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Transmission of business cycle shocks between the US and the euro area

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Editorial

The authors analyze the transmission of structural shocks between the US and the euro area within a two-country VAR framework. For that purpose, they simultaneously identify cost-push, demand and monetary policy shocks for both countries using sign restrictions. Their results show that domestic shocks explain the largest share of the forecast error variances for GDP, consumer prices and the interest rate in both countries in the short run, whilst spillovers from the other country and global factors gain importance in the medium run. The strength of the shock transmission between the two countries is quite symmetric. The authors' approach to the identification of structural shocks allows us to construct confidence bands that account both for estimation and identification uncertainty. The authors find impulse responses to domestic shocks to be significant while spillovers across countries are insignificant.

July 21, 2008

Transmission of business cycle shocks between the US and the euro area

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Oesterreichische Nationalbank
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Abstract

We analyze the transmission of structural shocks between the US and the euro area within a two-country VAR framework. For that purpose, we simultaneously identify cost-push, demand and monetary policy shocks for both countries using sign restrictions. Our results show that domestic shocks explain the largest share of the forecast error variances for GDP, consumer prices and the interest rate in both countries in the short run, whilst spillovers from the other country and global factors gain importance in the medium run. The strength of the shock transmission between the two countries is quite symmetric. Our approach to the identification of structural shocks allows us to construct confidence bands that account both for estimation and identification uncertainty. We find impulse responses to domestic shocks to be significant while spillovers across countries are insignificant.

JEL-Codes: C32 E37 E40

Keywords: VAR, shock transmission, sign restrictions, Metropolis-Hastings, confidence intervals, bootstrap.

1. Introduction

The manifold economic ties between the developed countries of the world economy create complex linkages between their business cycles. The various forces behind the globalisation process have changed these linkages in important ways over the past three decades. Three main features characterize these developments. First, there is clear evidence that the magnitude of global output fluctuations has diminished. Second, the degree of synchronisation of business cycles across countries has remained high and relatively stable. Third, there is evidence of the emergence of regional blocks with increased co-movement.

The decline in global business cycle fluctuations can mainly be attributed to the decreasing importance of global shocks (Stock and Watson, 2003). One main strand of the literature on international business cycle linkages focuses on the *extraction of common factors* that drive

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the global economy and assesses their importance relative to regional shocks, country-specific shocks and on the effects from international spillovers. This literature usually finds that – besides country-specific shocks – global shocks play a dominant role in explaining output fluctuations in the country under consideration. In a recent contribution, Dées and Vansteenkiste (2007) confirm these findings in a global VAR for several regions including the US and the euro area. Kwark (1999) finds that for the US domestic shocks are the most important source of output fluctuations followed by global shocks while foreign domestic shocks have only marginal effects. Canova *et al.* (2004) find that about 1/3 of US GDP fluctuations are explained by global factors, a result very similar to the findings in Kose *et al.* (2003) and Perez *et al.* (2006). In contrast, Mitra and Sinclair (2007) find only weak evidence for a world business cycle. Using an unobserved component model, they conclude that regional and country specific shocks are the dominating source of US business cycle fluctuations.

Another central feature of international business cycle linkages over the past thirty years is the *emergence of regional blocks,* which are typically characterized by an increasing degree of intra-block business cycle synchronisation. Helbing and Bayoumi (2003) and Stock and Watson (2003) find evidence for a euro area and an Anglo-American “convergence club” while the Japanese economy evolved autonomously. Especially the process of European integration and its effect on international business cycle linkages has attracted much attention in the literature. Furceri and Karras (2008) find that the business cycles of the EU countries have become more synchronised since the introduction of the euro. Besides the question whether the European economic and monetary union will trigger convergence of business cycles among member countries, research interest focuses on the comovement of fluctuations in the euro area and the US.

The fact that – despite the decline in the magnitude of global shocks – international business cycles show a stable comovement is usually explained by globalization. The surge in international trade and financial flows is generally believed to have increased the transmission of shocks across countries (Imbs (2004a), Imbs (2004b), Kose (2004)). Thus, another main strand in the literature on international business cycle linkages analyses the *strength of shock transmission between countries*. Most of the studies analyse the transmission of US shocks to other world regions (often with a special focus on monetary policy shocks). In a recent contribution, the IMF (2007) concludes that spillovers from the US have considerable effects on the rest of the world if the disturbances are either truly global in nature, correlated across countries or characterized by global movements in asset markets. The transmission of US shocks to Europe has been investigated thoroughly. Most of the studies confirm the role of the US as a locomotive for the world economy in general and the euro area in specific. Artis *et al.* (2003) find that on average about 2/3 of an US shock are transmitted to European countries. Canova and Marrinan (1998), Kwark (1999), Dassel (2002) and Eickmeier (2007) confirm these findings for the propagation of US shocks to Germany. According to Osborn *et al.* (2005), the US influence on the EU-15 is significant in low growth regimes but relatively small in high growth regimes. Concerning monetary policy shocks, Neri and Nobili (2006) and Pesaran *et al.* (2001) find that a decrease in US interest rates has negative effects on output in the euro area in the short run, but a positive effect in the medium run. In contrast, Dées *et al.* (2007) conclude that that US monetary policy shocks have only a small and insignificant effect on the euro area.

A key research question in that respect is whether *euro area-shocks have a significant effect on the US economy* and not just the other way round. Most studies find that the US economy leads the European economies (e.g. Osborn *et al.* (2003)) and that the transmission of European shocks to the US economy is not strong. However, there is also evidence that shows some impact of European business cycle fluctuations on the US economy. Perez, Osborn and Artis (2006) find an increasing impact of EU-15 on the US economy over time. In the recent past about one fifth of output fluctuations in both regions can be attributed to shocks in the other country. Gaggl *et al.* (2007) find significant responses of both US and euro area GDP to output shocks emanating from the other country. Moreover, results from simple Granger causality tests show that the euro area output gap has some predictive power for the US gap (as well as vice versa, see table 1).

Table 1: Test for Granger causality of US versus euro area output gap (p-values)

	1 quarter	2 quarters	3 quarters	4 quarters	5 quarters
US to euro area	0.00	0.01	0.05	0.09	0.11
Euro area to US	0.01	0.17	0.07	0.45	0.32

The null hypothesis is that the first country does not Granger cause the second country.
Source: The authors' own calculations.

From a methodological point of view, the vast majority of studies is based on multi-country VAR models (Artis *et al.* (2003), Canova and Marrinan (1998), Canova *et al.* (2004), Kwark (1999), Dassel (2002), Papanyan (2005), Osborn *et al.* (2005), Pérez *et al.* (2003)) or global VAR models (Pesaran *et al.* (2001), Dées *et al.* (2007), Dées and Vansteenkiste (2007)). Mitra and Sinclair (2007) use an unobserved component model and Eickmeier (2007) combines a dynamic factor model with a VAR model.

The focus of our paper is on the linkage between the US and the euro area business cycles. We identify global and country specific shocks simultaneously. This allows us to investigate the transmission of country specific shocks from the US to the euro area as well as from the euro area to the US. We identify three different country specific shocks in each of the two country blocks: a cost-push shock, a demand shock and a monetary policy shock. Therefore, we set up a VAR model with the US and the euro area as separate country blocks plus a block with global variables. We identify the global shocks by means of a Cholesky decomposition. The identification scheme for country specific shock is based on the idea of imposing sign restrictions on impulse responses introduced by Faust (1998), Canova and de Nicolo (2003) and Canova (2005). They use rotation matrices (see section 3) and systematically search over a grid of bivariate rotation angles to find valid rotations of an initial orthogonalization. Peersman (2005, 2007) and Uhlig (2005) use a Bayesian approach for estimation and inference by drawing from a uniform distribution of the rotation angles. Canova (2007) recently proposed the QZ decomposition as an alternative to the use of rotation matrices.

