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The High Cross-Country Correlations of Prices and Interest Rates*

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Abstract

We document that, at business cycle frequencies, fluctuations in nominal variables, such as aggregate price levels and nominal interest rates, are substantially more synchronized across countries than fluctuations in real output. To the extent that domestic nominal variables are determined by domestic monetary policy, and central banks generally attempt to keep the domestic nominal environment stable, this might seem surprising. We ask if a parsimonious international business cycle model can account for this aspect of cross-country aggregate fluctuations. It can. Due to spillovers of technology shocks across countries, expected future responses of national central banks to fluctuations in domestic output and inflation generate movements in current prices and interest rates that are synchronized across countries even when output is not. Even modest spillovers produce cross-country correlations such as those in the data.

JEL Classification Codes: E31, E32, E43, F42.

Keywords: International business cycles, prices, interest rates.

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1 Introduction

We document cross-country movements at business cycle frequencies in two key nominal variables, the aggregate price level and the short-term nominal interest rate, and compare them with cross-country movements in output. We find that the fluctuations in the two nominal variables are substantially more synchronized across countries than the fluctuations in output. We ask if a dynamic general equilibrium model can account for this empirical regularity.

Our observation is based on a sample of the largest industrial economies.¹ Using business cycle components² of aggregate price levels, short-term nominal interest rates, and real GDP obtained with a band-pass filter, we find that the fluctuations in the three variables are similar in terms of their volatility and persistence, but markedly different in terms of their cross-country comovements. In particular, the cross-country correlations of prices and nominal interest rates are substantially higher than those of output: For the period 1960.Q1–2006.Q4 the average (across country pairs) bilateral correlation of price levels is 0.52, that of short-term nominal interest rates 0.57, while that of real GDP is only 0.25. Moreover, the bilateral correlations of the two nominal variables vary substantially less across country pairs than those of real GDP. This empirical regularity is broadly robust to the inclusion of other economies as the required data become available, the exclusion of the Bretton Woods years, and to splitting the sample into two subsamples in 1984, the year generally associated with the start of the so-called “Great Moderation” – a period of low macroeconomic volatility, and low and stable inflation.

Our empirical work is related to a literature studying the degree of comovement of macroeconomic variables across countries. It has been well documented that real economic activity tends to move together across industrialized economies over the business cycle (Backus, Kehoe and Kydland, 1992; Kose, Otrok and Whiteman, 2003). Recently, however, economists, as well as policy makers, became interested in the cross-country co-

¹In particular, Australia, Canada, Germany, Japan, the United Kingdom, and the United States for the period 1960.Q1–2006.Q4. In addition, from 1970.Q1 our sample includes also Austria and France.

²Medium-term fluctuations in the data with periodicity of approximately 8 to 32 quarters.

movement of inflation (Besley, 2008; Ciccarelli and Mojon, 2005; Mumtaz and Surico, 2008; Wang and Wen, 2007). An empirical contribution of this paper lies in documenting, in a unified way, comovements across countries of *cyclical* fluctuations in both output and prices, as well as in a short-term nominal interest rate.³

To the extent that at business cycle frequencies domestic nominal variables are largely determined by domestic monetary policy, and central banks generally attempt to keep the domestic nominal environment stable, our empirical finding might seem surprising. Although we would expect some positive cross-country correlations of prices and nominal interest rates, due to, for instance, the cross-country comovement of output, it is not obvious why variables that individual central banks are more likely to be able to control at these frequencies co-move more strongly across countries than real economic activity. We view this empirical regularity as a key aspect of international aggregate fluctuations and believe that accounting for it can provide valuable insights into how nominal variables are determined in an international environment – an issue that has recently received a lot of attention from policy makers.⁴

For a part of our sample period – the Bretton Woods years – national monetary policies were, to some extent, constrained by governments’ obligations to maintain fixed exchange rates with the dollar. It is well known that under fixed exchange rates, the domestic economy is not insulated from nominal shocks that occur abroad.⁵ As controlling for the Bretton Woods period does not affect our empirical finding, however, and our sample is not biased towards countries participating in the European Monetary System (EMS), it seems that there are other reasons for the strong cross-country comovements of the two nominal variables than past exchange-rate arrangements.

A large literature argues that monetary policy of major central banks is reasonably well

³Wang and Wen (2007) compare cross-country comovements of inflation rates with cross-country comovements of cyclical fluctuations in output. They find that inflation rates are more strongly correlated across countries than cyclical fluctuations in output. In contrast, we focus on cyclical fluctuations in both output and prices.

