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# How do Fiscal and Technology Shocks affect Real Exchange Rates? New Evidence for the United States*

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**Abstract:**
Using vector autoregressions on U.S. time series relative to an aggregate of industrialized countries, this paper provides new evidence on the dynamic effects of government spending and technology shocks on the real exchange rate and the terms of trade. To achieve identification, we derive robust restrictions on the sign of several impulse responses from a two-country general equilibrium model. We find that both the real exchange rate and the terms of trade – whose responses are left unrestricted – depreciate in response to expansionary government spending shocks and appreciate in response to positive technology shocks.

**JEL Classification:** F41, F42, E32

**Keywords:** Real Exchange Rate, Terms of Trade, International Transmission Mechanism, Government Spending Shocks, Technology Shocks, VAR, Sign Restrictions

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# 1 Introduction

How do international relative prices—measured by the real exchange rate or the terms of trade—respond to government spending and technology shocks? This question is pivotal to understanding the international transmission mechanism and has become the topic of a considerable debate. Overall, the existing evidence appears to be hard to reconcile with the predictions of both Mundell-Fleming type and intertemporal business cycle models under standard calibrations. These modeling frameworks suggest that relative prices of domestic goods increase in response to expansionary government spending shocks, because such shocks raise the total demand for domestic goods; technology shocks, instead, lower relative prices, because they raise the supply of domestic goods.[1]

When confronted with the data, these predictions have found little support. Several studies have identified government spending shocks within vector autoregresssion (VAR) models on the basis of short-run restrictions, notably by ruling out a contemporaneous response of government spending to the state of the economy. Considering quarterly data, Kim and Roubini (2008), Monacelli and Perotti (2006) and Ravn, Schmitt-Grohé and Uribe (2007) find a depreciation of the real exchange rate in response to an expansionary government spending shock. Beetsma, Giuliodori and Klaasen (2008), in contrast, consider annual data and find an exchange rate appreciation. The evidence on the terms of trade, as we discuss below, is also mixed. Concerning technology shocks, Corsetti, Dedola and Leduc (2006) and Enders and Müller (2008) estimate VAR models and identify positive innovations to technology on the basis of long-run restrictions. Considering different samples, both studies find an appreciation of the real exchange rate and the terms of trade.

In this paper, we employ an alternative, conceptually quite distinct approach to simultaneously identifying government spending and technology shocks within an estimated VAR model in order to re-examine the dynamic behavior of international relative prices. Following Uhlig (2005), we impose sign restrictions on the impulse response functions of selected variables for a limited period after the shock which we thereby attempt to identify.[2] Crucially, we leave the response of the real exchange rate and the terms of trade unrestricted, but restrict some of the signs of the responses of other variables included in the VAR model; notably those of output, investment, the government budget balance, inflation and the short-term interest rate. In our view, the restrictions reflect what most economist have in mind when thinking about the effects of technology and government spending shocks.

[1]In the following, we do not explicitly consider the possibility of a Harrod-Balassa-Samuelson effect. Instead, we focus on the behavior the real exchange rate *and* the terms of trade.

[2]Early contributions to the development of this approach include Canova and Pina (1999) and Canova and de Nicolo (2002), who put sign restrictions on impulse response correlations. Faust (1998) also proposes to impose sign restrictions on impulse responses, which are, however, set only on impact. Recent open economy applications of the sign restriction approach have been mostly focusing on monetary policy shocks, including Faust and Rogers (2003), Farrant and Peersman (2006), and Scholl and Uhlig (2007). Fratzscher, Juvenal and Sarno (2007) focus on the behavior of the U.S. current account.

At the same time, to give a formal underpinning of the restrictions and to quantify the horizon over which the sign of a selected response is restricted, we use a richly specified dynamic stochastic general equilibrium (DSGE) model. Specifically, we use a two-country framework with price rigidities where each country specializes in the production of a particular set of goods. We study the predictions of the model for a wide range of possible parameterizations by randomizing the values of parameters which are critical in shaping the international transmission mechanism. For each draw, we compute the impulse responses to shocks to government spending, technology and, in addition, monetary policy. On the basis of this experiment, we find that the model does not provide clear predictions for the behavior of international relative prices. Yet it delivers robust implications for the behavior of several important variables. This result is key to our empirical strategy: it allows us to use the model to derive identification restrictions while simultaneously leaving the response of international prices unrestricted.

In a second step, we estimate a VAR model on quarterly time series for the U.S. relative to an aggregate of industrialized countries for the post-Bretton-Woods period 1975Q1–2005Q4. In the baseline specification we identify government spending and technology shocks using our sign restrictions, assuming that these shocks are orthogonal to each other. We find that the real exchange rate as well as the terms of trade depreciate in response to expansionary government spending shocks and appreciate in response to positive shocks to total factor productivity. Sensitivity analyses suggest that these findings are quite robust. For instance, if we additionally identify monetary policy shocks, our results are virtually unaltered. The same applies to changes in sample period as well as to the inclusion of additional variables.

Taking a theoretical perspective, our findings may shed new light on the extent of international risk sharing. In a benchmark scenario of complete international financial markets, country-specific risk is effectively pooled across countries. This has important implications for the international transmission of government spending and technology shocks, because both shocks alter the amount of resources available to the private sector. While government spending shocks increase the tax burden of domestic residents, technology shocks increase domestic output for a given amount factor inputs. Full risk sharing under complete financial markets spreads the wealth effect induced by these shocks across countries; as a consequence, the impact of country-specific shocks on domestic variables relative to their foreign counterpart is rather contained. In fact, the effect of a particular shock on domestic and foreign consumption (and work effort in case preferences are non-separable in consumption and leisure) will differ only to the extent that consumption baskets differ across countries—as reflected by the response of the real exchange rate.

However, it is empirically plausible to assume that the set of state-contingent securities traded across countries and, hence, the scope of explicit risk-sharing, is limited. Movements in international relative prices, i.e. the terms of trade and the real exchange rate, are crucial for the extent of implicit international risk-sharing under these circumstances, see Cole and Obstfeld (1991). Specifically, if—as standard calibrations of international business cycle models suggest—the terms of trade depreciate in response to technology shocks and appreciate in response to government spending shocks, one obtains an implicit ex-post insurance of country-specific risk. These movements in relative prices imply a revaluation of national outputs which tends to counteract the immediate effect of the shocks on available resources.

Yet, under incomplete financial markets, relative price movements can also amplify the risk associated with country-specific shocks, as shown in a recent contribution by Corsetti, Dedola and Leduc (2007). In fact, for a particular calibration, an otherwise standard business cycle model is shown to predict an appreciation of the real exchange rate in response to a country-specific technology shock. Below, we use our DSGE model to show that international relative price movements may similarly amplify the consumption risk stemming from government spending shocks. In the light of these theoretical results, our empirical findings are consistent with the notion that international price movements tend to amplify rather than to reduce consumption risk across countries.

The remainder of the paper is organized as follows. In section 2 we discuss existing evidence and identification strategies. In section 3 we outline a standard general equilibrium business cycle model, which we simulate to derive sign restrictions for selected impulse responses. In section 4 we discuss our VAR specification and present results obtained on the basis of our identification strategy. Section 5 concludes.

## 2 Identification

### 2.1 Recent approaches and results

Before outlining our approach to identification, we briefly discuss a number of recent VAR studies, which are concerned with either government spending or technology shocks and their effect on real exchange rates. The evidence to date is mixed and to some extent conflicting with conventional wisdom.

**Government spending shocks** The textbook version of the Mundell-Fleming model predicts that an exogenous increase in government spending appreciates the real exchange rate.[3] Intertemporal business cycle models under standard calibrations also predict that exogenous increases in govern-

[3]The implicit assumption is that the increase in spending is debt financed. In the case of tax finance, Frenkel and Razin (1987) show that the exchange rate may depreciate because of exogenous money supply: lump-sum taxes lower disposable income and thus money demand such that the exchange rate depreciates. Also, in Obstfeld and Rogoff (1995) the nominal exchange rate depreciates in response to an increase in domestic government spending due to a fall in money demand (PPP holds in their model) and money supply being exogenously determined.

ment spending appreciate international relative prices. Backus, Kehoe and Kydland (1994) provide an early analysis within a frictionless two-country business cycle model. The result, however, survives under various frictions. Erceg, Guerrieri and Gust (2005), for instance, employ a richly specified dynamic general equilibrium model with incomplete financial markets, sticky prices and rule-of-thumb consumers; they also find an appreciation of the real exchange rate.

Recently, several attempts have been made to identify government spending shocks in quarterly time series data. The identifying assumption which is commonly employed goes back to Blanchard and Perotti (2002) and excludes a contemporaneous response of government spending to other key macroeconomic variables. Kim and Roubini (2008) analyze U.S. times series for the period 1973–2002 and find that the real exchange rate depreciates in response to spending shocks. Monacelli and Perotti (2006) consider data for the U.S. as well as data for Canada, Australia and the U.K. covering the years 1975–2001. They also find a depreciation of the real exchange rate, except for Canada. Ravn et al. (2007) pool the data of all four countries and estimate a panel VAR for the period 1975–2005. In line with the aforementioned papers they find a depreciation of the real exchange rate.

Beetsma et al. (2008) obtain different results for the effects of government spending shocks on the real exchange rate. Within a panel VAR model estimated on annual data for 14 European countries they find an appreciation. Clearly, differences may be due to identification assumptions. While Beetsma et al. (2008) also exclude a contemporaneous response of government spending to the other variables included in the VAR model, this assumption is more restrictive in the context of annual data. At the same time, the identification scheme is arguably less prone to be biased by anticipation effects.

The narrative approach to the identification of government spending shocks, suggested by Ramey and Shapiro (1998), is a widely applied alternative to the Blanchard-Perotti approach. Monacelli and Perotti (2006) discuss it in an open economy context. Specifically, they estimate the effects of the Carter-Reagan military buildup using a dummy variably for the first quarter of 1980. They find that government spending falls, while the real exchange rate depreciates during the first year after the shock, i.e. they find a co-movement of government spending and the real exchange rate which squares well with conventional wisdom.

Taken together, these results illustrate the importance of identification in the analysis of the effects of government spending in the open economy. Discussing the vices and virtues of both the Blanchard-Perotti and the narrative approach to the identification is beyond the scope of this paper. Instead, we attempt to complement the existing evidence on the basis of an alternative identification scheme based on sign restrictions.[4]

Before providing a brief summary of the existing evidence on the effects of technology shocks on international relative prices, we note that there is also evidence on the terms of trade response to

[4]See Ramey (2006) and Perotti (2007) for a detailed discussion of identification issues in the empirical analysis of the fiscal transmission mechanism.

government spending shocks. Employing variants of the Blanchard-Perotti identification scheme, Müller (2008) and Monacelli and Perotti (2008) find an appreciation of the terms of trade considering quarterly U.S. data for and 1954–2006, respectively. Corsetti and Müller (2006), on the other hand, consider data from 1980 onwards for the U.S., Australia, Canada and the U.K. and report mixed results.

**Technology shocks** Intertemporal business cycle models typically predict that technology shocks depreciate the terms of trade, see, e.g. Backus et al. (1994). The real exchange rate is also likely to depreciate, except if technology shocks are concentrated in the traded goods sector of the economy. If so, technology shocks may induce an increase in the prices of non-traded goods, possibly inducing the domestic price level to increase relative to foreign. Importantly, in this case, the terms of trade, i.e. the relative price of traded goods, are typically depreciating as domestic supply of traded goods increases more than demand.

In a recent contribution, however, Corsetti et al. (2007) provide an important qualification of this result. They show that a depreciation of the terms of trade is obtained only under a specific, albeit quite frequently used calibration of the standard international business cycle model. For alternative calibrations, the model predicts that technology shocks appreciate international relative prices. Loosely speaking, three features are critical for such a reversal of the standard transmission mechanism: incomplete financial markets, substantial home bias, and low trade price elasticities. Intuitively, if financial markets are incomplete, a positive technology shock increases domestic wealth and generates a more than proportional increase in the demand for the domestic good; the more so, the more pervasive the home bias and the less responsive trade flows are to movements in relative prices. As a consequence, the relative price of domestic goods may appreciate—thereby amplifying the initial effect of the shock on domestic wealth relative to foreign.