On the methodological side, this paper makes two contributions to the sign restriction approach. *First*, given the size of our VAR model, a systematic search for valid rotations over a grid is computationally not feasible. We therefore propose Monte Carlo simulation techniques as a natural alternative. We use the Metropolis-Hastings (MH) algorithm to search the rotation space. The objective function we seek to maximize sums up the share of domestic shocks in the forecast error variance decomposition for domestic variables. This assures that truly country-specific shocks are identified. Our procedure provides us with a distribution of valid draws for each bivariate rotation angle. The variance of this distribution gives us an idea of the relative precision with which a pair of two shocks can be identified. *Second*, we deal with the fact that the proposed identification procedure is subject to two kinds of uncertainty. In addition to the conventional estimation uncertainty, we face an identification uncertainty since there are (usually) many impulse responses that satisfy the theoretical restrictions. We suggest an adapted version of the bootstrap algorithm outlined in Benkwitz *et al.* (2001) to construct confidence intervals that account for both identification and estimation uncertainty.

The paper is organized as follows. Section 2 presents two-country VAR model. The identification of shocks is discussed in section 3. In section 4, the empirical results are presented. Section 5 illustrates the construction of confidence bands. Finally, we summarize our findings and draw some conclusions in section 6.

2. A two-country VAR model

We analyze the transmission of structural shocks within a two-country VAR model including the US and the euro area. In addition, a block of two global variables controls for international developments. The identification of the structural shocks follows the sign restriction approach suggested by Canova (2005). We simultaneously identify *cost-push*, demand and monetary policy shocks for both the US and the euro area.

The VAR model consists of eight endogenous variables. Each regional block includes real GDP as a measure of real activity, the CPI as a measure of inflation, and the short-term interest rate (three-month money market rate) as proxy for monetary policy. Additionally, two global variables enter the VAR: real world trade and the HWWI index of raw material prices. These two variables control for international disturbances. All variables (with exception of the interest rates, which are in levels) are in logs and have been de-trended using the HP-filter.[2] The model is given by:

$$\begin{bmatrix} x_t^{GL} \\ x_t^{US} \\ x_t^{EA} \end{bmatrix} = \begin{bmatrix} B_{11}(L) & 0 & 0 \\ B_{21}(L) & B_{22}(L) & B_{23}(L) \\ B_{31}(L) & B_{32}(L) & B_{33}(L) \end{bmatrix} \begin{bmatrix} x_{t-1}^{GL} \\ x_{t-1}^{US} \\ x_{t-1}^{EA} \end{bmatrix} + \begin{bmatrix} \varepsilon_t^{GL} \\ \varepsilon_t^{US} \\ \varepsilon_t^{EA} \end{bmatrix} \tag{1}$$

where $\left(\varepsilon_t^{GL}, \varepsilon_t^{US}, \varepsilon_t^{EA}\right)' \sim (0, \Sigma)$, $\Sigma = blockdiag(\Sigma_{\varepsilon^{GL}}, \Sigma_{\varepsilon^{US}}, \Sigma_{\varepsilon^{EA}})$. x_t^{GL} represents the set of global variables, x_t^{US} the set of US variables and x_t^{EA} the euro area variables. We assume

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[2] The euro area data we use are from the area wide model (AWM) data base, the US data from the Bureau of Labor Statistics, world trade figures from the International Financial Statistics (IMF) and the HWWI-index form the Hamburgische WeltWirtschaftsInstitut data base. Data reach from 1982Q1 to 2006Q2

that the global variables (world trade and the HWWI-index) are not influenced by US and by euro area variables.[3] The underlying structural model is given by:

$$\begin{bmatrix} C_{11} & 0 & 0 \\ C_{12} & C_{22} & C_{12} \\ C_{12} & C_{12} & C_{12} \end{bmatrix} \begin{bmatrix} x_t^{GL} \\ x_t^{US} \\ x_t^{EA} \end{bmatrix} = \begin{bmatrix} G_{11}(L) & 0 & 0 \\ G_{21}(L) & G_{22}(L) & G_{23}(L) \\ G_{31}(L) & G_{32}(L) & G_{33}(L) \end{bmatrix} \begin{bmatrix} x_{t-1}^{GL} \\ x_{t-1}^{US} \\ x_{t-1}^{EA} \end{bmatrix} + \begin{bmatrix} u_t^{GL} \\ u_t^{US} \\ u_t^{EA} \end{bmatrix} \tag{2}$$

where $\left(u_t^{GL}, u_t^{US}, u_t^{EA}\right)' \sim (0, I)$ and u_t^m is the vector of structural disturbances of region *m*. The model was estimated with quarterly data ranging from 1983Q3 to 2006Q2. The optimal lag length is one and was selected according to the Schwarz information criteria.

3. Simultaneous identification of structural shocks

Our approach to identify structural shocks is a straightforward extension of the identification scheme proposed by Faust (1998), Canova and de Nicoló (2003) and Canova (2005). The basic idea is to identify underlying structural shocks by using sign restrictions on the impulse responses to orthogonalized disturbances. We start by orthogonalizing the variance covariance matrix of the innovations (Σ) by means of a Cholesky decomposition $\Sigma = PP'$. This gives us a vector of orthonormal residuals $\tilde{\varepsilon}_t^m \sim (0, I)$. However, this orthogonalization is by no means unique since for any orthonormal matrix $Q : QQ' = I$, $\Sigma = \tilde{P}\tilde{P}' = PQQ'P'$ is an admissible decomposition. Thus, we can construct a set of admissible decompositions by using different orthonormal matrices *Q*. Within the class of orthonormal matrices, rotation matrices are a reasonable candidate to consider. They allow us to cover the whole space of *Q* matrices in a straightforward way. Rotation matrices use sine and cosine functions to rotate the orthogonalized residuals. In a VAR system with *N* variables there are *N(N-1)/2* bivariate rotation angles. Since we are interested in the identification of structural shocks for the US and the euro area only, we keep the original Cholesky decomposition for the two global variables. We decided to order world trade first thereby assuming that there is a contemporaneous effect of world-trade-innovations to the HWWI index but not vice versa.

