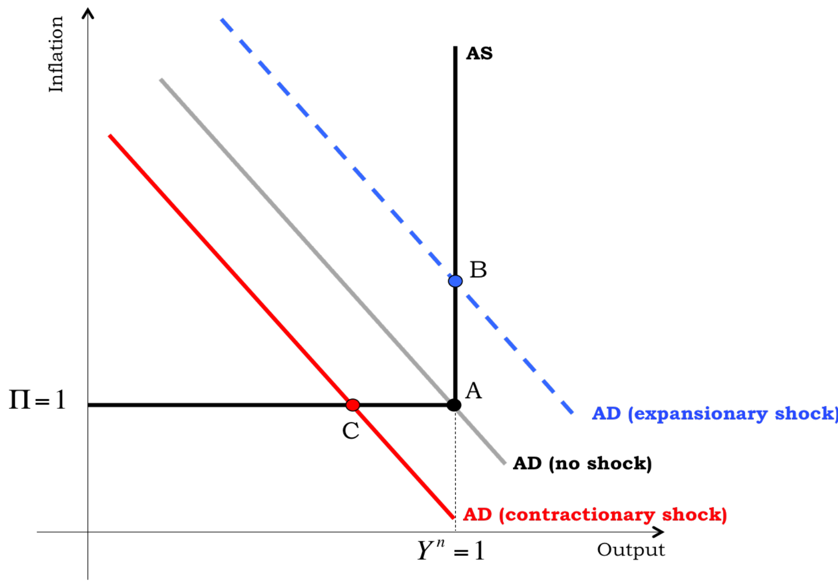
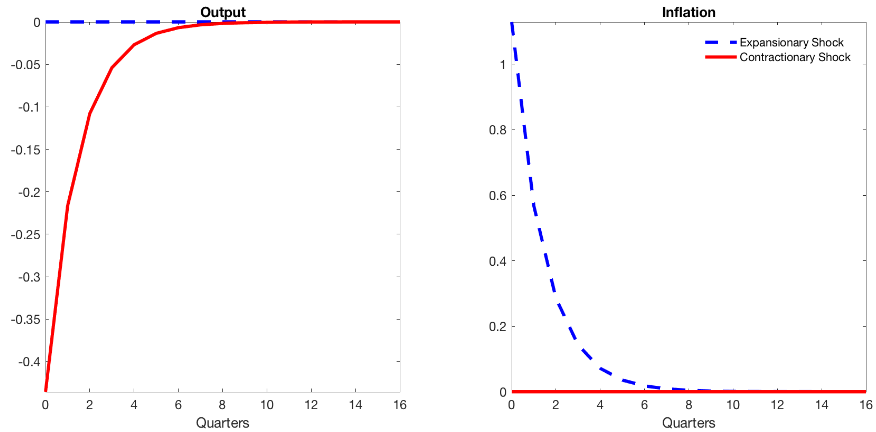
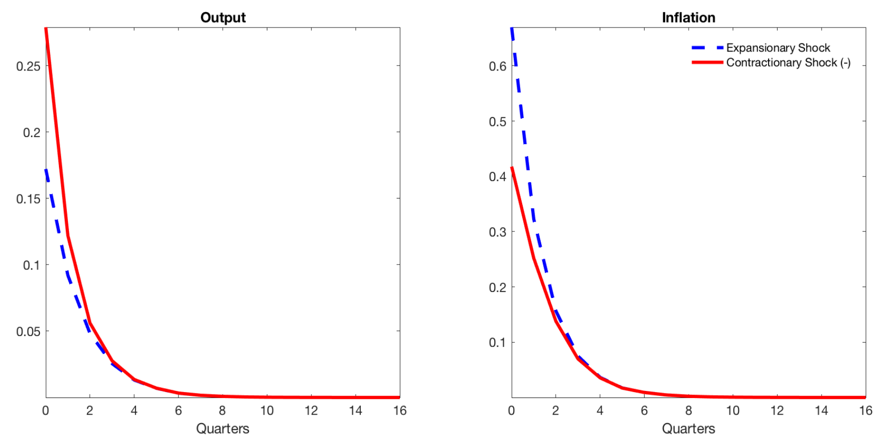


Figure 10: Asymmetric Effects of Monetary Shocks in the model of Section 4

Panel (a): At Steady State (No Technology Shock)



Panel (b): On Average



Panel (c): Estimation on simulated data

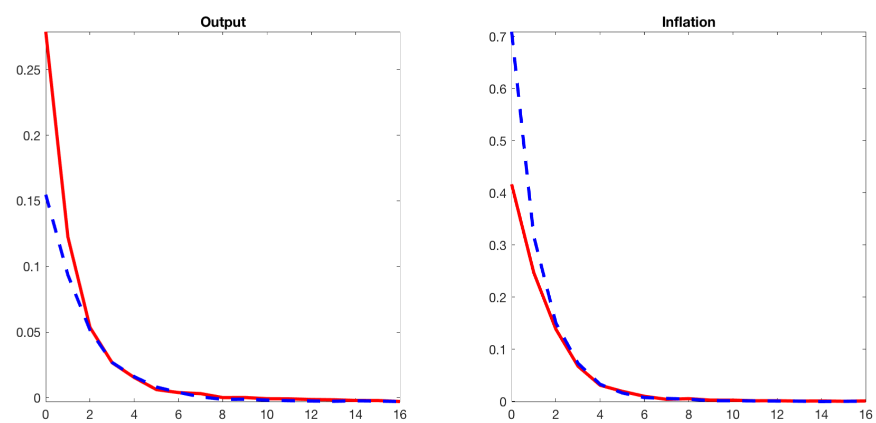


Figure 11: Impulse Responses to Monetary Policy Shocks in the model of Section 4