The existing evidence appears to be consistent with this mechanism. Drawing on earlier work by Galí (1999), Corsetti et al. (2006) and Enders and Müller (2008) impose long-run restrictions within a VAR model to identify technology shocks. Corsetti et al. (2006) specify their VAR model in relative terms: they use a sample of G7 economies and consider relative variables, i.e. the value of a domestic variable relative to the aggregate counterpart of the remaining countries. In order to identify (relative) technology shocks, they assume that only these shocks affect *relative* labor productivity in the long run. For the U.S. and Japan they find that relative technology shocks appreciate the real exchange rate and the terms of trade. Enders and Müller (2008) use an alternative identification scheme assuming that technology shocks are the only shocks which affect the level of U.S. labor productivity in the long run. They also find an appreciation of the terms of trade and the exchange rate in response to positive technology shocks.

## 2.2 Identification via sign restrictions

Given that part of the evidence based on short-run and long-run restrictions is conflicting with the predictions of Mundell-Fleming type models or conventionally calibrated business cycle models, we explore an alternative identification scheme based on sign restrictions. We start from the following reduced form VAR model

$$Y_t = B_{(1)}Y_{t-1} + B_{(2)}Y_{t-2} + ...B_{(m)}Y_{t-m} + u_t, \quad E[u_t u_t'] = \Sigma, \tag{1}$$

$t = 1...T$, for some $\ell$-dimensional vector of variables $Y_t$, coefficient matrices $B_{(i)}$ of size $\ell \times \ell$ and a variance-covariance matrix for the one-step ahead prediction error $\Sigma$. Letting $\upsilon_t$, with $E[\upsilon_t \upsilon_t'] = I_\ell$, denote the vector of structural shocks, we need to find a matrix $A$ such that $u_t = A\upsilon_t$ in order to achieve identification.

Instead of restricting the matrix $A$ a priori, we follow Uhlig (2005) and Mountford and Uhlig (2005) and identify structural shocks by imposing sign restrictions on impulse response functions of selected variables for a certain period $k = 0, ..., K$ following the shock. Intuitively, we consider various matrices $A$ and check, for each case, whether the sign restrictions are fulfilled and dismiss the matrix if this is not the case. In section 3, we use international business cycle theory to derive the sign restrictions. Note that we will leave the sign of those responses unrestricted on which our interest is centered.

To fix ideas, let $n$ be the number of structural shocks that we seek to identify. Mountford and Uhlig (2005) show that identifying $n$ shocks is equivalent to identifying an impulse matrix of rank $n$ that is a sub-matrix of matrix $A$ satisfying $AA' = \Sigma$. Any impulse matrix can be written as

$$[a^{(1)}, ..., a^{(n)}] = \tilde{A}Q \tag{2}$$

where $\tilde{A}$ is the lower triangular Cholesky factor of $\Sigma$ and $Q = [q^{(1)}, ..., q^{(n)}]$ is a $n \times \ell$ matrix consisting of orthonormal rows $q^{(s)}$, $s = 1, ..., n$, such that $QQ' = I_n$.

Similarly to Uhlig (2005), one can show that the impulse response to $a^{(s)}$ can be written as linear combination of the impulse responses obtained under a Cholesky decomposition of $\Sigma$. Let $c_{ji}(k)$ be the impulse response of the jth variable at horizon k to the ith shock in the Cholesky decomposition of $\Sigma$ and define $c_i(k) \in \mathbb{R}^\ell$ to be the vector response $[c_{1i}(k), ..., c_{\ell i}(k)]$. Then the impulse response $r_a^{(s)}(k)$ to the impulse vector $a^{(s)}$ is given by

$$r_a^{(s)}(k) = \sum_{i=1}^{\ell} q_i^{(s)} \; c_i(k). \tag{3}$$

The identifying restrictions we impose to identify an impulse vector characterizing shock $s$ are that $(r_a^{(s)}(k))_j \geq 0, j \in \mathcal{J}_+$ and $(r_a^{(s)}(k))_j \leq 0, j \in \mathcal{J}_-$ for some subsets of variables $\mathcal{J}_+$ and $\mathcal{J}_-$ and some horizon $k = 0, \ldots, K$.

For the actual estimation we employ a Bayesian approach. Specifically, we use a flat Normal-Wishart prior, see Uhlig (1994) for a detailed discussion of the properties, while the numerical implementation follows Rubio-Ramirez, Waggoner and Zha (2005) and can be summarized as follows. We take a draw from the Normal-Wishart posterior for $(B, \Sigma)$ and construct an arbitrary independent standard normal matrix $M$. We obtain the orthonormal matrix $Q$ using the QR-decomposition of $M$ such that $QQ' = I$ and $QR = M$. We construct impulse vectors $a$ according to (2) and use (3) to compute the impulse responses.

Considering orthogonal structural shocks may result in tight identifying sign restrictions in the sense that many draws from the Normal-Wishart posterior for the VAR parameters $(B, \Sigma)$ are rejected because they do not permit any impulse matrices that satisfy the sign restrictions. This means that many draws receive zero prior weight, even in cases where only few of the restrictions are mildly violated. This issue gets more severe if the number of orthogonal shocks and the number of variables included in the VAR model rises. To account for this we allow for small deviations $\varepsilon$ from the sign restrictions and define

$$(\omega_a^{(s)}(k))_j = \begin{cases} \max\{-(r_a^{(s)}(k))_j, 0\} & \text{for } j \in \mathcal{J}_+,\ k = 0, ..., K \text{and } s = 1, .., n \\ \max\{(r_a^{(s)}(k))_j, 0\} & \text{for } j \in \mathcal{J}_-,\ k = 0, ..., K \text{and } s = 1, .., n \end{cases}$$

We keep the impulse responses if the sum of the squared deviations over all structural shocks, variables and horizons is smaller than $\varepsilon$:

$$\sum_s \sum_j \sum_k \left[ (\omega_a^{(s)}(k))_j \right]^2 < \varepsilon, \qquad \varepsilon \geq 0. \tag{4}$$

Inference statements are based on the posterior distribution of those draws for which (4) is satisfied. In our robustness analysis we provide some discussion on the choice of $\varepsilon$.[5]

# 3 Sign restrictions implied by international business cycle theory

## 3.1 A two-country business cycle model

We now turn to a state-of-the-art business cycle model which we use to derive sign restrictions. The model is a fairly standard medium-scale DSGE model featuring various frictions which earlier research has found to improve the empirical performance of this class of models.[6] Notably, we allow

[5] Alternatively, Mountford and Uhlig (2005) minimize a penalty function for sign restriction violations for *each* draw from the posterior distribution for the VAR parameters. However, to account for several orthogonal shocks they sequentially determine the optimal impulse vectors such that the ordering of the structural shocks may be important. To avoid this, we simply allow for small deviations and draw the impulse vectors simultaneously. This also implies that, in contrast to Mountford and Uhlig (2005), we simultaneously estimate the reduced form parameters together with the impulse matrix.

[6] The model is similar to those proposed by Backus et al. (1994), Heathcote and Perri (2002), Chari, Kehoe and McGrattan (2002) or Kollmann (2002).

for the possibility that prices are adjusted infrequently. The purpose of this assumption is twofold. First, price rigidities potentially alter the transmission of real shocks, as forcefully argued by Galí (1999). Second, this assumption allows us to study the behavior of international relative prices in response to monetary policy shocks.

In the following we outline the model structure, while section 3.2 discusses the model simulation. The world economy consists of two symmetric countries $i \in \{1, 2\}$. We refer to country $1$ as the domestic economy or 'home', and to country $2$ as 'foreign'.

**Households** In country $i$ households allocate resources to consumption goods, $C_{it}$, and supply labor, $H_{it}$, to monopolistic firms. Preferences are given by

$$E_0 \sum_{t=0}^{\infty} \bar{\beta}_{it} \frac{[C_{it}^{\mu}(1-H_{it})^{1-\mu}]^{1-\gamma}}{1-\gamma} \tag{5}$$
$$\bar{\beta}_{i0} = 1, \quad \bar{\beta}_{it+1} = \left(1 + \psi[\bar{C}_{it}^{\mu}(1-\bar{H}_{it})^{1-\mu}]\right)^{-1} \bar{\beta}_{it}, \qquad t \geq 0.$$

Here, $\bar{\beta}_{it}$ is an endogenous discount factor such that discounting is higher if average per capita consumption and leisure, denoted by $\bar{C}_{it}$ and $(1-\bar{H}_{it})$, respectively, are above their steady-state values.[7] $\mu$ and $\gamma$ are positive constants specifying the preferences of households.

Labor and capital are internationally immobile; households in country $i$ own the capital stock $K_{it}$ and rent it to intermediate good firms on a period-by-period basis. It may be costly to adjust the level of investment, $I_{it}$. As in Christiano, Eichenbaum and Evans (2005), the law of motion for capital is given by

$$K_{it+1} = (1-\delta)K_{it} + [1 - \Psi(I_{it}/I_{it-1})]I_{it}, \tag{6}$$

where $\delta$ denotes the depreciation rate; restricting $\Psi(1) = \Psi'(1) = 0$, and $\Psi''(1) = \chi > 0$ ensures that the steady-state capital stock is independent of investment adjustment costs captured by the parameter $\chi$. Across countries there is trade in nominal non-contingent bonds, $\Theta_{it}$, denominated in the currency of country $i$. The budget constraint of the representative household in country $i$ reads as

$$\begin{aligned} & (1-\tau_{it})(W_{it}H_{it} + R_{it}^{K}K_{it} + \Upsilon_{it}) - P_{it}C_{it} - P_{it}I_{it} \\ = & \begin{cases} (\Theta_{1t+1} + D_{1t+1})R_{1t}^{-1} + S_t\Theta_{2t+1}R_{2t}^{-1} - \Theta_{1t} - D_{1t} - S_t\Theta_{2t}, & \text{for } i = 1, \\ (\Theta_{2t+1} + D_{2t+1})R_{2t}^{-1} + \Theta_{1t+1}(R_{1t}S_t)^{-1} - \Theta_{2t} - D_{2t} - S_t^{-1}\Theta_{1t}, & \text{for } i = 2, \end{cases} \end{aligned} \tag{7}$$

where $W_{it}$ and $R_{it}^{K}$ denote the nominal wage rate and the rental rate of capital, and $\Upsilon_{it}$ are nominal profits earned by monopolistic firms and transferred to households. $\tau_{it}$ denotes the tax rate levied on

[7] In other words, the effect of consumption and leisure on the discount factor are not internalized by the household. The parameter $\psi$ determines how the discount factor responds to consumption and leisure; it also pins down the value of the discount factor in steady state. See Schmitt-Grohé and Uribe (2003) for further discussion and Corsetti et al. (2007) for an application in a two-country model.

households' income; $P_{it}$ is the price of the final good defined below; $R_{it}$ is the gross nominal interest rate, $D_{it}$ denotes debt issued by the government in country $i$ held by domestic residents, and $S_t$ is the nominal exchange rate. In each country, households maximize (5) subject to (6), (7) and a non-Ponzi scheme condition.