⁴See, for example, Bean (2006), Bernanke (2007), Mishkin (2007), and Sentance (2008).

⁵Some researchers (e.g., Eichengreen, 1996), however, argue that during this period central banks were able to retain a significant degree of monetary autonomy by imposing various capital controls, and thus were able to control the domestic nominal environment.

approximated by the so-called ‘Taylor rule’ – a parsimonious feedback rule whereby the central bank sets the short-term nominal interest rate in response to movements in domestic output and changes in the domestic price level.⁶ The high cross-country correlations of short-term nominal interest rates can thus potentially be accounted for by the high cross-country correlations of prices. But in equilibrium, prices and nominal interest rates are jointly determined. How, then, do responses of national central banks to domestic economic conditions lead to substantially stronger cross-country comovements of the two nominal variables than of output?

In the second part of the paper, we provide a quantitative-theoretical account of our empirical finding. As a first step it is natural to ask if a parsimonious international business cycle model, such as the two-good two-country model of Backus, Kehoe and Kydland (1994), can help us understand this feature of international business cycles. In order to make the model suitable for our question, we augment it by including nominal assets in the households’ budget constraints and in each country a central bank which, in line with the above literature, follows a Taylor rule. We find that, to a large extent, the model does account for our empirical finding. When calibrated to be consistent with long-run features of the data and standard values of the Taylor rule, the model produces a slightly lower cross-country correlation of output and slightly higher cross-country correlations of the two nominal variables than the averages of those observed in the data.

In order to highlight the mechanism behind this result, we show that in a recursive equilibrium the absence of arbitrage between real and nominal assets, together with a Taylor rule, implies that the current price level and nominal interest rate depend on expected future output and real returns to capital. Due to spillovers of technology shocks across countries, a persistent domestic technology shock affects future productivity in the foreign economy, in addition to current and future productivity in the domestic economy. Thus, although *current* output (determined in large part by the current level of technology) in the

⁶See, among others, Taylor (1993) and Clarida, Galí and Gertler (2000) for the United States, Clarida, Galí and Gertler (1998) for most of the G7 countries, and Nelson (2000) for the United Kingdom. Woodford (2003), chapter 1, provides a useful survey. Most studies estimate Taylor rules only for the post-1979 period, although some, for example Clarida et al. (2000), Orphanides (2002), and Taylor (1999), provide estimates also for the 1960s and 1970s.

two economies may be different, *future* output and returns to capital in the two economies are expected to be similar, leading to similar responses of *current* prices and nominal interest rates. Thus, according to the model, fluctuations in nominal variables will be highly synchronized across countries even when national central banks focus squarely on stabilizing domestic output and prices.

We find that even a modest degree of spillovers, in the range of some of the smaller estimates found in the literature, produces correlations such as those in the data. The result is robust also to a broad range of parameter values of the Taylor rule, as well as to a simple extension that allows the model to be consistent with the observed dynamics of domestic prices and interest rates in relation to domestic output. Interestingly, the result survives when monetary policy reduces the volatility of the two nominal variables well below their average volatility in the postwar period. This is consistent with our empirical finding that the ‘international nominal cycle’ is substantially more synchronized across countries than the ‘international real cycle’ even in the Great Moderation period.

The outline of the rest of the paper is as follows. Section 2 documents the empirical regularity, Section 3 introduces the model, Section 4 describes its calibration, Section 5 presents findings for a benchmark experiment, Section 6 conducts sensitivity analysis, and Section 7 concludes. An appendix describes the data sources.

2 Properties of nominal business cycles

Our empirical analysis is based on quarterly data series for real GDP, price levels measured by the consumer price index, and short-term nominal interest rates, usually yields on 3-month government bills, for Australia, Canada, Germany, Japan, the United Kingdom, and the United States, for the period 1960.Q1-2006.Q4. In addition, we include Austria and France from 1970.Q1. For other developed economies, the required data are available only from either late 1970s or early 1980s. However, we prefer to trade off the number of countries for series that include both the relatively stable 1960s, as well as the volatile 1970s. Furthermore, most of the economies for which the data are available from either late

1970s or early 1980s are European economies that participated in the EMS. Including those countries into our sample would therefore make the sample biased towards economies that operated under a fixed-exchange-rate regime for a substantial period of time.

All statistics discussed in this section are for business cycle components of the three variables of interest obtained with the Christiano and Fitzgerald (2003) band-pass filter. Before applying this filter, the series for real GDP and price levels were transformed by taking logs. Their fluctuations can thus be expressed as percentage deviations from trend.