The two regional blocks of the VAR have six endogenous variables. This gives us 15 rotation axes $\theta_i, i = 1 \ldots 15$. The alternative *Q* matrices thus take the form

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[3] The exogeneity of raw material prices seems to be plausible given that the huge hikes in raw material prices over the past decades were mainly driven by geopolitical events. Test for exogeneity confirm this assumption. World trade on the other hand is not exogenous in a strictly statistical sense. Nevertheless, we have assumed that there are no feedbacks from US and euro area variables on both global variables for the sake of simplicity. Sensitivity analyses clearly indicate that this assumption does not change our results qualitatively, i.e. impulse responses from VARs with global variables being either endogenous or exogenous are qualitatively equivalent.

$$Q(\theta_1,\theta_1...\theta_{15})=\begin{pmatrix}\cos(\theta_1) & -\sin(\theta_1) & 0 & 0 & 0 & 0\\ \sin(\theta_1) & \cos(\theta_1) & 0 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0 & 0\\ 0 & 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 0 & 0 & 1\end{pmatrix}\cdot\begin{pmatrix}\cos(\theta_2) & 0 & -\sin(\theta_2) & 0 & 0 & 0\\ 0 & 1 & 0 & 0 & 0 & 0\\ \sin(\theta_2) & 0 & \cos(\theta_2) & 0 & 0 & 0\\ 0 & 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 0 & 0 & 1\end{pmatrix}\cdots\begin{pmatrix}1 & 0 & 0 & 0 & 0 & 0\\ 0 & 1 & 0 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0 & 0\\ 0 & 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 0 & \cos(\theta_{15}) & -\sin(\theta_{15})\\ 0 & 0 & 0 & 0 & \sin(\theta_{15}) & \cos(\theta_{15})\end{pmatrix}. \quad (4)$$

One can easily verify that $QQ'=I$ holds for any value of $\theta_i \in (0,2\pi), i=1,2...,15$.

Identification restrictions suggested by economic theory

The next step is to identify decompositions with a meaningful economic interpretation. We aim to identify three structural shocks - a demand shock, a *cost-push* shock and a monetary policy shock for both the US and the euro area. Following Canova (2005), we rotate the orthogonalized disturbances and impose sign restrictions on the impulse responses to structural shocks. According to standard macroeconomic theory, a positive demand shock will generate a positive response of output and a rise in inflation. Monetary authorities will increase interest rates thereby generating a positive co-movement between all three variables. Contrary, a positive *cost-push* shock will increase output but decrease prices. In that case, monetary policy faces a trade-off between price stability and the output goal. Hence, theory gives us no clear guidance for the reaction of interest rates.

Table 2: Identification restrictions for simultaneous identification of structural shocks

Structural Shocks	Sign of the impulse response for the first period					
	GDP$_{US}$	Prices$_{US}$	Interest rate$_{US}$	GDP$_{EA}$	Prices$_{EA}$	Interest rate$_{EA}$
Demand$_{US}$	+	+	+			
Cost-push$_{US}$	+	-				
Monetary$_{US}$	+	+	-			
Demand$_{EA}$				+	+	+
Cost-push$_{EA}$				+	-	
Monetary$_{EA}$				+	+	-

Finally, a positive monetary policy shock is defined by a decrease of the interest rate and increases in output and inflation. These sign restrictions can be derived from a large set of theoretical models. We impose these restrictions on the contemporaneous reaction of the variables only. They are consistent with the standard textbook aggregate-demand aggregate-supply framework as well as with more advanced models like DSGE models in the line of Smets and Wouters (2003). We do not impose any sign restrictions on the spillovers of domestic idiosyncratic shocks on other countries or the global variables. Hence, these variables are free to react to the shocks in the foreign country.[4]

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[4] Paustian (2007) investigates the conditions, under which the sign restriction approach is able to pin down the correct sign of unrestricted responses. He finds that the number of variables whose impulse responses are restricted, the number of periods for which the restrictions are imposed and the relative variance of the shocks determine the precision, with which the unrestricted responses can be estimated.

The Metropolis-Hastings algorithm

Canova and de Nicoló (2003) and Canova (2005) systematically searched for valid rotations over a grid. This procedure is feasible for a small number of variables and hence rotation axes, since the number of rotation axes *r* is given by $r = n(n-1)/2$. A three variable model has three rotation axes. A grid size of 15 results in 15^3 = 3375 different rotations. Considering our six variable model would result in 15^15 = $4.4*10^{17}$ rotations. A reduction of the grid size does not help much. Considering a (very crude) grid size of five still results in $3.1*10^{10}$ rotations. A systematic search is therefore not feasible. We have tried out a random search by drawing each θ_i from a uniform distribution $\theta_i \in \{0,...,2\pi\}$. This also turned out to be no feasible alternative. Out of 1,000,000 random draws, we have found seven valid rotations only. A natural alternative both to a systematic and a random search is the use of Monte Carlo simulation techniques. We decided to use the Metropolis-Hastings algorithm to search the parameter space. Our algorithm works as follows.

Step 1: Start with an initial vector $\Theta = (\theta_1,...,\theta_{15})$ of rotation angles.

Repeat steps 2 to 6 *N* times:

Step 2: Generate a random walk proposal $\tilde{\Theta} = \Theta + \Delta$ by drawing Δ from a multivariate normal distribution $\Delta \approx N(0,\sigma^2)$[5].

Step 3: Compute impulse responses for $\tilde{\Theta}$ and calculate the value of the *objective function* $\chi(\tilde{\Theta})$ described below.

Step 4: Check whether the sign restrictions outlined in table 2 are satisfied. If all sign restrictions are fulfilled, multiply the value of the objective function by 10^6. This ensures that the algorithm does not accept invalid draws, once a valid draw has been found.

Step 5: Compute the acceptance probability $\alpha = \min(1, \chi(\tilde{\Theta}) / \chi(\Theta))$ by dividing the value of the objective function of the proposal draw by the value of the objective function of the last accepted draw. Accept the proposal draw with probability α .

Step 6: If the draw has been accepted, add it to the list of accepted valid draws. Otherwise, keep the last accepted draw.

The objective function

The crucial point of the identification procedure is to attribute shocks to one of the two countries. As the analysis of the international shock transmission lies at the core of our analysis, we do not restrict the transmission itself. Alternatively, we use an objective function approach to discriminate between domestic and foreign shocks. To see the necessity of using an objective function, one has to keep the two-country setup in mind. Since the transmission of shocks is positive in many cases, the responses of output, interest

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[5] σ^2 is chosen to reach an acceptance probability in the range between 20 and 40%.

rates and prices have the same sign in the euro area and in the US. Hence, the pure sign restriction approach is not capable to attribute a specific shock to one of the two countries. [6]

Our objective function χ sums up the share of domestic shocks in the forecast error variance decomposition (FEVD) for the domestic variables over the first five periods. The FEVD has four dimensions *(HxQxNxJ)*, where *H* denotes the number of forecasting periods to be considered (5), *Q* the number of domestic shocks to be identified (3), *N* the number of variables per country (3) and *J* the number of countries (2). We use the draw that maximizes our objective function as the point estimate.[7]

$$\chi = \sum_{j=1}^{J} \sum_{n=1}^{N} \sum_{q=1}^{Q} \sum_{h=1}^{H} FEVD_{qn}^{hj}$$

This objective function works efficiently in separating US from euro area shocks, but has the drawback that it maximizes the share of domestic shocks in total forecast variance decomposition per definition. Thus one has to interpret our point estimates as the maximum or upper limit for domestic shocks and as the minimum or lower limit for foreign shocks.

Results of the shock identification

We identify the shocks by taking 50,000 draws with the Metropolis-Hastings algorithm. The algorithm has found 1,322 (=2.7%) valid draws. We discard the first 20% as burn-in draws, resulting in 1,057 valid draws. Figure A1 shows the resulting chains for the parameter vector $\Theta = (\theta_1, \ldots, \theta_{15})$; figure A2 the corresponding densities[8]. We can interpret the variance of a rotation angle θ_i as the ability of our identification procedure to differentiate between the two shocks associated with θ_i [9]. To see this, let us consider the case where the variance of θ_i is large. In this case, a wide range of values of θ_i produces impulse responses that fulfil the sign restriction. Hence, the effects of the two shocks associated with θ_i cannot be separated precisely. The opposite holds for a small variance of θ_i.