**Final good firms** Consumption and investment goods are composite goods which households purchase from final good firms. These firms operate under perfect competition and buy intermediate goods from a continuum of monopolistic competitive firms. We use $j \in [0, 1]$ to index those intermediate good firms as well as their products and prices. Further, let $A_{it}(j)$ and $B_{it}(j)$ denote the amount of good $j$, originally produced in country 1 and 2, respectively, used in country $i$ to assemble the final goods $F_i$. These are produced under the following technology

$$F_{it} = \begin{cases} \left[ \begin{array}{c} \omega^{\frac{1}{\sigma}} \left( \left[ \int_0^1 A_{1t}(j)^{\frac{\epsilon-1}{\epsilon}} dj \right]^{\frac{\epsilon}{\epsilon-1}} \right)^{\frac{\sigma-1}{\sigma}} \\ + (1-\omega)^{\frac{1}{\sigma}} \left( \left[ \int_0^1 B_{1t}(j)^{\frac{\epsilon-1}{\epsilon}} dj \right]^{\frac{\epsilon}{\epsilon-1}} \right)^{\frac{\sigma-1}{\sigma}} \end{array} \right]^{\frac{\sigma}{\sigma-1}}, & \text{for } i = 1 \\ \left[ \begin{array}{c} \omega^{\frac{1}{\sigma}} \left( \left[ \int_0^1 B_{2t}(j)^{\frac{\epsilon-1}{\epsilon}} dj \right]^{\frac{\epsilon}{\epsilon-1}} \right)^{\frac{\sigma-1}{\sigma}} \\ + (1-\omega)^{\frac{1}{\sigma}} \left( \left[ \int_0^1 A_{2t}(j)^{\frac{\epsilon-1}{\epsilon}} dj \right]^{\frac{\epsilon}{\epsilon-1}} \right)^{\frac{\sigma-1}{\sigma}} \end{array} \right]^{\frac{\sigma}{\sigma-1}}, & \text{for } i = 2 \end{cases} \tag{8}$$

where $\sigma$ denotes the elasticity of substitution between foreign and domestic goods ('trade price elasticity', for short) and $\epsilon$ measures the elasticity of substitution between goods produced within the same country. The parameter $\omega$ measures the home bias in the composition of final goods. Let $P_{it}^A(j)$ be the price in country $i$ of an intermediate good produced in country 1 and $P_{it}^B(j)$ the price in country $i$ of a good produced in country 2. Assuming that the law of one price holds, we have

$$P_{1t}^B(j) = S_t P_{2t}^B(j); \qquad P_{1t}^A(j) = S_t P_{2t}^A(j). \tag{9}$$

The price for final goods is given by

$$P_{it} = \begin{cases} \left[ \omega \left( P_{1t}^A \right)^{1-\sigma} + (1-\omega) \left( P_{1t}^B \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}}, & \text{for } i = 1 \\ \left[ (1-\omega) \left( P_{2t}^A \right)^{1-\sigma} + \omega \left( P_{2t}^B \right)^{1-\sigma} \right]^{\frac{1}{1-\sigma}}, & \text{for } i = 2 \end{cases}, \tag{10}$$

where

$$P_{it}^A = \left( \int_0^1 P_{it}^A(j)^{1-\epsilon} dj \right)^{\frac{1}{1-\epsilon}} \text{ and } P_{it}^B = \left( \int_0^1 P_{it}^B(j)^{1-\epsilon} dj \right)^{\frac{1}{1-\epsilon}} \tag{11}$$

denote the GDP deflators in home and foreign, respectively.

The problem of final good firms is to minimize expenditures in assembling intermediate goods subject to (8) and the requirement that $F_{it} = C_{it} + I_{it}$. The first order condition that characterizes final good firms' behavior in equilibrium implicitly defines the demand for a generic intermediate goods, $Y_{it}^{D}(j)$. For future reference, taking the perspective of the home country, we define the real exchange rate as follows

$$RX_t = S_t P_{2t}/P_{1t}, \tag{12}$$

such that an increase corresponds to a depreciation. Terms of trade are defined as the price of imports relative to the price of exports: $P_{1t}^{B}/P_{1t}^{A}$. Note that up to a first order approximation the terms of trade and the real exchange rate are perfectly correlated to the extent that $\omega > 1/2$.

**Intermediate good firms** At the intermediate good level, firms specialize in the production of differentiated goods. A generic firm $j \in [0,1]$ in country $i$ engages in monopolistic competition facing imperfectly-elastic demand from domestic and foreign final good producers, as well as domestic governments which are assumed to consume only domestically produced goods, as discussed below. Production of intermediate goods is Cobb-Douglas:

$$Y_{it}(j) = e^{Z_{it}} K_{it}(j)^{\theta} H_{it}(j)^{1-\theta}, \tag{13}$$

where $Z_{it}$ denotes the level of technology common to all firms. It evolves exogenously according to

$$Z_{it} = \rho_z Z_{it-1} + \rho_{zz} Z_{\ell t-1} + \varepsilon_{it}^{z}, \tag{14}$$

such that $\rho_z$ captures the degree of autocorrelation and $\rho_{zz}$ possible spillovers across countries. Labor and capital inputs of firm $j$, $H_{it}(j)$ and $K_{it}(j)$, are adjusted freely in each period. Price setting, however, is constrained exogenously by a discrete time version of the mechanism suggested by Calvo (1983). Each firm has the opportunity to change its price with a given probability $1-\xi$. When a firm has the opportunity, it sets the new price in order to maximize the expected discounted value of net profits; otherwise prices are indexed to past inflation, where the degree of indexation is given by $\iota \in [0,1]$. When setting the new price $P_{1t}^{A}(j)$ or $P_{2t}^{B}(j)$, the problem of a generic intermediate good firm $j$ in country $i$ is given by

$$\max \sum_{k=0}^{\infty} \xi^k E_t \begin{cases} \rho_{it,t+k} Y_{it+k}(j) \left[ P_{it}^{A}(j) (P_{it+k-1}^{A}/P_{it-1}^{A})^{\iota} - MC_{it+k} \right] / P_{it+k}, & \text{for } i = 1 \\ \rho_{it,t+k} Y_{it+k}(j) \left[ P_{it}^{B}(j) (P_{it+k-1}^{B}/P_{it-1}^{B})^{\iota} - MC_{it+k} \right] / P_{it+k}, & \text{for } i = 2 \end{cases} \tag{15}$$

subject to the production function (13) and the optimal choice of factor inputs which minimizes marginal costs, $MC_{it}$.[8] Profits are discounted with the factor $\rho_{it,t+k}$, for which we assume $\rho_{it,t+k} = \bar{\beta}_{it+k} U_C(C_{it+k}, H_{it+k}) / (\bar{\beta}_{it} U_C(C_{it}, H_{it}))$, because firms are owned by households.

[8]In this formulation we impose the constraint that demand is met by actual production at all times: $Y_{it}(j) = Y_{it}^{D}(j) + Y_{it}^{G}(j)$, where that last term denotes the demand stemming from government consumption.

**Fiscal and monetary policy** Government policies are characterized by feedback rules. Turning to fiscal policy first, we assume that government spending, $G_{it}$, consists of a bundle of intermediate goods. Specifically, we use an aggregation technology analogous to (8), except that only domestically produced goods enter the consumption basket of the government.[9] Government consumption evolves according to the following feedback rule:

$$G_{it} = (1-\rho_g)G_i + \rho_g G_{it-1} + \varphi_y(Y_{it} - Y_i) - \varphi_d(D_{it} - D_i) + \varepsilon_{it}^G, \tag{16}$$

where letters without time subscript refer to steady state values; $\rho_g$ captures persistence, while $\varphi_y$ and $\varphi_d$ measure to what extent government spending responds to the deviation of output and debt from their steady-state values. $\varepsilon_{it}^G$ is an i.i.d. innovation to government spending.[10] Regarding the tax rate we assume the following relationship

$$\tau_{it} = \tau_i + \varphi_\tau \frac{D_{it} - D_i}{Y_i}, \tag{17}$$

where $\varphi_\tau \geq 0$ measures how strongly the tax rate adjusts to the level of debt.[11] The budget constraint of the government in country $i$ is given by

$$D_{it} - \frac{D_{it+1}}{R_{it}} = \tau_{it}(W_{it}H_{it} + R_{it}^K K_{it} + \Upsilon_{it}) - P_{it}^G G_{it}, \tag{18}$$

where $P_{it}^G$ is the price index of government consumption.

Monetary policy is characterized by an interest feedback rule, whereby the nominal interest rate is adjusted in response to domestic (i.e. producer-price) inflation and the output gap as, for instance, in Galí and Monacelli (2005):

$$R_{it} = \rho_r R_{it-1} + (1-\rho_r)\left(R + \phi_\pi(\Pi_{P,it} - \Pi_P) + 0.25\phi_y y_{it}\right) + \nu_{it}, \tag{19}$$

where $\Pi_{P,it}$ and $y_{it} = (Y_{it} - Y_i)/Y_i$ denote domestic inflation and the output gap (defined as deviations from the steady-state value), respectively; $\rho_r \geq 0$ captures interest rate smoothing, while $\phi_\pi$ and $\phi_y$ denote the long-run (producer-price) inflation and output gap semi-elasticity of short-term interest rates; $\nu_{it}$ is an i.i.d. exogenous monetary policy shock.

[9] Put differently, we assume that government goods are assembled in the same way as in (8), with $\omega = 1$. The evidence discussed in Corsetti and Müller (2006) suggests that the import content in government spending is generally less than half the import content in private spending. As a first approximation it is thus reasonable to assume zero import content in government spending.

[10] Rules of this type have been estimated by Galí and Perotti (2003), among others.

[11] In the simulation of the model we only allow for values of $\{\varphi_\tau, \varphi_d\}$ such that government debt is stationary. It is interesting to observe that in the case of $\varphi_\tau = 0$, all financing of government spending occurs through reduced future spending. As a result, the standard wealth effect of government spending is absent in this case.

**Equilibrium** We characterize the equilibrium of the model through the first-order conditions of households and firms as well as the feedback rules (16), (17), and (19). In specifying the firms' problem we implicity imposed market clearing conditions. Hence, to pin down the equilibrium allocation, we merely require the budget constraints of both governments and the domestic household to be satisfied.

### 3.2 Model simulations

We are interested in the model predictions regarding the sign of the responses of various variables to technology, government spending as well as monetary policy shocks. We also consider the effects of the latter, because they are likely to contribute considerably to real exchange rate fluctuations, as documented, for instance, by Clarida and Galí (1994). To compute the responses, we solve numerically a linear approximation of the equilibrium conditions around a deterministic, symmetric, zero-debt steady state. Because the terms of trade display the same dynamics as the real exchange rate as long as domestic goods make up for more than half of final goods production, we focus on the behavior on the real exchange rate in the following discussion. Yet, when turning to the data we will consider both variables separately.

The structure of our model is fairly rich and based on earlier work aimed at increasing the quantitative realism of this class of models. Yet, there remains uncertainty as to the values of certain parameters which may have a bearing not only on the quantitative effects of a particular shock, but may govern even the sign of the response of certain variables. In order to ensure that our sign restrictions are robust with respect to different parameterizations of the model, we adopt the following procedure.

A first set of parameters is held constant throughout all simulations. It is displayed in the upper panel of table 1. These parameters are fairly uncontroversial in the literature or directly related to first moments of the data through steady-state relationships. Regarding preferences and technology, characterized by $\beta, \gamma, \mu, \theta$ and $\delta$, we follow Backus et al. (1994). We assume that there is considerable home bias in the composition of final goods, i.e. $\omega = 0.85$. Assuming that government spending accounts for $20$ percent of GDP implies an import share of $12$ percent in steady state—corresponding to the average import share in the U.S. in our sample period. The government share also implies that, absent steady-state zero debt, the tax rate is $20$ percent in steady state. Finally, for the elasticity of substitution between monopolistically produced goods, $\epsilon$, we use a value which implies a markup of intermediate good producers close to 15 percent.

The values of a second set of parameters are more controversial. In order to derive sign restrictions which are robust with respect to variations in these parameters, we randomize the parameterization of the model and compute impulse responses for each draw. The second panel of table 1 displays the intervals from which we draw values for each simulation of the model, assuming uniform and

Table 1: PARAMETER VALUES USED IN SIMULATION

| Parameter | Description | Value/Range |
|---|---|---|
| *Constant values* | | |
| $\beta$ | Discount factor (steady state) | $0.99$ |
| $\mu$ | Consumption share | $0.34$ |
| $\gamma$ | Risk aversion | $2.00$ |
| $\theta$ | Capital share | $0.36$ |
| $\delta$ | Depreciation rate | $0.025$ |
| $\omega$ | Home bias in final goods | $0.85$ |
| $g$ | Government spending (steady state) | $0.2$ |
| $\epsilon$ | Elasticity of substitution | $8$ |
| *Randomized parameter values* | | |
| $\chi$ | Investment adjustment costs | $[0.10, 3.00]$ |
| $\xi$ | Fraction of prices kept unchanged | $[0.10, 0.90]$ |
| $\iota$ | Indexation of prices | $[0.00, 1.00]$ |
| $\phi_\pi$ | Inflation elast. of interest rate | $[1.50, 2.15]$ |
| $\phi_y$ | Output elast. of interest rate | $[0.00, 0.50]$ |
| $\rho_i$ | Interest rate smoothing | $[0.50, 0.95]$ |
| $\rho_g$ | Government spending persistence | $[0.70, 0.90]$ |
| $\varphi_y$ | Output gap elasticity of G-spending | $[-0.2, 0.20]$ |
| $\varphi_d$ | Debt elasticity of G-spending | $[0.02, 0.04]$ |
| $\varphi_\tau$ | Debt semi-elasticity of tax rate | $[0.02, 0.04]$ |
| $\rho_z$ | Technology persistence | $[0.80, 0.90]$ |
| $\rho_{zz}$ | Technology spillover | $[0.00, 0.09]$ |
| $\sigma$ | Trade elasticity | $[0.10, 0.30]$ or $[1.00, 2.00]$ |

Notes: Parameter values used in simulation of the model. Parameter values in upper panel are kept constant; lower panel displays intervals from which values are drawn for each simulation of the model.

independent distributions. Regarding $\chi$, the parameter capturing investment costs, we consider values from $0.1$ of up to 3, the upper end of the values reported in Christiano et al. (2005). Concerning price rigidities we allow for the whole range from zero to full indexation and, similarly, we consider a wide range for the degree of price rigidities $\xi$, thereby accounting for the recent debate on the extent of price rigidities.[12] With respect to the interest rate feedback rule, we allow for values which span the range of results reported by Clarida, Galí and Gertler (2000) and others. Our admissible range of parameter values for coefficients in the government spending feedback rule is guided by the results reported in Galí and Perotti (2003). The tax rule coefficient is specified such that deficits display considerable persistence, see Corsetti and Müller (2008). Finally, for the persistence of technology

[12]While the early new Keynesian literature, e.g. Galí and Gertler (1999), has suggested considerable price rigidities, recent microeconomic evidence suggests shorter price durations, see Bils and Klenow (2004).

shocks we assume $\rho_z$ to lie within the range of $0.8$ to $0.9$, while possible cross-country technology spillovers are captured by $\rho_{zz} \in [0.00, 0.09]$.

Regarding the trade price elasticity $\sigma$, we consider two distinct intervals.[13] First, an interval with low values, where we let $\sigma$ vary from $0.1$ to $0.3$. Second, we consider values in the range of $1$ to $2$.[14] We report the results for the low and the high case separately, in order to gauge the impact of different values of the trade price elasticity on the international transmission of *both* government spending and technology shocks. As discussed above, Corsetti et al. (2007) show how this parameter may alter the transmission of technology shocks, notably by governing the extent of implicit risk sharing through relative price movements under incomplete financial markets. Our results below suggest that the same mechanism is at work in the transmission of government spending shocks.

Figure 1 displays the impulse responses of the model based on 10,000 draws of the parameter vector for both scenarios regarding the trade price elasticity, $\sigma$: the dashed lines cover 95 percent of the responses (pointwise) if values are drawn from the high interval; the shaded area covers 95 percent of the responses in case values are drawn from the low interval. Impulse response bands are displayed for an expansionary shock to government spending (left), a positive innovation to technology (middle) and expansionary monetary policy shock, i.e. an exogenous reduction in the short-term interest rate (right). On the horizontal axis we measure the periods after the shock (in quarters), on the vertical axis we measure the difference across countries in percentage deviation from steady-state values. We focus on relative variables (home relative to foreign), because eventually we are concerned with the behavior of the real exchange rate, which is determined by these relative variables.[15] The only variables for which we report the response of the home country are net exports and the real exchange rate.

The predictions of the model regarding the behavior of output and investment in response to all three shocks are fairly clear-cut, see figure 1a. All shocks increase output and investment, except for government spending shocks which crowd out investment. The response of private consumption, while being unambiguously positive for technology and monetary policy shocks, depends on the particular parameterization of the model when it comes to government spending. Conversely, the sign of

[13]Our experiment is thus similar to Peersman and Straub (2007), who derive sign restrictions for responses to technology shocks in a new Keynesian model, but explicitly distinguish the 'RBC'-case by considering a distinct set of parameterizations of the model where price rigidities are absent.

[14]We omit the middle range, because in this case the model predicts too high levels of exchange rate volatility. The lower interval implies a fairly limited trade price elasticity. In this context, it interesting to observe that by virtue of a distribution sector it is possible to obtain a low effective trade price elasticity together with a nominally high trade price elasticity, see Corsetti et al. (2007). Moreover, note that several recent macroeconometric studies point to low values of trade price elasticities, see Lubik and Schorfheide (2006), Kollmann (2006), and Enders and Müller (2008).

[15]As a consequence, the identified shocks correspond to the level of relative government spending, technology, or relative monetary policy stance. A positive innovation may thus be due to a positive innovation at home which exceeds an equally positive innovation in foreign, or a negative innovation at home which is smaller than a negative innovation abroad—as well as intermediate cases.

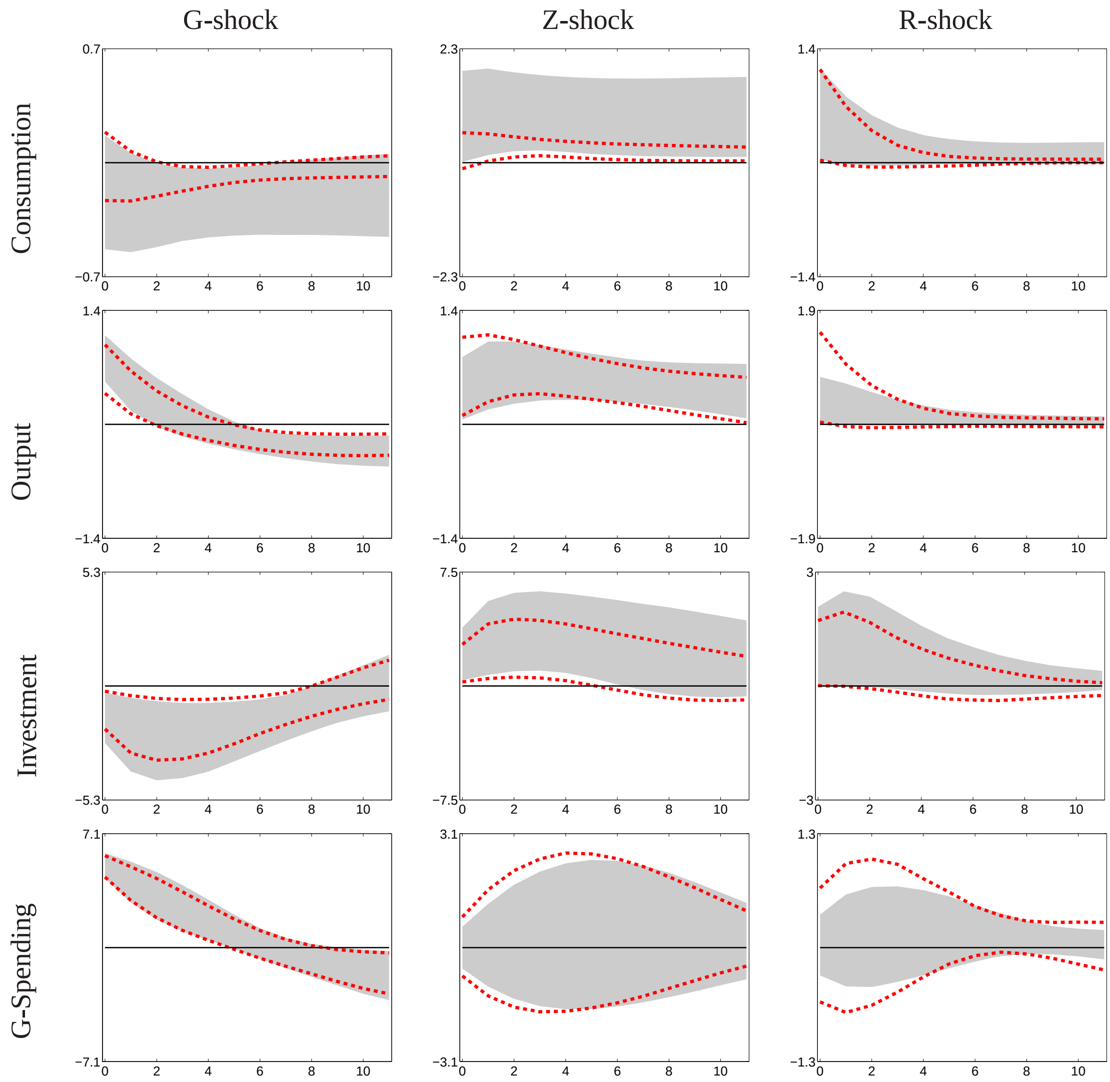


Figure 1a: Shock transmission according to business cycle theory; Notes: Responses are in relative terms, i.e. variables are expressed relative to foreign counterparts; Left column: increase in government spending; Middle: increase in technology; Right: reduction in nominal interest rates; the shaded area covers 95 percent of responses (pointwise) for low trade price elasticity case; The dashed lines display the same statistic for the high trade price elasticity case; number of draws: 10,000. Horizontal axes: quarters; vertical axis: percentage deviation from steady state.

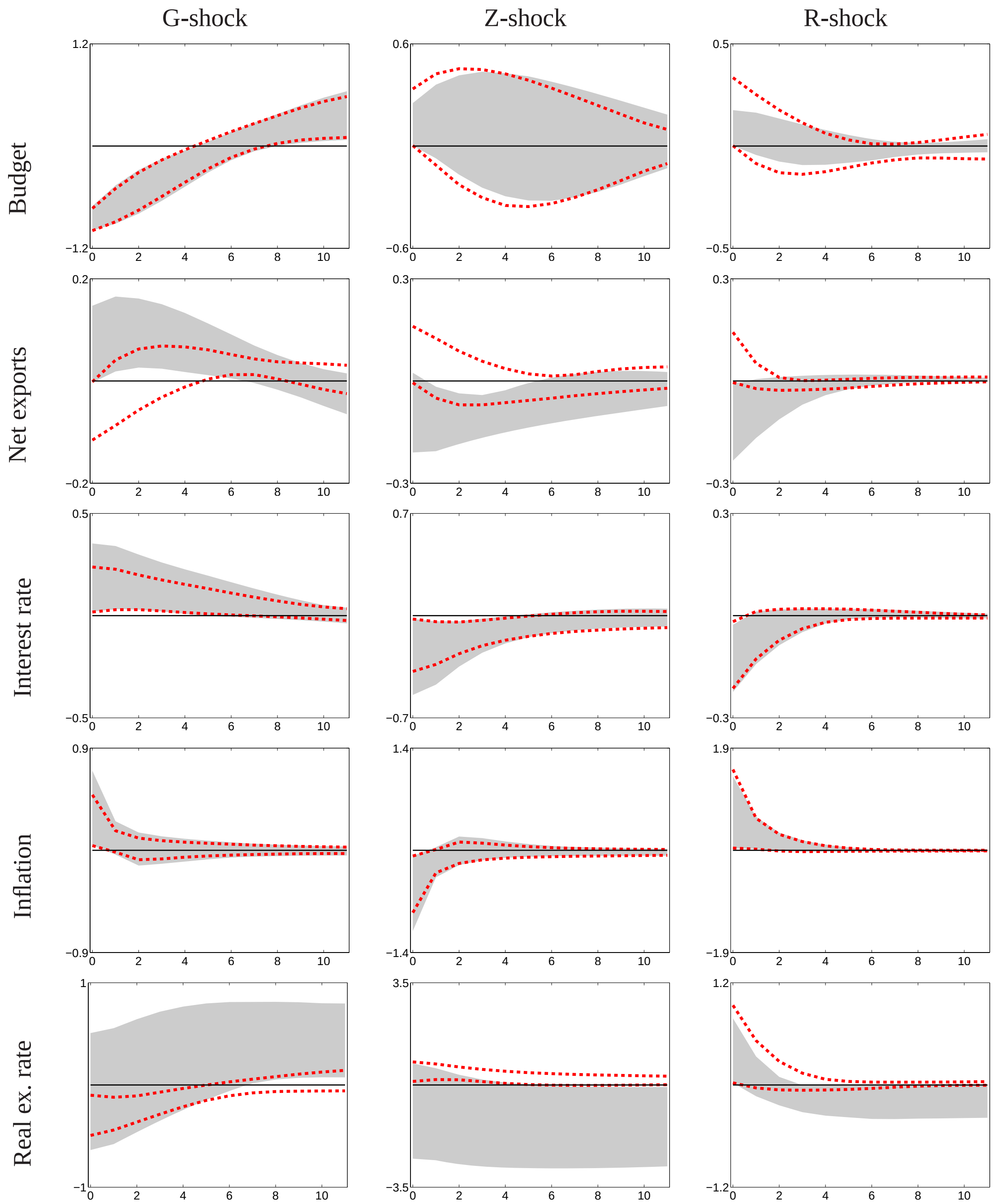


Figure 1b: Shock transmission according to business cycle theory; Notes: see figure 1a; furthermore, variables are expressed in percentage deviation from steady state, except for the budget balance (percentage point of GDP) and inflation (percentage points). All variables, except for the real exchange rate and net exports, are expressed relative to foreign counterparts.

the response of government spending, while being unambiguously positive for government spending shocks, is less robust in response to technology and monetary policy shocks. These findings are the result of assuming a quite general fiscal policy rule that allows current government expenditures to be financed through debt and to be adjusted in response to the output gap.