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[6] One alternative would be to use the additional restriction that the size of the shock transmission to the other region must be significantly smaller than the original shock. Peersman (2005) uses this kind of approach to discriminate between *cost-push* shocks and oil shocks by assuming that an oil price shock has the "largest" contemporaneous effect on oil prices.

[7] Uhlig (2005) uses a similar approach, which he refers to as a "penalty function" approach

[8] One sees immediately that $Q(\theta_i) = Q(\theta_i + 2\pi)$. Hence the decomposition is not unique. In those cases, where the MCMC algorithm runs out of the range $(0 \ldots 2\pi)$, we have calculated $\theta_i = \theta_i \bmod 2\pi$. In cases, where the distribution fluctuates around the zero line $(\theta_1, \theta_8, \theta_{10}, \theta_{11}, \theta_{15})$, we have subtracted 2π to avoid the otherwise huge standard deviation.

[9] In order to get a better understanding of what rotating by an angle θ_i means, let us consider rotating θ_1 by $\pi/4$. So $\Theta = (\pi/4,0,0,0,0,0,0,0,0,0,0,0,0,0,0)$. In this case, the contemporaneous impact of the first shock (*cost-push* shock US) on the six variables $(GDP_{US}, CPI_{US}, R_{US}, GDP_{EA}, CPI_{EA}, R_{EA})$ changes (relative to the impact of the Cholesky decomposition) by $(-.10\ .28\ .03\ .00\ 0.08\ .01)$. The impact of the second shock (demand shock US) changes by $(.24\ -.67\ -.08\ .01\ -.19\ -.03)$. The main impact of this rotation is that the first shock has a stronger contemporaneous impact on US prices and a slightly weaker impact on US GDP. Shock two primarily has a more negative effect on US prices and a more positive impact on US GDP.

Within the US, we are able to separate the demand shock from the two other domestic shocks with the highest degree of precision (see table 3 and figure A2). The variance of the rotation angle between the US monetary policy shock and the US *cost-push* shock is considerably larger. Within the euro area, the variances are of a similar size as in the US with no noticeable differences across rotation angles. Concerning the differentiation of shocks across countries, we find a similar degree of precision as within countries. Only the euro area demand shock is more difficult to be disentangled from the US monetary policy shock and the US *cost-push* shock. Generally, the US demand shock can be distinguished with the highest precision from all other shocks.

Table 3: Variance of rotation angles

	US shocks				Euro area shocks				Average
	Cost push	Demand	Monetary	Average	Cost push	Demand	Monetary	Average	
Cost push US		0.08	0.21	0.15	0.09	0.14	0.09	0.11	0.12
Demand US	0.08		0.05	0.07	0.07	0.08	0.07	0.07	0.07
Monetary US	0.21	0.05		0.13	0.09	0.15	0.11	0.12	0.12
US-Average	0.15	0.07	0.13	0.11	0.08	0.12	0.09	0.10	0.11
Cost push EA	0.09	0.07	0.09	0.08		0.12	0.13	0.13	0.10
Demand EA	0.14	0.08	0.15	0.12	0.12		0.09	0.11	0.12
Monetary EA	0.09	0.07	0.11	0.09	0.13	0.09		0.11	0.10
EA-Average	0.11	0.07	0.12	0.10	0.13	0.11	0.11	0.11	0.11
Average	0.12	0.07	0.12	0.11	0.10	0.12	0.10	0.11	0.10

Source: The authors' own calculations.

4. Responses to structural shocks

The forecast error variance decomposition of US and euro area GDP gives us important insights into the driving forces of business cycle fluctuations (see table 4). First and foremost, the FEVD for both countries is strikingly similar. In the medium run, domestic shocks account for about 60% of business cycle fluctuations in both the US and the euro area[10]. International shocks explain 25% and spillovers from the other country the remaining 15% of the US (euro area) forecast error variance. These results confirm findings by Canova *et al.* (2004), Kose *et al.* (2003) and Perez *et al.* (2006), that about 1/3 of GDP fluctuations are explained by global factors. Moreover, Perez *et al.* (2006) show that in the recent past – similar to our results - about one fifth of output fluctuations in both countries can be attributed to spillovers from the other country. Second, in the short run the euro area seems to respond stronger to foreign shocks (global shocks and spillovers from the US) than the US. Third, the influence of domestic shocks is dominating but declining with the forecast horizon in both countries. Fourth, domestic *cost-push* shocks are the most important source of fluctuations in the medium run with a share of about 30%. The only noticeable difference between the US and the euro area concerns the importance of monetary policy shocks. For the US, we find that 11% of the forecast error variance are explained by

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[10] As pointed out in section 3, this result is (partly) a consequence of our identification approach, where we have maximized the share of domestic shocks in the forecast error variance decomposition. The point estimates have to be interpreted as upper limits for domestic shocks. Confidence bands can be found in section 5.

monetary policy shocks in the medium run. This is consistent with other empirical findings (Christiano *et al.*, 1999).[11] In the euro area, monetary policy shocks explain 16% of the variance after 20 quarters.

Table 4: Forecast error variance decomposition for US and euro area GDP

	US GDP										
	Global			US				EA			
	WT	HW	Sum	Cp	Dem	Mon	Sum	Cp	Dem	Mon	Sum
1 quarter	0.00	0.00	0.00	0.30	0.35	0.30	0.95	0.03	0.02	0.00	0.05
4 quarters	0.04	0.02	0.06	0.40	0.30	0.18	0.87	0.03	0.01	0.03	0.07
8 quarters	0.09	0.11	0.20	0.34	0.23	0.12	0.70	0.04	0.02	0.04	0.10
12 quarters	0.10	0.15	0.25	0.31	0.20	0.12	0.63	0.07	0.01	0.04	0.12
20 quarters	0.09	0.16	0.25	0.29	0.19	0.11	0.60	0.08	0.03	0.04	0.15

	Euro area GDP										
	Global			US				EA			
	WT	HW	Sum	Cp	Dem	Mon	Sum	Cp	Dem	Mon	Sum
1 quarter	0.06	0.03	0.09	0.05	0.00	0.09	0.14	0.33	0.22	0.22	0.77
4 quarters	0.04	0.05	0.09	0.04	0.01	0.05	0.09	0.43	0.14	0.25	0.82
8 quarters	0.04	0.06	0.10	0.03	0.04	0.05	0.12	0.39	0.17	0.22	0.78
12 quarters	0.04	0.13	0.16	0.05	0.05	0.04	0.13	0.33	0.19	0.18	0.70
20 quarters	0.04	0.20	0.23	0.05	0.04	0.04	0.13	0.30	0.18	0.16	0.63

WT: World trade, HW: HWWI index, Cp: Cost push shock, Dem: Demand shock, Mon: Monetary policy shock

WT: World trade, HW: HWWI index, Sup: *Cost-push* shock, Dem: Demand shock, Mon: Monetary policy shock
Source: The authors' own calculations.