Figure 1b shows the responses of the government budget, which unambiguously falls after a expansionary government spending shock. Yet, it increases on impact after a technology shock and an expansionary monetary policy shock, while, after both shocks, it may further increase or decline in due course. The response of net exports is quite distinct depending on whether high or low values for the trade price elasticity are assumed. This finding reflects the fact that the size of the trade price elasticity determines whether value or substitution effects dominate the short-run dynamics of net exports, see, for instance, the discussion in Müller (2008) regarding government spending.

The response of the interest rate differs sharply across shocks. It increases after a government spending shock, but falls after a technology and an expansionary monetary policy shock for all specifications of the the model. The same holds for domestic (i.e. producer price) inflation. Before turning to the response of the real exchange rate, we note that the model—for a wide range of parameterizations—delivers fairly robust predictions for the *sign* of the response of most variables.

Yet, as shown in the last row of figure 1b, the model's prediction for the behavior of the real exchange rate is ambiguous—even qualitatively—in response to government spending and technology shocks. Interestingly, the sign of the real exchange rate response to both government spending and technology shocks differs systematically with the trade price elasticity. If the trade price elasticity is allowed to take only values from the high interval (dashed lines), the real exchange rate always appreciates (i.e. falls) for the first six quarters after the government spending shock and always depreciates (i.e. increases) in response to technology shocks, as standard business cycle theory would suggest. Different responses can be observed once we restrict the trade price elasticity to vary within the low interval. In this case, we observe that the sign of the real exchange rate may change such that a depreciation (appreciation) of the real exchange rate in response to government spending (technology) shocks is possible.

At the same time we observe much stronger responses in relative consumption for the low elasticity case (first row of figure 1a). This finding reflects the fact that under incomplete financial markets a reversal of the response of international prices, relative to the predictions of standard business cycle theory, brings about an amplification of consumption risk. While Corsetti et al. (2007) provide a detailed analysis in the context of technology shocks, our results suggest that also the consumption risk stemming from government spending shocks can be amplified through relative price movements; this amplification becomes manifest in a depreciation of the real exchange rate in response to government spending shocks.

Table 2: SIGN RESTRICTIONS: BASELINE VAR

| | Expansionary shock to | | |
|---|---|---|---|
| Variable | Government spending | Technology | Monetary policy |
| Private consumption | ? | $+8$ | $+0$ |
| Output | $+2$ | $+8$ | $+0$ |
| Investment | $-4$ | $+4$ | $+0$ |
| Government spending | $+4$ | ? | ? |
| Government budget | $-4$ | $+0$ | $+0$ |
| Net exports | ? | ? | ? |
| Nominal interest rate | $+4$ | $-4$ | $-1$ |
| Inflation | $+0$ | $-0$ | $+0$ |
| Real exchange rate (terms of trade) | **?** | **?** | $+0$ |

Notes: Table entries refer to quarters for which the response of a variable (in relative terms) is restricted to be non-negative (+) or non-positive (-), '0' refers to the impact response. '?' indicates that the response is left unrestricted.

Table 2 summarizes the restrictions which we actually impose on the data below. Table entries refer to quarters for which the response of a variable is restricted to be non-negative (+) or non-positive (-), '0' refers to the impact response. '?' indicates that the response is left unrestricted. It should be noted that these restrictions, while formally shown to be consistent with international business cycle theory, are also in line with the received wisdom. Shocks to government spending are identified by imposing that output does not fall for at least two quarters after the shock, while investment must remain non-positive for at least one year. Government spending itself is restricted to remain non-negative and the government budget is assumed to stay in deficit for the year following the shock. The response of net exports to government spending shocks, whenever included in the VAR model, is not restricted. Similarly, the nominal interest rate is restricted to remain non-negative for one year, while inflation has to be non-negative on impact.[16] Finally, note that in line with the predictions of the model, we leave the response of private consumption unrestricted. This seems quite reasonable, given the fierce debate on and the conflicting evidence of its behavior in response to government spending shocks.[17] Technology shocks are identified by assuming that both consumption and output increase for two

[16]While the existing evidence on the effects of fiscal shocks on inflation and the interest rate based on alternative identification schemes is mixed, see, e.g., Perotti (2005) and Laubach (2005), we nevertheless impose the restriction for the impact response in line with both received wisdom and standard business cycle theory.

[17]Theoretical contributions pointing to a fall in consumption include Baxter and King (1993) and Linnemann and Schabert (2003). Galí, López-Salido and Vallés (2007) show that an increase in consumption may be obtained in a variant of the new Keynesian framework under the assumption that a fraction of households consumes disposable income in each period. Blanchard and Perotti (2002) document an increase in consumption in response to government spending shocks using a VAR model estimated on U.S. data. Mountford and Uhlig (2005), in contrast, find no significant effect of spending shocks on consumption.

years after the shock, while investment is restricted to increase for at least one year. The responses of government spending is left unrestricted, while the response of the primary government budget is assumed to be non-negative on impact. We also restrict the impact response of inflation to be non-positive and the nominal interest rate to fall for at least four quarters after the shock.[18]

To identify monetary policy shocks in addition to technology and government spending shocks, we restrict the responses of output, investment, consumption, the government budget, and inflation to be non-negative and the response of the nominal interest rate to be non-positive for at least one quarter after the shock. In addition, we also restrict the response of the real exchange rate to be non-negative.

# 4 New evidence on the behavior of U.S. real exchange rates

## 4.1 Baseline specification

We estimate the VAR model (1) where—in the baseline specification—the vector of endogenous variables includes real private consumption, real GDP, real private investment, real government spending, the primary budget balance scaled by GDP, inflation computed using the GDP deflator, nominal short-term interest rates and the real exchange rate or the terms of trade. All variables except for the real exchange rate and the terms of trade are in relative terms, i.e. we consider the value of a variable in the U.S. relative to the aggregate value of the euro area, Japan, Canada and the U.K. This aggregate is taken to be the foreign country, or the 'rest of the world'.[19] For the exchange rate and the terms of trade we use U.S. data. Our sample consists of quarterly time series for the post-Bretton-Woods period, ranging from 1975Q1 to 2005Q4. All variables are in logs except the interest rate and the government budget balance. We estimate the VAR in levels and include 4 lags and a constant.

In our baseline specification, we identify shocks to government spending and technology on the basis of sign restrictions as discussed in section 2.2. The specific restrictions are derived in section 3 using international business cycle theory and are summarized in table 2. Since in some cases it may be difficult to find impulse matrices $Q$ that generate impulse responses that fulfill all the sign restrictions we allow for small deviations and set $\varepsilon = 0.002$. Below we perform a sensitivity analysis with respect to the following modifications of our baseline specification: we include net exports in the VAR model, identify monetary policy shocks in addition to government spending and technology shocks, and explore the robustness of our results for different sample periods. Moreover, we impose the restriction $\varepsilon = 0$ to show that allowing for small deviations from the sign restrictions is not crucial for our findings.

[18] Also Altig, Christiano, Eichenbaum and Lindé (2005), using long-run restrictions, find that inflation and short-term interest rates fall in response to technology shocks.

[19] Aggregation issues and data sources are described in appendix A.

### 4.2 Results for baseline specification

Given the estimated VAR model and the identified shocks to government spending and technology, we compute the impulse responses functions of all variables included in the VAR model. Results are displayed in figure 2. In all panels we plot the median as well as the 16% and 84% quantiles of the posterior distribution of impulse responses. In our discussion of the results we will use the term 'significance' whenever both of these quantiles are either above or below zero at a particular point in time after the shock. The left column shows the responses to a government spending shock, the right column the responses to a technology shock. A vertical line at a particular period after the shock indicates that the response of a variable is restricted to be non-negative or non-positive up to this point.

The dynamic response of consumption is displayed in the first row of figure 2a. Recall that we do not restrict its response to government spending shocks, which we find to be insignificant (left panel). This finding is in line with the evidence reported by Mountford and Uhlig (2005) for a deficit spending shock. Technology shocks increase private consumption for an extended period. In fact, while the response is restricted to be positive for 8 quarters, we find a significant increase for about 10 quarters. In line with the evidence reported by Perotti (2005) for a post-1980 sample as well as Mountford and Uhlig (2005), we find a very short-lived increase in output in response to government spending shocks. In contrast, technology shocks increase output significantly for about 3 years after the shock. The response of private investment differs sharply for both shocks. While it is restricted to be negative (positive) for one year following government spending (technology) shocks, we find that the identified shocks induce significant investment responses for at least 2-3 years. The last row of figure 2a displays the response of government spending. We do not find a significant response to technology shocks, but detect considerable persistence after a spending shock: government spending is likely to exceed its trend value for up to four years after the spending shock.

The response of the government budget balance, which is displayed in the first row of figure 2b partially reflects this: while by construction its response to a government spending shock is negative for two quarters, it remains in deficit during the first 15 quarters. In contrast, the budget balance improves significantly for an extended period in response to a technology shock. The interest rate response, depicted in the second row, is positive (negative) after a spending (technology) shock. The response, however, is reversed at some point for both shocks. The inflation response shown in the third row of 2b shows considerable persistence. While its impact response is restricted to be positive (negative), it remains positive (negative) for an extended period after the government spending (technology) shock.

The last two rows of figure 2b display the dynamic behavior of the real exchange rate and the terms of trade. We find that both the real exchange rate and the terms of trade *depreciate* (i.e. increase) after an

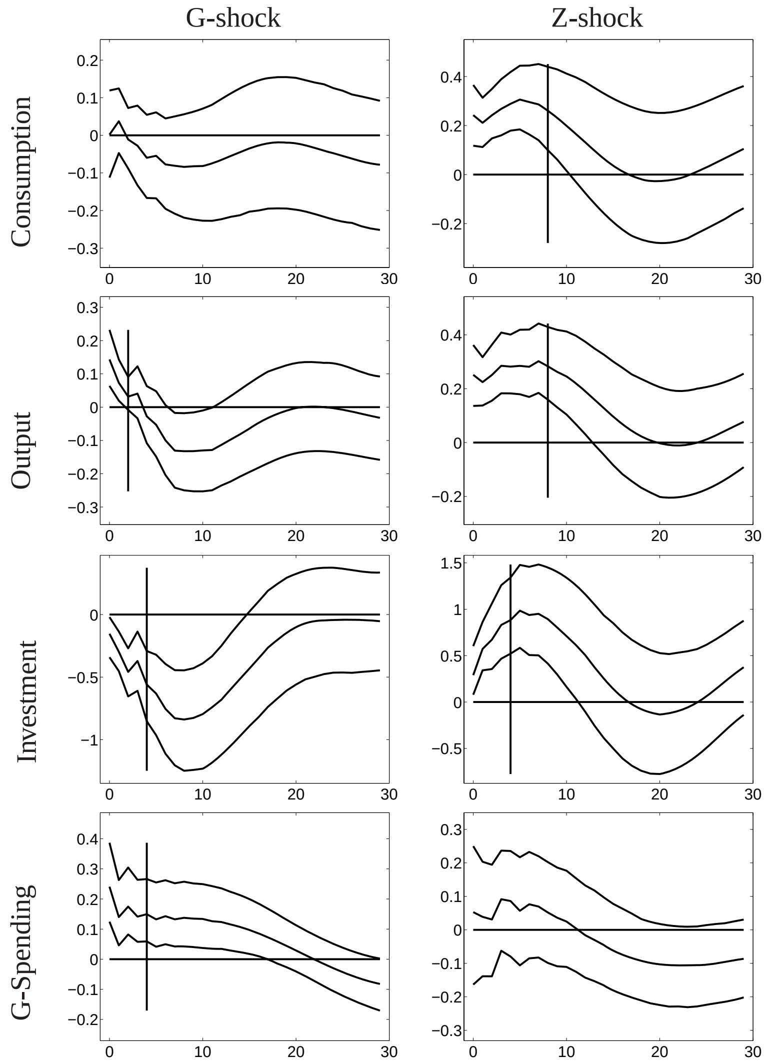


Figure 2a: Results for baseline specification; Notes: solid lines display the median responses as well as the 16 and 84 quantiles. Vertical lines indicate that the sign of a response has been restricted for the period up to the vertical line. Horizontal axes: quarters; vertical axis: percent. All variables are expressed in relative terms, i.e. U.S. vs. ROW aggregate.

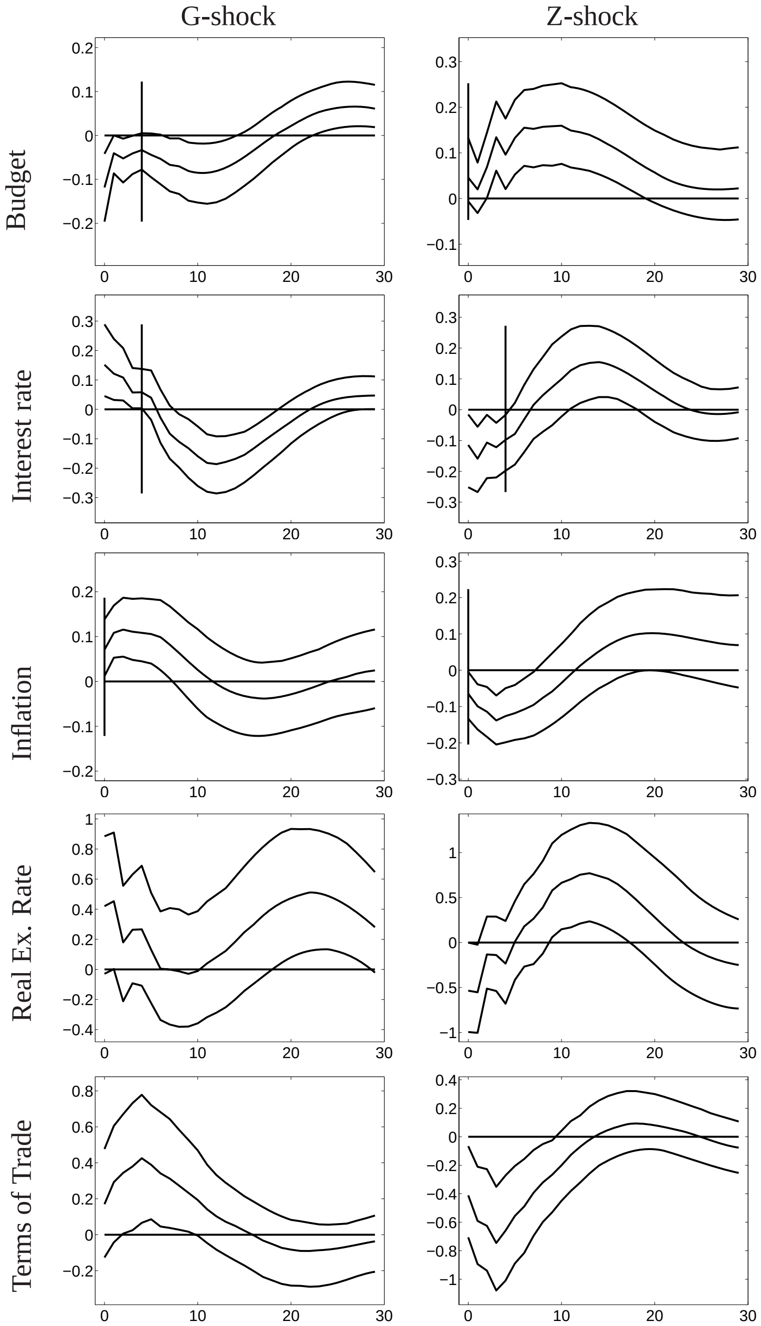


Figure 2b: Results for baseline specification; Notes: see figure 2a; vertical axis show responses in percent, except for budget (percentage points of GDP), interest rate and inflation (percentage points). All variables are expressed in relative terms, i.e. U.S. vs. ROW aggregate, except for real exchange rate and terms of trade (U.S.).

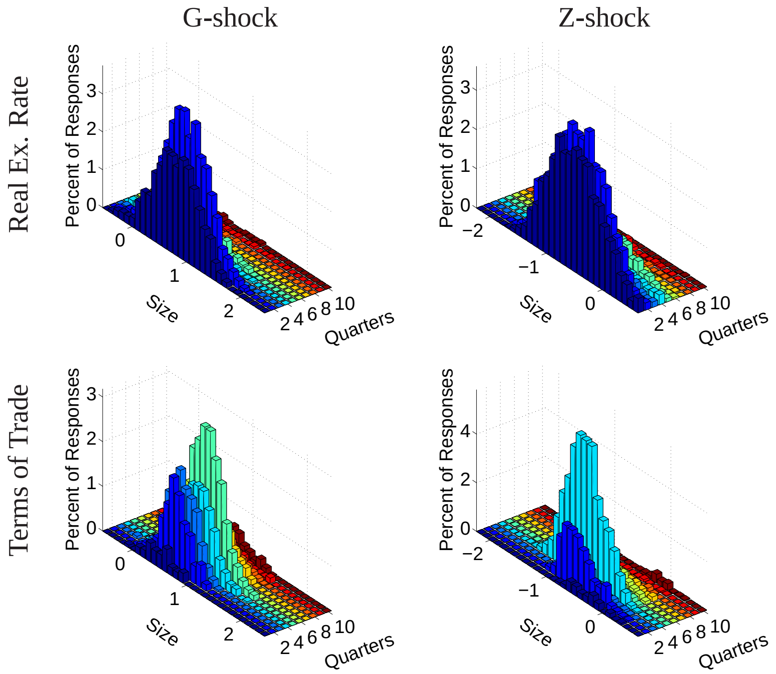


Figure 3: The posterior distribution of the peak responses; Notes: posterior joint distribution of quarter and size of the maximal absolute value of the response to a government spending shock (left) and technology shock (right) within the first 10 quarters. Results are based on 5000 draws satisfying the sign restrictions.

increase in government spending, but *appreciate* (i.e. fall) after a positive technology shock, at least in the first year after the shock. Recall that the response of neither variable is restricted, because—as shown in section 3 above—international business cycle theory does not deliver clear-cut predictions for the behavior of international relative prices in response to both shocks. While the real exchange rate tends to depreciate for an extended period after a spending shock, it appreciates after a technology shock only on impact and tends to depreciate significantly after about two years. In contrast, there is no evidence for a reversal of the sign of the terms of trade response to either of the shocks.

Overall, our findings are broadly in line with recent evidence based on alternative identification schemes (short-run restrictions in the case of government spending shocks, long-run restrictions in the case of technology shocks) which have questioned the received wisdom on the response of real exchange rates to government spending and technology shocks, see the discussion in section 2.1 above. In the following we take up several issues in order to assess the robustness of our findings.

First, to give a more systematic account of the uncertainty surrounding the median responses, we follow Scholl and Uhlig (2007) and report in figure 3 the posterior joint distribution of the timing and the size of the peak responses of the real exchange rate and the terms of trade. The distribution of peak responses to government spending and technology shocks are displayed in the left and right column, respectively, against the size of the response and the quarter when the peak response occurs.

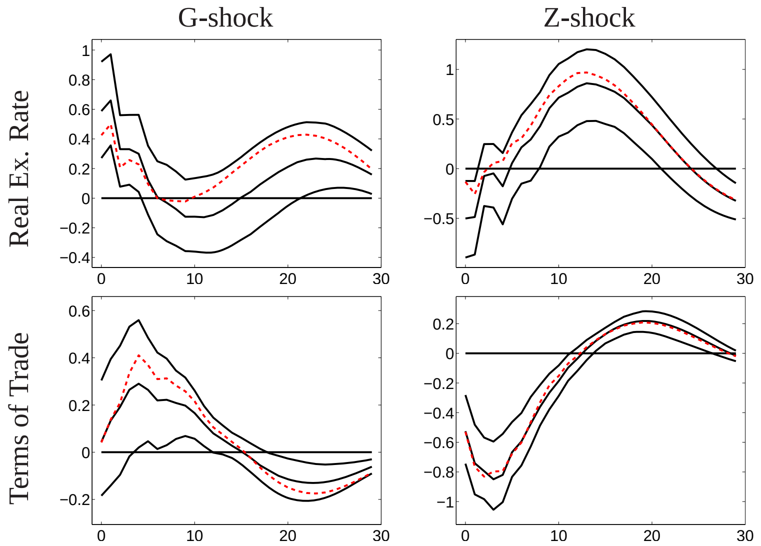


Figure 4: Responses of real exchange rate and terms of trade; Notes: VAR coefficients are fixed at their OLS estimate. The median as well as the $16$ and $84$ quantiles are presented. The dashed line plots the impulse responses generated by a single model as proposed by Fry and Pagan (2007). Horizontal axes: quarters; vertical axes: percent.

Overall, the distribution of peaks is fairly well behaved. In case of both shocks almost the entire mass of the distribution leans towards the median response.

Note, however, that the posterior distribution reflects both sampling and model uncertainty. In order to gauge the extent of model uncertainty, we rule out sampling uncertainty by holding the coefficients fixed at the OLS point estimate when computing the posterior distribution of impulse response functions. The solid lines in figure 4 display the median as well as the $16$ % and $84$ % quantiles of the posterior distribution of the responses of the real exchange rate and the terms of trade. While considerable model uncertainty is apparent, the posterior distribution of the responses is much tighter relative to the results reported in figure 2b. A casual comparison of figures 4 and 2b suggests that the uncertainty surrounding our baseline results is equally due to sampling and model uncertainty.

Finally, we note that focusing on the median of the posterior distribution of impulse responses might be problematic, particularly if several structural shocks are identified. Fry and Pagan (2007) point out that the posterior distribution of impulse responses is a distribution *across* different identified models such that the median impulse response functions to two shocks are generated by two different impulse matrices $Q$. Since this means that the responses are generated from two different models, the identified shocks associated to the median responses are not necessarily orthogonal. We therefore follow Fry and Pagan (2007) and present the impulse responses that are simultaneously generated by a single model. We apply their suggested rule and choose the impulse matrix $Q$ that generates responses which are as close to the medians as possible. Results are displayed by the dashed line in figure 4. Reassuringly, we find that the median responses obtained under our baseline specification

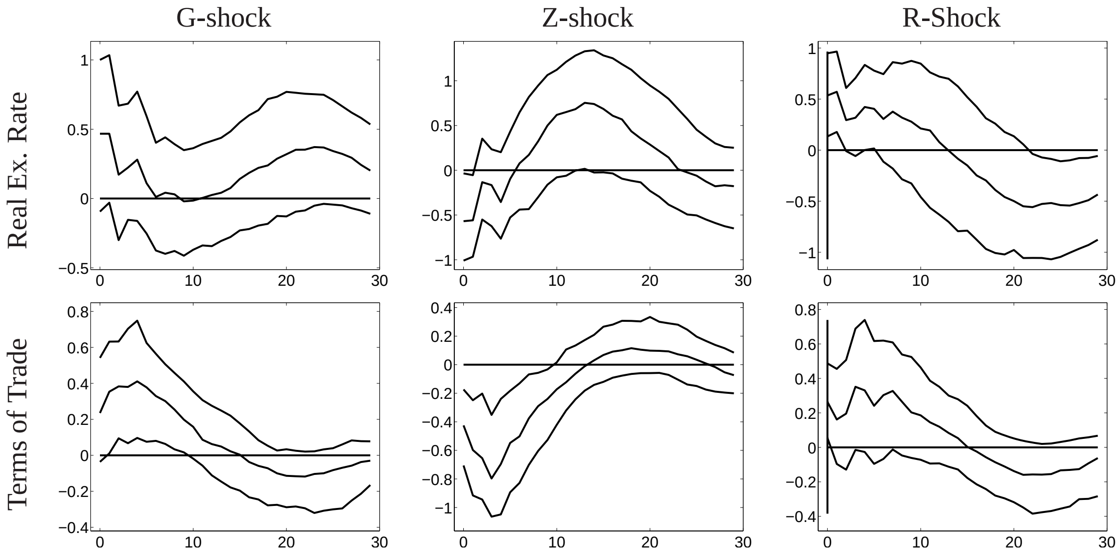


Figure 5: Responses of real exchange rate and the terms of trade under three shock identification scheme; Notes: see figure 2a.

are not very sensitive to this adjustment.