Concerning prices (see table A1 in the appendix), direct spillovers form the US to the euro area and vice versa are small in the short run. While spillovers from the euro area to the US remain small in the medium run, spillovers form the US to the euro area become somewhat more important. At a horizon of 20 quarters, US shocks explain 17% of the CPI forecast error variance in the euro area while euro area shocks account for only 6% of US CPI. Global shocks play a very important role in explaining inflation innovations. They contribute between $^1/_3$ and ¼ to the variance at a horizon of one quarter and around ½ in the medium run. This result is in line with evidence from the literature. Ciccarelli and Mojon (2005) find that a common global factor is an important source of variability of inflation in 22 OECD countries. The impact of country-specific factors for inflation computed by Mumtaz and Surico (2007) is also comparable to our results. Any identification scheme that imposes zero restrictions on the contemporaneous impact would therefore lead to misleading results.

Finally, monetary policy shocks account for a considerable part of variations in the short-term interest rates only in the short run - especially in the euro area. However, this share declines with the forecast horizon to 8% in the US and 16% in the euro area. In the long run, the bulk of interest rate variance in the US is explained by demand shocks (see Evans

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[11] The fact that monetary policy shocks account only for a negligible part of output and inflation fluctuations does not imply that monetary policy itself has no effect. The systematic component of monetary policy may still have a significant effect on output and prices.

and Marshall, 1998 for a similar finding), while *cost-push* shocks are the dominating factor in the euro area.

5. Bootstrapped confidence intervals

Besides model uncertainty, there are two sources of uncertainty in constructing impulse responses from a VAR model: *estimation uncertainty* and *identification uncertainty*. Concerning *estimation uncertainty*, there are three widely used approaches in the literature, namely asymptotic expansion based on a delta method (Lütkepohl, 1990), Bayesian posterior distributions (Sims and Zha, 1999) and bootstrapping (MacKinnon, 2002). Peersman (2005, 2007) and Uhlig (2005) computed confidence bands for the sign restriction approach by using the Bayesian approach. They took a joint draw from the posterior for the usual unrestricted normal-Wishart posterior for the VAR parameters as well as from a uniform distribution for the rotation angles. They report median responses as well as lower and upper percentiles. *Identification uncertainty* is associated with the necessity to impose n^2 restrictions in a VAR model for identification purposes. $(N\cdot(n+1)/2)$ restrictions result from the orthogonality assumption of the structural shocks. As shown in section 2, the decomposition is by no means unique and the orthogonalization of the covariance matrix can be multiplied with any arbitrary orthonormal matrix. The sign restriction approach puts restrictions on the sign of the contemporaneous impulse responses but the magnitude and the shape of the responses in the consecutive periods are not predetermined. Hence, one may obtain many impulse responses that satisfy the restrictions derived from theory.

Our identification approach allows us to exploit the uncertainty associated with the identification of the shocks by utilizing the distributions of the rotation angles. We calculate *two types of confidence intervals* to account for these two types of uncertainties. First, confidence interval CI_{IU} accounts for the identification uncertainty only. CI_{IU} can easily be constructed by ordering the distribution of valid impulse responses $\Theta\left(\hat{\phi}_T \middle| \hat{B}\right)$ obtained during the identification of the structural shocks (see section 3) for each forecasting horizon and taking percentiles $CI_{IU} = \left[s_{\gamma/2}, s_{1-\gamma/2}\right]$, where $s_{\gamma/2}$ and $s_{1-\gamma/2}$ denote the 5% and 95% percentiles, respectively.

Accounting for both estimation and identification uncertainty gives us the confidence intervals CI_{EIU}. We use an adapted version of the bootstrap algorithm outlined in Benkwitz, Lütkepohl and Wolters (2001) to construct intervals CI_{EIU}.[12] It consists of the following steps:

Step 1: Estimate the VAR model and obtain residuals ε_t.

Step 2.1: Generate bootstrap residuals $\tilde{\varepsilon}_t$ by drawing randomly from ε_t with replacement.

Step 2.2: Use $\tilde{\varepsilon}_t$ to construct bootstrap time series $\tilde{x}_t = B(L)\tilde{x}_t + \tilde{\varepsilon}_t$.

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[12] We suspect that the bootstrap algorithm used in this paper to account for parameter uncertainty leads to very similar conclusions as the Bayesian approach used in Peersman (2005, 2007) and Uhlig (2005). It would be interesting to check this more carefully, but this beyond the scope of the paper.

Step 2.3: Re-estimate $\tilde{B}(L)$ from $\tilde{x}_t$.

Step 2.4: Identify the structural shocks using the Metropolis-Hastings algorithm presented in section 3 until 1,250 valid impulse responses are found. Discard the first 20% as burn-in draws. Keep the remaining 1,000 impulse responses. The valid impulse responses are denoted by $\Theta_{EIU}\left(\hat{\phi}_T \middle| \hat{B}\right)$.

Step 3: Sort $\Theta_{EIU}\left(\hat{\phi}_T \middle| \hat{B}\right)$ to construct $CI_{EIU} = \left[s_{\gamma/2}^{EIU}, s_{1-\gamma/2}^{EIU}\right]$, where $s_{\gamma/2}$ and $s_{1-\gamma/2}$ denote the 5% and 95% percentiles of the impulse responses, respectively.

The results are presented in figure 1. The bold solid line gives us the point estimate obtained by the identification scheme based on the point estimates of the VAR parameters. Remember that we only have restricted the reaction of domestic variables. Foreign variables are free to react. We see that a positive demand shock causes an initial positive reaction in the foreign country. Spillovers to the euro area are stronger than to the US. For *cost-push* shocks the evidence is more mixed. A positive US *cost-push* shocks leads to a small initial contraction of euro area GDP growth, which is reversed after one year, whilst US GDP growth initially increases after a positive euro area *cost-push* shock and decreases in the medium run. An expansive monetary shock in the US leads to a positive growth impulse in the euro area in the short run that fades out quickly. These results conflict with findings in Neri and Nobili (2006) and Pesaran *et al.* (2001), who find a reverse propagation pattern. Finally, an expansive monetary shock in the euro area leads to a small positive reaction in the US.

When we look at the confidence intervals for the impulse responses, three interesting insights arise. *First*, the bands are asymmetric. This is caused by the fact that the point estimate is the draw with the highest value of the objective function, which needs not be in the centre of all draws that fulfil the theoretical sign restrictions. Note that the confidence bands for identification uncertainty ($\mathrm{CI}_{\mathrm{IU}}$) by construction always fulfil the imposed restrictions, i.e. the reaction of GDP in the country in which the shock origins has to go up in the first periods (beside the reaction of the other domestic variables).

Second, IU and EIU bands look very similar. One might expect EIU to lie outside IU, but this is not necessarily the case since the different valid draws for the point estimate of the VAR parameters (IU) already explored a large part of the space of valid impulse responses. Adding estimation uncertainty does not necessarily lead to wider bands, since imposing the theoretical restrictions prevents the impulse responses to move out of the valid space[13]. Hence, theory prevents the band from becoming larger.

Third, we find that responses to domestic shocks are typically significant within each country while the transmission of shocks between countries is generally not significant with one notable exception. US demand shock causes a significant increase of euro area GDP after one year (when considering identification uncertainty only). Spillovers from all other shocks are subject to considerable uncertainty.