## 4.3 Monetary policy shocks

In our baseline specification, we have identified only government spending and technology shocks while imposing that these shocks are mutually uncorrelated. In this subsection, we identify monetary policy shocks as well, because results from earlier studies suggest that monetary policy shocks are an important source of exchange rate fluctuations. Identifying monetary policy shocks jointly with technology and government spending shocks and imposing that all three structural shocks are orthogonal allows us to assess whether our baseline results are somehow contaminated by monetary policy shocks. Once more, we rely on sign restrictions derived from international business cycle theory as discussed in section 3 and summarized in table 2.

Figure 5 displays the results for the real exchange rate and the terms of trade obtained under this identification scheme. We find that the responses of international relative prices are hardly altered relative to the identification scheme where we do not identify monetary policy shocks explicitly. In response to expansionary monetary policy shocks, both the real exchange rate and the terms of trade depreciate. While we restrict the impact response to be non-negative, we find a protracted depreciation and a mildly hump-shaped adjustment. Such a pattern is well documented for the response of the nominal exchange rate in response to monetary policy shocks. It has been dubbed 'delayed overshooting puzzle', because standard models predict the exchange rate to peak in the period of the

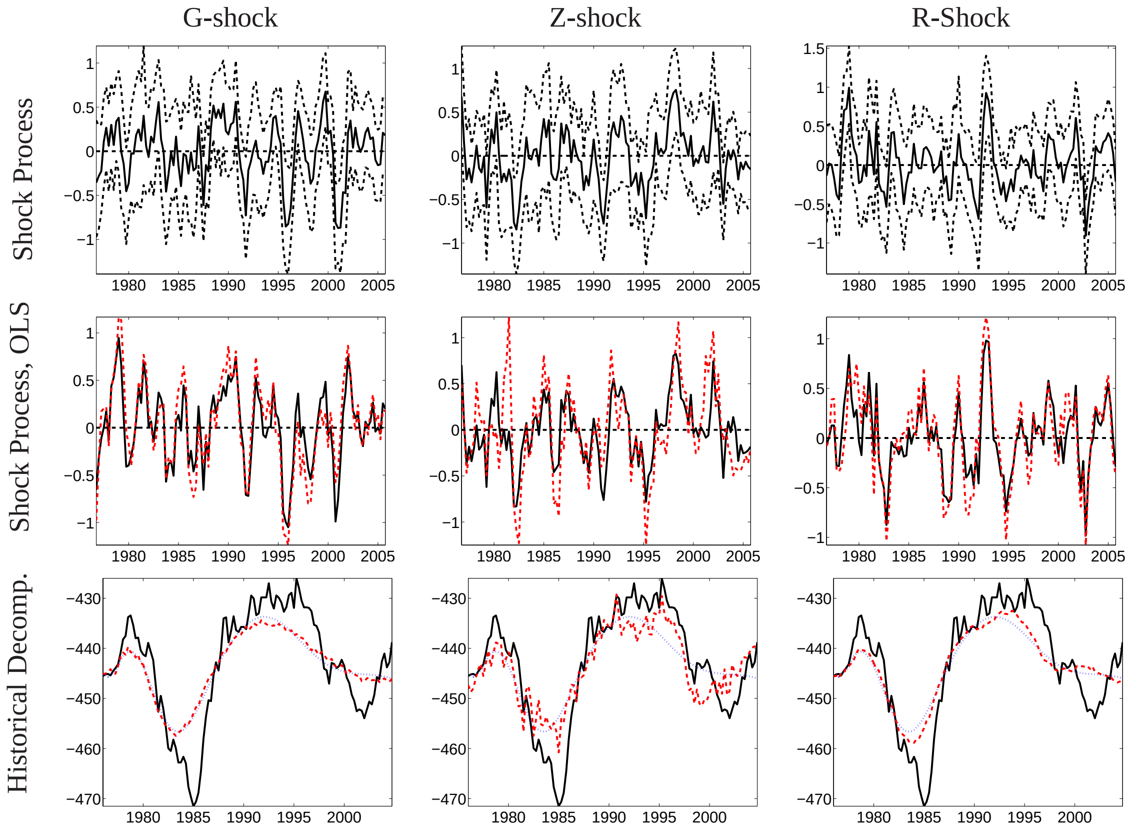


Figure 6: Estimated shock processes and historical decomposition of the real exchange rate under three-shock identification scheme; Notes: First row shows four quarter moving average of median of estimated shock series as well as the 16 and 84 quantiles. Second row displays the median response holding the VAR parameters fixed at OLS point estimate (solid line) and the shock processes generated by a single model as proposed by Fry and Pagan (2007) (dashed line). Third row shows historical decomposition of the real exchange rate (in logs) generated by a single model as proposed by Fry and Pagan (2007); solid line plots the data; dotted line plots decomposition if no shocks had occurred; dashed line plots decomposition if only fiscal, technology or monetary shocks had occurred.

shock, see Scholl and Uhlig (2007) for recent evidence.[20]

As a way to assess the plausibility of our identification scheme, in figure 6, we plot four quarter moving averages of the estimated shocks obtained under the three-shock identification scheme. In the panels of the upper row, the solid lines display the median, while the dashed lines display the 16 and 84 % quantiles of the estimated shock process. However, since these shocks may come from different models, they are potentially correlated. Therefore, we again follow the suggestion of Fry and Pagan (2007) and compute shock series from a single model. The results are displayed in the panels of the second row of figure 6. The solid line refers to the median response holding the VAR parameters fixed at the OLS point estimate while the dashed lines display the shocks obtained under the single model which generates impulse responses as close to the median as possible. The median

[20] Figure A-1 displays the responses of all endogenous variables for the three shock identification scheme.

Table 3: BUSINESS CYCLE VARIANCE DECOMPOSITION

| | Business cycle variation due to shocks to | | |
|---|---|---|---|
| Variable | Government spending | Technology | Monetary policy |
| Private consumption | 0.09, [0.09] | 0.25, [0.30] | 0.17, [0.14] |
| Output | 0.08, [0.08] | 0.24, [0.23] | 0.28, [0.27] |
| Investment | 0.08, [0.08] | 0.09, [0.13] | 0.44, [0.29] |
| Government spending | 0.25, [0.41] | 0.21, [0.23] | 0.12, [0.26] |
| Government budget | 0.07, [0.08] | 0.54, [0.12] | 0.33, [0.34] |
| Nominal interest rate | 0.33, [0.37] | 0.16, [0.15] | 0.58, [0.40] |
| Inflation | 0.12, [0.12] | 0.31, [0.34] | 0.41, [0.32] |
| Real exchange rate | 0.15, [0.18] | 0.52, [0.41] | 0.22, [0.27] |

Entries refer to the business cycle variance decompositions generated by a single model as proposed by Fry and Pagan (2007). Statistics are computed on HP-filtered series using a smoothing parameter of 1600. Statistics in brackets are the medians of the posterior distribution given the fixed OLS point estimate.

shock processes (upper row) and those implied by the single model look rather similar.

Overall, the identified shock processes are consistent with several familiar narratives concerning important macroeconomic episodes during the last three decades. Focusing on the results obtained under the single model (second row, dashed line) and turning first to relative government spending shocks, we observe spikes during the Carter-Reagan build-up around 1980 and as well as after 9/11. Regarding relative technology shocks, strong positive innovations during the late 1990s can be detected consistent with the notion of a distinct productivity driven upturn in the U.S. Finally, our measure for relative monetary policy shocks indicates a considerable monetary tightening during the early 1980s under the Volcker chairmanship. We also find expansionary monetary policy shocks during the early 1990s, followed by a sharp monetary contraction. It is conceivable that these relative shocks reflect not only developments in the U.S., but also in Europe where monetary policy was excessively tight in a number of countries after German reunification and become much looser after the EMS crisis in 1992, notably in the U.K. after its exit from the exchange rate arrangement.

The last row of figure 6 plots the historical decomposition of the real exchange rate considering shocks to government spending, technology and monetary policy separately. A casual interpretation suggests that among the three shocks technology shocks explain most of the variance. Additionally, table 3 displays results of a business cycle variance decomposition. Entries correspond to the fraction of variance due to each of the identified shocks (under the single model) after applying the HP-filter to time series obtained from the VAR model under the counterfactual simulation that only one of the shocks had occurred. In brackets, we report the corresponding statistic from the medians of the posterior distribution given the fixed OLS point estimates. Overall, shocks to government spending explain a small fraction of the business cycle variation: only 8 to 9 percent of the variation in consumption, output and investment is due to fiscal policy. In contrast, technology (monetary policy) shocks generate 25 and 24 (17 and 28) % of the variation in consumption and output. The business cycle variance of investment is to a large extent driven by monetary policy shocks (44 %). Moreover, monetary policy shocks account for 58 and 41 % of the business cycle variance of the nominal interest rate and inflation, respectively. Technology shocks have a large impact on inflation while government spending shocks seem to matter for the variance of the nominal interest rate. Turning to the real exchange rate, we find that $15$, $52$ and $22$ percent of its variance is due to shocks to government spending, technology and monetary policy, respectively.

### 4.4 Further sensitivity analysis

In this section we consider additional variations of our baseline specification in order to assess the sensitivity of our results. First, we set $\varepsilon = 0$, i.e. we impose the sign restrictions in a restrictive way. We find little change in the responses of the real exchange rates, see figure A-2 in the appendix. Note however, that for $\varepsilon = 0$ many draws from the Normal-Wishart posterior for the VAR parameters $(B, \Sigma)$ receive zero prior weight such that the search for impulse responses that fulfill all sign restrictions is cumbersome. Therefore, in case $\varepsilon = 0$ is imposed, inference is based on approximately 100 draws satisfying the sign restrictions compared to 5000 draws in our baseline specification shown in figures 2a, 2b and 3.

We conduct additional sensitivity analysis regarding the sample period. Specifically, we consider two alternative starting dates: 1973Q1 and 1980Q1. The results, reported in figure A-3, indicate that results obtained under the baseline specification are fairly robust with respect to the sample period under consideration.

Finally, we assess whether our results are sensitive to the inclusion of net exports in the VAR model. Our results, reported in figure A-4, show that this is not the case. Interestingly, we find no significant response of net exports to either spending or technology shocks, consistent with the findings of several other VAR studies suggesting that the effect of government spending shocks on the trade balance is quite contained, see Corsetti and Müller (2006) for the U.S. With respect to technology shocks, we find a marginally significant decline of the trade balance after about two years. This squares well with the evidence reported in Enders and Müller (2008) who find a hump-shaped decline in the trade balance in response to positive technology shocks identified on the basis of long-run restrictions.

## 5 Conclusion

In this paper we provide fresh evidence on the response of international relative prices to government spending and technology shocks. We start from three observations. First, the real exchange rate and the terms of trade are key variables governing the international transmission mechanism. This has been most forcefully illustrated by Corsetti et al. (2007) in the context of technology shocks. Second, the existing evidence on the behavior of international relative prices in response to technology and spending shocks conflicts with the predictions of international business cycle models under standard calibrations. Third, the evidence to date is mostly based on estimated VAR models where identification is achieved either through short-run or long-run restrictions.

We establish new evidence by employing an alternative identification scheme. Specifically, we follow Uhlig (2005) and restrict the sign of those responses which we can show to be largely uncontroversial. Our baseline VAR model contains eight variables: private consumption, output, private investment, government spending, the primary government budget balance, inflation, the nominal interest rate—all measured for the U.S. relative to an aggregate of industrialized countries—and the real effective exchange rate or the terms of trade.

We derive sign restrictions from a two-country DSGE model by simulating its impulse response functions for a wide range of parameterizations. In response to government spending and technology shocks, the model does provide robust predictions for the sign of several key variables, which conform well with the conventional wisdom on the international transmission mechanism. It does not, however, provide clear-cut predictions for the behavior of the real exchange rate and the terms of trade, because of the wide range of parameterizations which we consider. This result is key to our identification strategy: it allows us to restrict the responses of several variables included in the VAR model, but to remain agnostic about the response of the real exchange rate and the terms of trade.

We estimate the VAR model on quarterly time series covering the period 1975–2005. Considering various specifications, we find that expansionary government spending shocks depreciate the real exchange rate as well as the terms of trade. Positive technology shocks, in contrast, appreciate the real exchange rate and the terms of trade. Our results are largely in line with the evidence reported in recent studies which employ alternative identification schemes. They also appear robust with respect to several variations of our baseline specification.

Taking a theoretical perspective, our results support to the notion that movements in international relative prices amplify rather than mitigate the consumption risk associated with government spending and technology shocks—in contrast with the predictions of conventionally calibrated business cycle models.

# A Data

## A.1 Sources

The data used in this paper are from the OECD Economic Outlook and the Main Economic Indicators databases taken from OECD (2008), and the Area-Wide Model database of the ECB, as described in Fagan, Henry and Mestre (2001). Government spending includes government spending on goods and services (government consumption), but neither investment nor transfers. We leave out government investment because of an accounting problem in the U.K. in 2005Q2. We do not consider transfers, in order to ensure comparability of our results with those obtained under the Blanchard-Perotti identification scheme.

OECD Economic Outlook for Canada, the United Kingdom, Japan, the United States and the euro area: 'Gross domestic product (market prices), volume'; 'Private consumption, volume'; 'Government consumption, volume'; 'Private fixed investment (excl. stockbuilding), volume'; same source except for the euro area: 'Interest rate, short-term'; 'Primary government balance, % GDP'; 'Exports of goods and services, value, local currency', 'Imports of goods and services, value, local currency', and 'Gross domestic product (Market prices), value' for the calculation of the trade balance over GDP; 'Export price goods and services, local currency', and 'Import price goods and services, local currency' for the construction of the terms of trade.

AWM database:'Short-term interest rate (nominal in percent)' [STN]; 'Exports of goods and services' [XTN], 'Imports of goods and services' [MTN], and 'GDP' [YEN] for the calculation of the trade balance over GDP; 'Exports of goods and services deflator' [XTD], and 'Imports of goods and services deflator' [MTD] for the construction of the terms of trade; 'Ratio gov. primary surplus/GDP' [GPN_YEN].

OECD Main Economic Indicators for the United States 'Real effective exchange rate – CPI based'.

## A.2 Aggregation

In order to avoid national basis effects, we aggregate the rest of the world series by first calculating quarterly growth rates, then aggregating these series weighted by each country's GDP share. Euro area growth rates include West-Germany until 1990Q4, and unified Germany from 1991Q1 onwards (applicable only where OECD data is used, similar reasoning had been applied to construct the ECB AWM database). The weights were calculated at annual purchasing power parity (PPP) values in the year 2000, based on data from International Monetary Fund (2007).

# B Impulse Response Functions

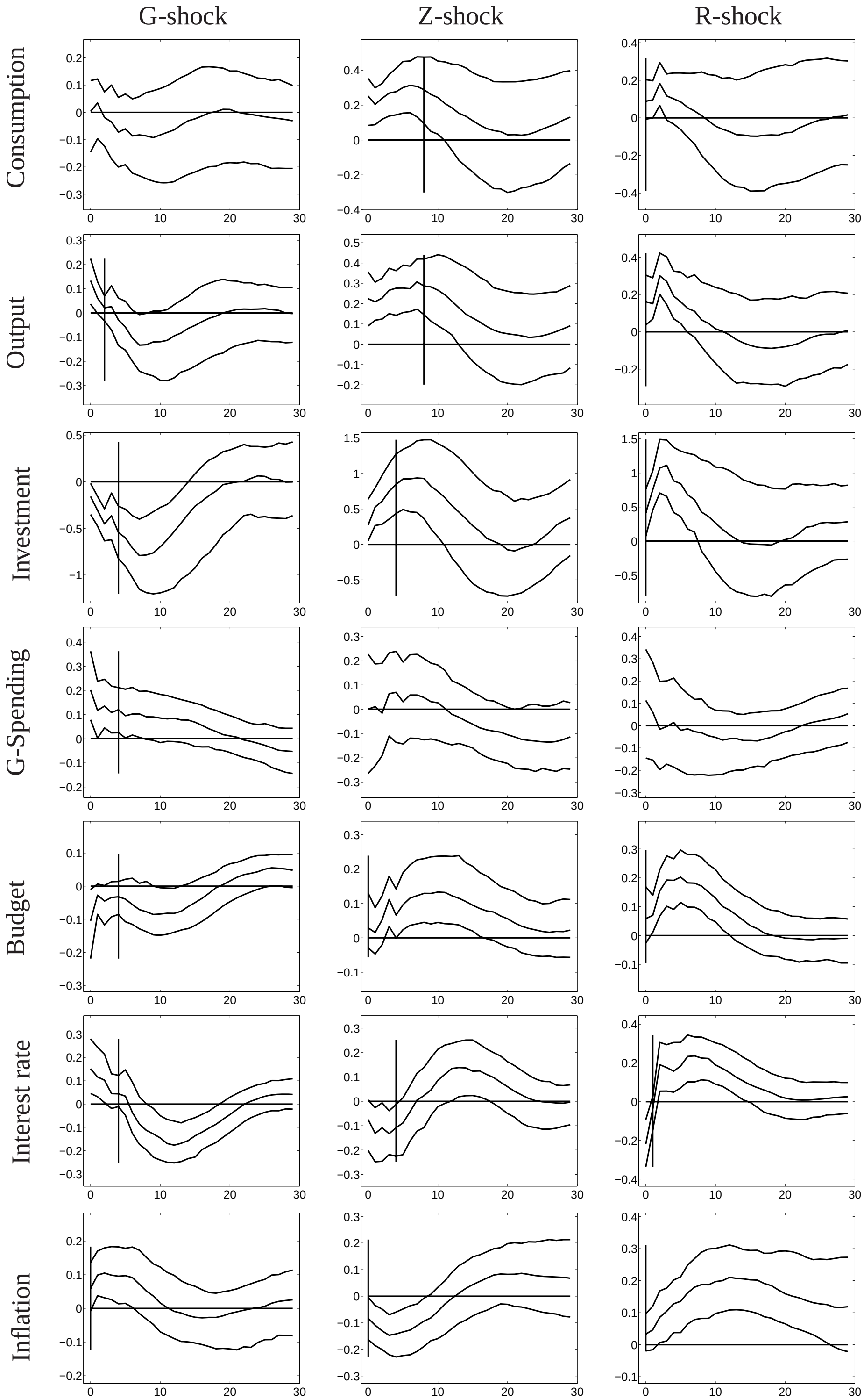


Figure A-1: Results from three shock identification scheme; Notes: see figure 2a.

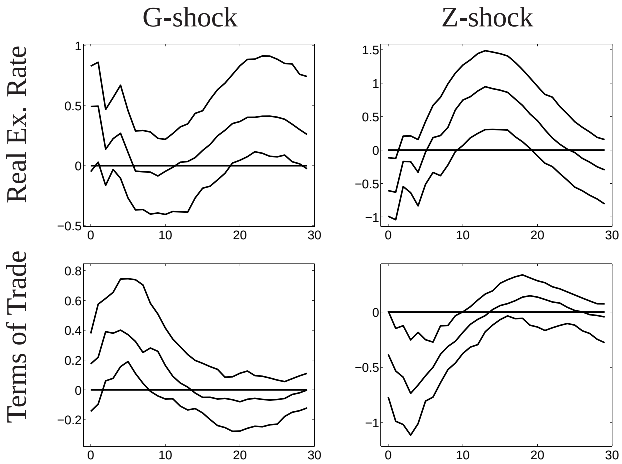


Figure A-2: Robustness Checks: $\varepsilon = 0$; The median as well as the 16 and 84 quantiles are presented. Horizontal axes: quarters; vertical axis: percent.

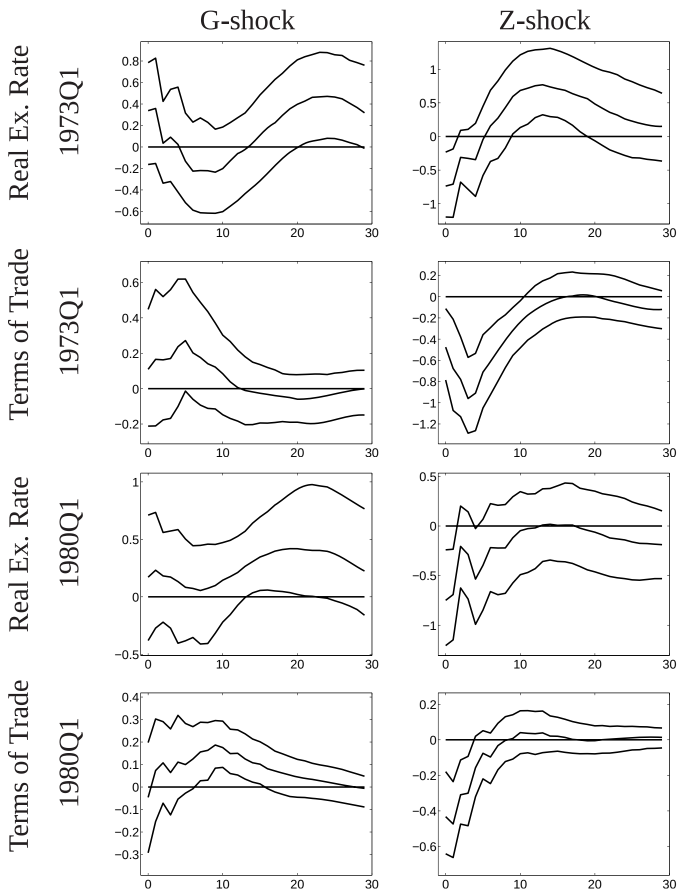


Figure A-3: Robustness Checks; The median as well as the 16 and 84 quantiles are presented. Horizontal axes: quarters; vertical axis: percent.

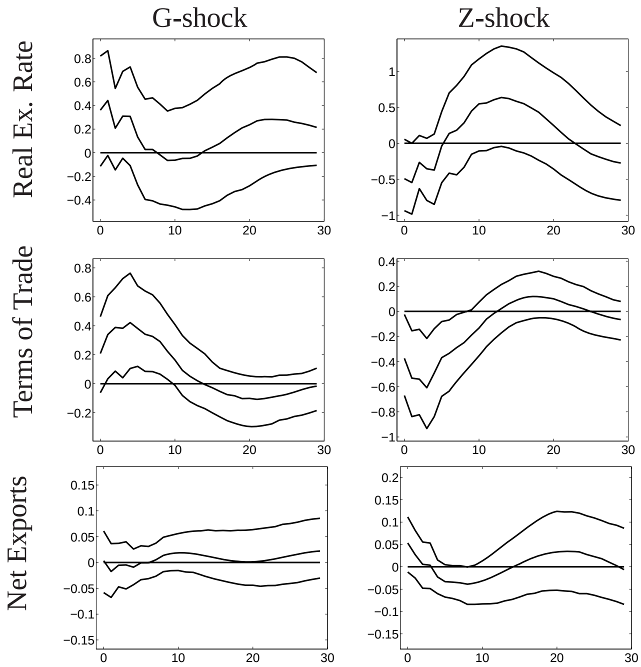


Figure A-4: Net exports; The median as well as the 16 and 84 quantiles are presented. Horizontal axes: quarters; vertical axis: percent.

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