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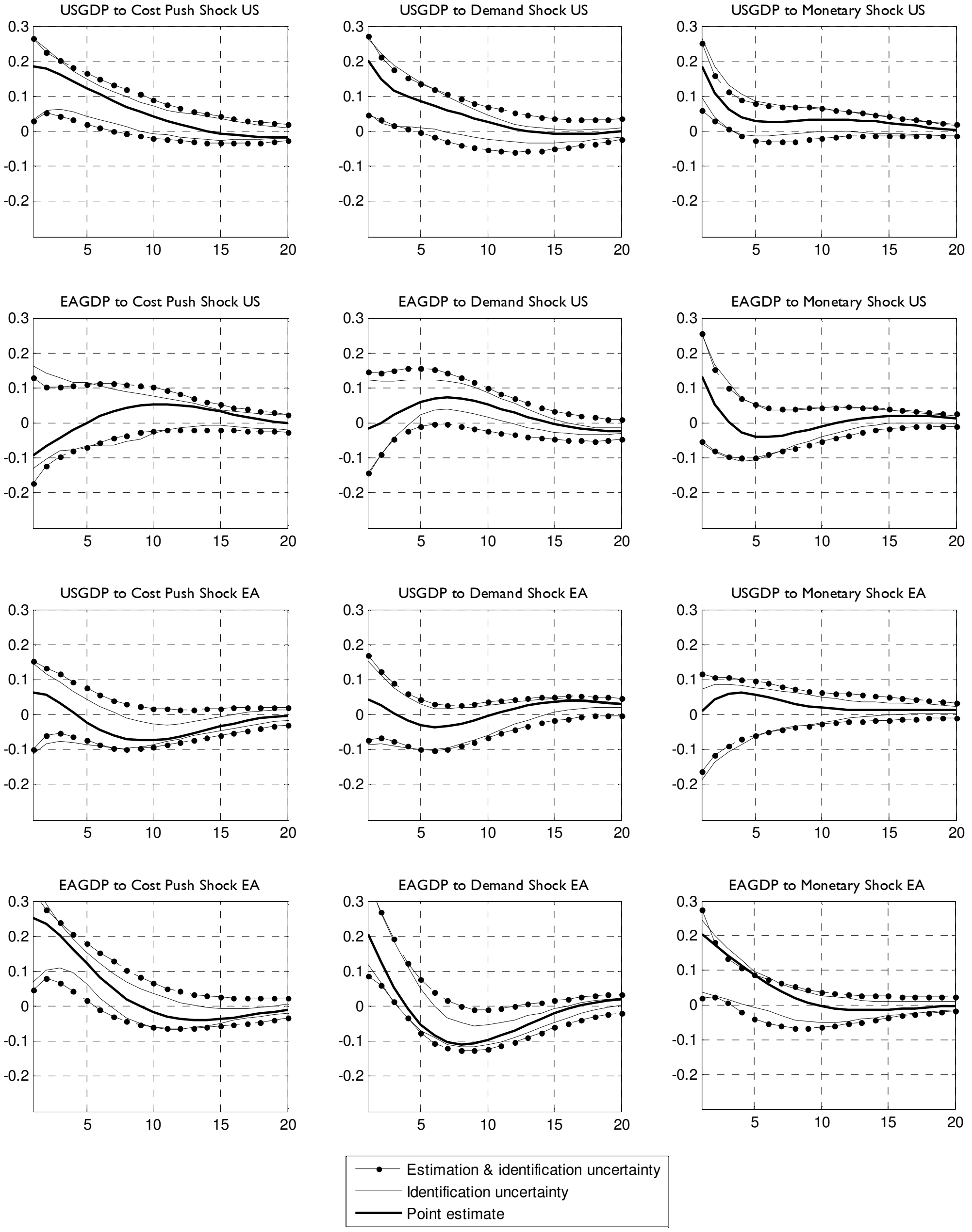
[13] Note that for few bootstrap draws one or more restrictions had to be relaxed in order to find valid rotations.

Figure 1: Confidence intervals for the effects of US and euro area shocks on GDP



Looking at the confidence bands for the forecast error variance decomposition of US and euro area GDP (figure A4), we can obtain an additional important insight. Both the point estimate and the upper bands are higher for domestic shocks than for shocks originating from the other country. This is an obvious consequence of our identification approach, which aims to maximize the impact of domestic shocks in the FEVD. When looking at the lower bounds, we see that they are close to zero. Whilst it seems plausible that foreign shocks might have (almost) zero contributions to domestic variables, zero contributions of domestic variables are o not look very reasonable. This results might be due to the failure of the identification procedure to assign the shocks properly to the countries. In the case of positive spillovers, domestic shocks may falsely be attributed to the foreign country. This shows that the sign restriction approach alone is not able to assign shocks to countries and highlights the importance of the objective function for a proper identification.

6. Summary and conclusions

This paper analyses business cycle linkages between the US and the euro area. Based on a modified version of the sign restriction approach on impulse responses proposed by Canova (2005), we simultaneously identify global and country specific shocks and investigate the transmission of country specific shocks in both directions. Our findings show that forecast error variance decompositions of GDP for the euro area and the US have a very similar pattern. In the short run, the variance of output fluctuations is mainly caused by domestic shocks. In the medium run, the influence of global shocks and – albeit to a lesser extent – of spillovers increases. Nevertheless, domestic shocks still explain about 60% of fluctuations. Since we have maximized this share by the choice of our objective function, this has to be interpreted as an upper limit. Direct spillovers between both countries remain rather limited and account for not more than 15%, while global shocks account for 25% of the forecast error variance.

Our identification procedure allows us to obtain a distribution for each rotation angle, i.e. for each pair of shocks. We can interpret the variance of these distributions as a measure of the relative precision with which the effects of two shocks can be distinguished. Our findings suggest that on average US demand shocks can be separated most accurately from other country specific shocks in both the US and the euro area. Finally, we construct confidence bands that account both for estimation and identification uncertainty. We find that responses to domestic shocks are typically significant within each country. Concerning the propagation of shocks across countries, only spillovers from US demand shocks to the euro area are significant.

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Appendix

Table A1: Detailed results for the forecast error variance decomposition

US GDP

	Global			US				EA			
	WT	HW	Sum	Cp	Dem	Mon	Sum	Cp	Dem	Mon	Sum
1 quarter	0.00	0.00	0.00	0.30	0.35	0.30	0.95	0.03	0.02	0.00	0.05
4 quarters	0.04	0.02	0.06	0.40	0.30	0.18	0.87	0.03	0.01	0.03	0.07
8 quarters	0.09	0.11	0.20	0.34	0.23	0.12	0.70	0.04	0.02	0.04	0.10
12 quarters	0.10	0.15	0.25	0.31	0.20	0.12	0.63	0.07	0.01	0.04	0.12
20 quarters	0.09	0.16	0.25	0.29	0.19	0.11	0.60	0.08	0.03	0.04	0.15

Euro area GDP

	Global			US				EA			
	WT	HW	Sum	Cp	Dem	Mon	Sum	Cp	Dem	Mon	Sum
1 quarter	0.06	0.03	0.09	0.05	0.00	0.09	0.14	0.33	0.22	0.22	0.77
4 quarters	0.04	0.05	0.09	0.04	0.01	0.05	0.09	0.43	0.14	0.25	0.82
8 quarters	0.04	0.06	0.10	0.03	0.04	0.05	0.12	0.39	0.17	0.22	0.78
12 quarters	0.04	0.13	0.16	0.05	0.05	0.04	0.13	0.33	0.19	0.18	0.70
20 quarters	0.04	0.20	0.23	0.05	0.04	0.04	0.13	0.30	0.18	0.16	0.63

US Consumer price index

	Global			US				EA			
	WT	HW	Sum	Cp	Dem	Mon	Sum	Cp	Dem	Mon	Sum
1 quarter	0.08	0.25	0.33	0.35	0.17	0.12	0.63	0.03	0.00	0.00	0.04
4 quarters	0.12	0.42	0.55	0.24	0.13	0.07	0.43	0.02	0.00	0.00	0.02
8 quarters	0.12	0.47	0.59	0.19	0.13	0.05	0.37	0.03	0.01	0.00	0.04
12 quarters	0.12	0.45	0.57	0.19	0.14	0.05	0.38	0.03	0.02	0.00	0.05
20 quarters	0.11	0.45	0.57	0.18	0.14	0.05	0.37	0.03	0.03	0.00	0.06

Euro area Consumer price index

	Global			US				EA			
	WT	HW	Sum	Cp	Dem	Mon	Sum	Cp	Dem	Mon	Sum
1 quarter	0.01	0.21	0.23	0.01	0.04	0.00	0.05	0.35	0.33	0.04	0.72
4 quarters	0.02	0.33	0.35	0.04	0.06	0.00	0.09	0.24	0.27	0.04	0.56
8 quarters	0.01	0.45	0.46	0.05	0.07	0.00	0.12	0.16	0.21	0.04	0.42
12 quarters	0.01	0.49	0.50	0.04	0.10	0.00	0.14	0.13	0.18	0.04	0.36
20 quarters	0.01	0.48	0.49	0.04	0.13	0.00	0.17	0.13	0.16	0.04	0.34

US short term interest rate

	Global			US				EA			
	WT	HW	Sum	Cp	Dem	Mon	Sum	Cp	Dem	Mon	Sum
1 quarter	0.06	0.06	0.13	0.00	0.52	0.21	0.74	0.06	0.06	0.02	0.14
4 quarters	0.08	0.05	0.13	0.01	0.63	0.17	0.81	0.02	0.03	0.01	0.06
8 quarters	0.09	0.06	0.15	0.03	0.60	0.11	0.73	0.05	0.06	0.01	0.12
12 quarters	0.11	0.11	0.21	0.04	0.51	0.08	0.63	0.10	0.06	0.00	0.16
20 quarters	0.14	0.11	0.25	0.03	0.45	0.08	0.56	0.12	0.06	0.01	0.19

Euro area short term interest rate

	Global			US				EA			
	WT	HW	Sum	Cp	Dem	Mon	Sum	Cp	Dem	Mon	Sum
1 quarter	0.08	0.03	0.11	0.00	0.01	0.00	0.01	0.02	0.38	0.47	0.88
4 quarters	0.04	0.05	0.09	0.04	0.01	0.05	0.09	0.43	0.14	0.25	0.82
8 quarters	0.04	0.06	0.10	0.03	0.04	0.05	0.12	0.39	0.17	0.22	0.78
12 quarters	0.04	0.13	0.16	0.05	0.05	0.04	0.13	0.33	0.19	0.18	0.70
20 quarters	0.04	0.20	0.23	0.05	0.04	0.04	0.13	0.30	0.18	0.16	0.63

WT: World trade, HW: HWWI index, Cp: cost push shock, Dem: Demand shock, Mon: Monetary policy shock

Figure A1: Chains of the Metropolis-Hastings algorithm

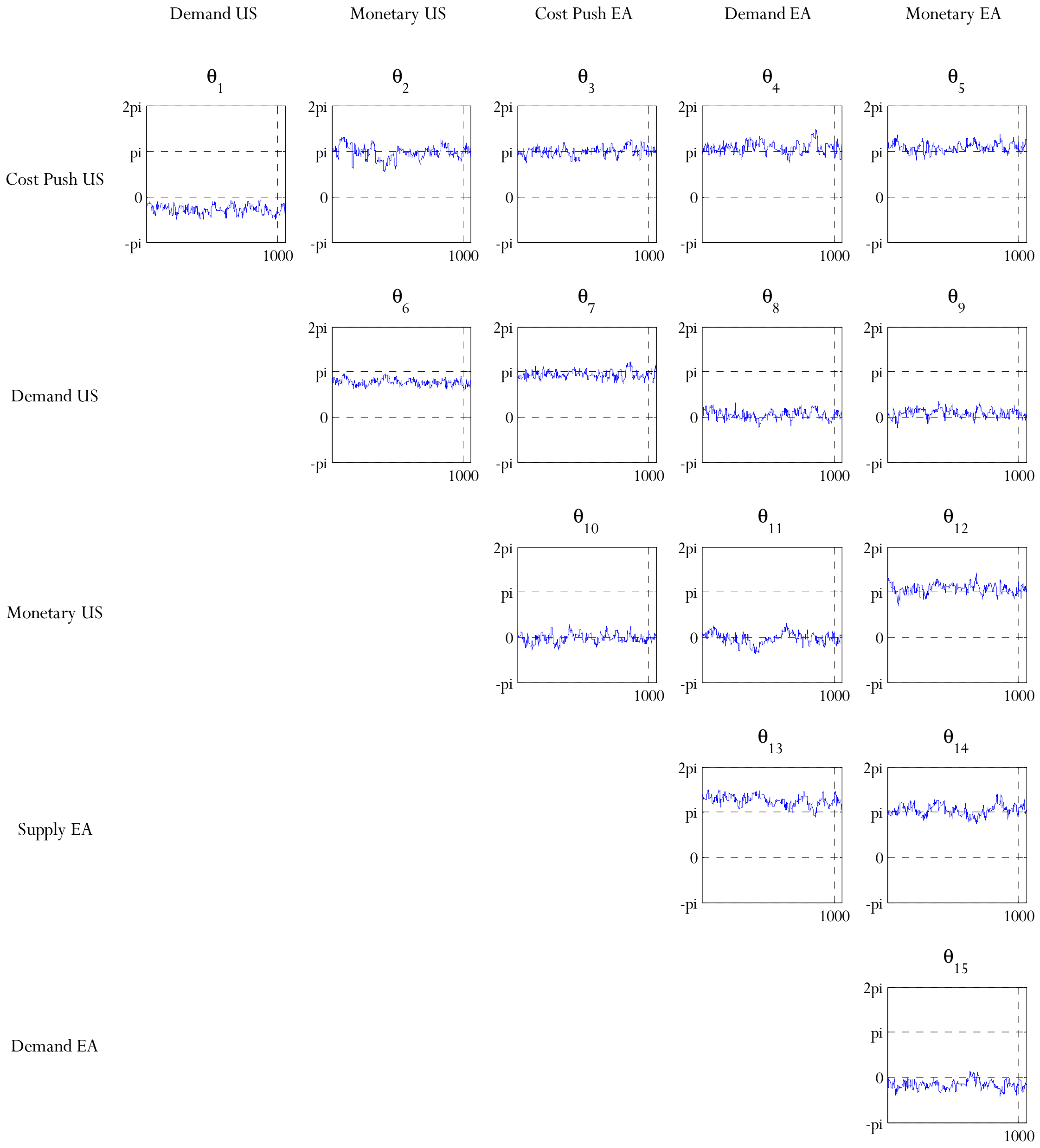


Figure A2: Densities of the rotation angles

Figure A3: Confidence bands for the forecast error variance decomposition for US GDP

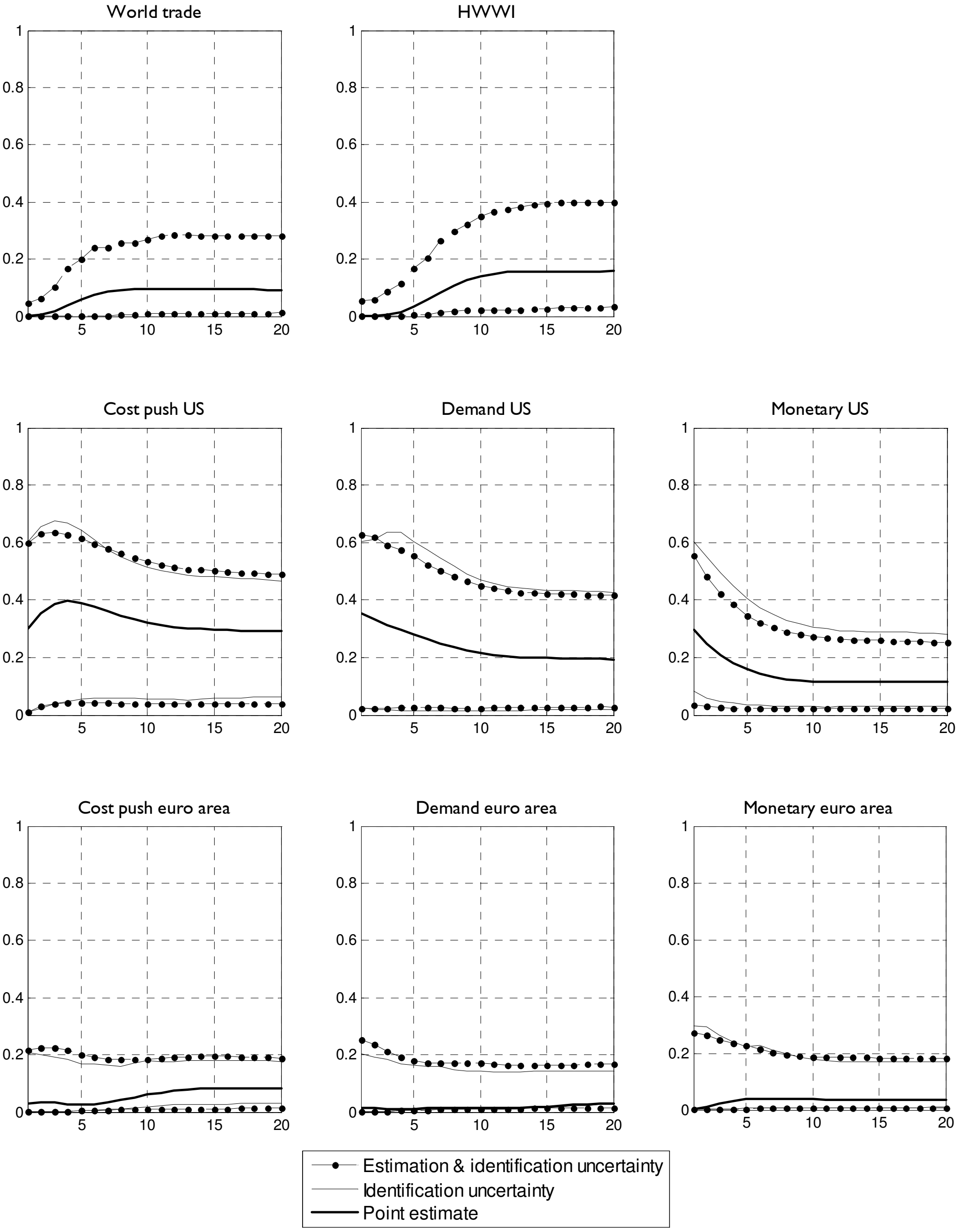
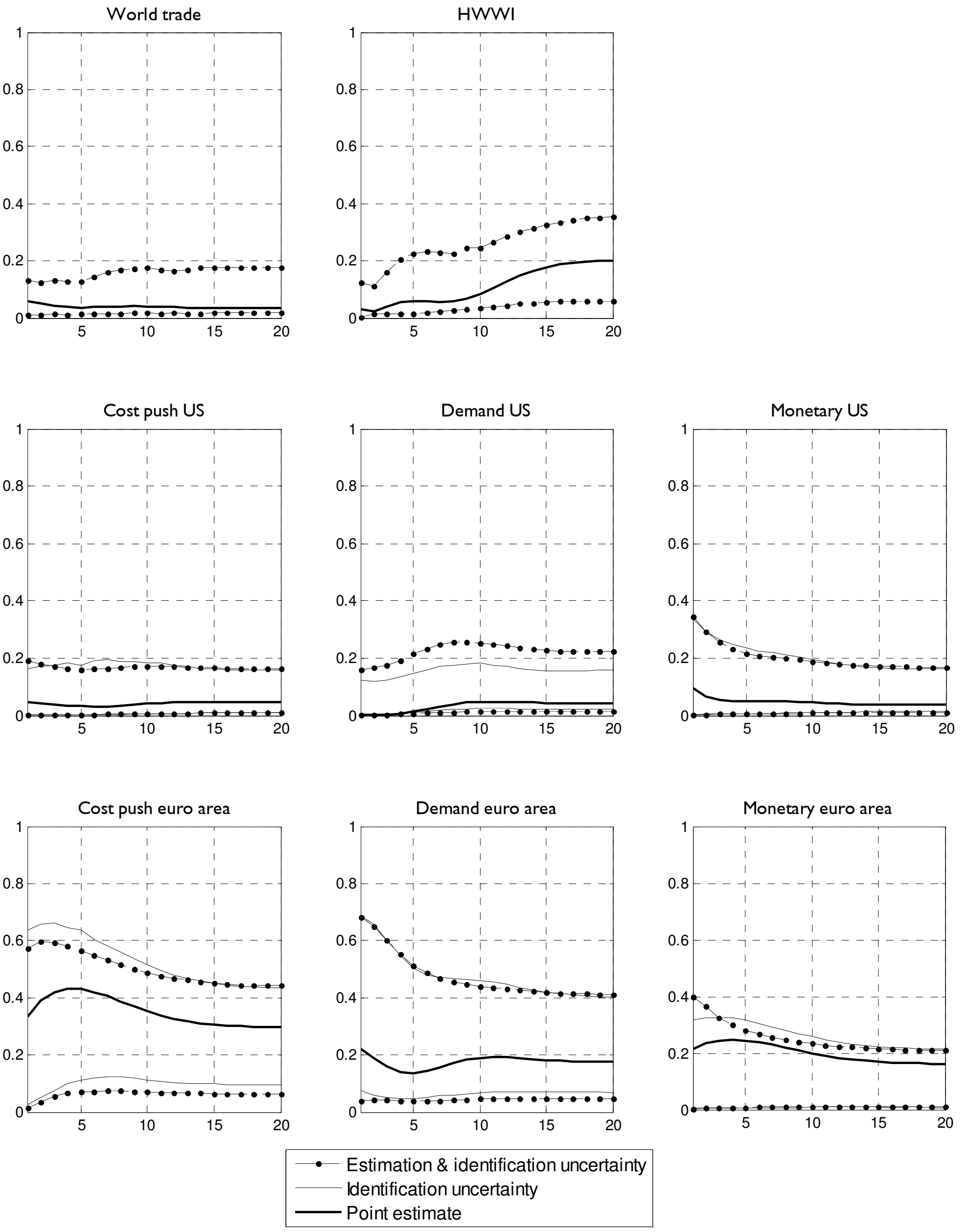


Figure A4: Confidence bands for the forecast error variance decomposition for euro area GDP



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