2.1 International nominal business cycles

In order to provide a general sense of the different degrees of synchronization of the international real and nominal business cycles, Figure 1 plots percentage deviations from trend of real GDP and price levels for the countries in our sample. We see from this figure that although the fluctuations in both variables tend to co-move across countries, the fluctuations in prices are more synchronized than those in real GDP.

The stronger cross-country comovement of prices, as well as nominal interest rates, relative to that of output, becomes clearly apparent once we calculate the bilateral cross-country correlations for these two nominal variables (i.e., the correlations of a country's variable with the same variable of each of the other countries) and compare them with those for real GDP. These correlations are contained in Tables 1-3, for the six-country sample going back to 1960.Q1, and in Tables 4-6 for the eight-country sample, which goes back to 1970.Q1.

In the six-country sample, the mean (in the cross-section) bilateral correlations of the nominal interest rate and the price level are 0.57 and 0.52, respectively – about twice the mean bilateral correlation of real GDP, which is 0.27. In addition, the bilateral correlations of the two nominal variables are substantially less dispersed in the cross-section than those of real GDP. The coefficient of variation (i.e., the standard deviation divided by the mean) of the bilateral correlations of the nominal interest rate and the price level are 0.22 and 0.28, respectively, while that of the bilateral correlations of real GDP is 0.89. These findings hold broadly also in the eight-country sample, where the mean bilateral correlations of the

nominal interest rate and the price level are both 0.59, while that of real GDP is only 0.43 (the coefficients of variation are around 0.2 for the two nominal variables, and slightly above 0.5 for real GDP).

Even though the two nominal variables differ markedly from output in terms of their cross-country comovements, they are comparably volatile and persistent. For example, the mean standard deviation of output in the sample of the six countries is 1.39, while the mean standard deviation of the price level is 1.28 and that of the nominal interest rate is 1.31⁷; and the mean first-order autocorrelation coefficient of output is 0.92, while that of the price level is 0.94 and that of the nominal interest rate is 0.91.

Figure 2 provides an additional representation of the stronger cross-country comovement of the two nominal variables, relative to that of output. It plots the bilateral correlations of the price level and the nominal interest rate against the bilateral correlations of output for the eight-country sample. As we can see, most of the points lie above the 45-degree line, meaning that for most country pairs, the bilateral correlations of the two nominal variables are higher than those of real GDP.

In order to check that the high cross-country correlations of prices and nominal interest rates are not driven by a strong comovement only in the period during which the countries in our sample operated under the Bretton Woods agreement, we report in Tables 1-6 also the mean bilateral correlations and coefficients of variation for the period 1974.Q1-2006.Q4, which excludes the Bretton Woods years. As we can see, for all three variables the two summary statistics are little affected by excluding the Bretton Woods period from our sample.

Besides fixed exchange rates, ‘global’ commodity price shocks could be another source of the strong cross-country comovements of prices and nominal interest rates observed in the data. Visual inspection of Figure 1, however, shows a striking comovement of the price levels in all postwar business cycles, not just the two cycles commonly associated with the oil price shocks of 1973 and 1979 – the two largest commodity price shocks in the post-war period. In order to check this more formally, we split the sample into two subsamples in

⁷The standard deviation of the nominal interest rate is for fluctuations measured in percentage points.

1984, the year broadly associated with the start of the Great Moderation. During this period of relative output and inflation stability, the world economy did not experience large commodity price shocks, such as those of the 1970s. We find that although the mean cross-country correlations of all three variables declined after 1984, those of the two nominal variables are still substantially higher than that of output (see Tables 1-6). For example, in the eight-country sample, the post-1984 mean bilateral correlation of the nominal interest rate is 0.46, that of the price levels is 0.45, while that of real GDP is only 0.19.

2.2 Domestic nominal business cycles

Kydland and Prescott (1990) have pointed out that a key characteristic of the nominal side of the U.S. business cycle is the countercyclical behavior of prices – i.e. the aggregate price level is negatively correlated with output over the business cycle. We find that this characteristic of the cyclical behavior of prices is not specific to the U.S. economy. Figure 3 plots the correlation of a country’s price level in period $t + j$ with its output in period t , for $j \in \{-5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5\}$. We see that for all economies in our sample, the contemporaneous correlation (i.e., that for $j = 0$) is negative. Notice also that the price level in all eight economies exhibits a phase shift in the direction of negatively leading the cycle; i.e., the price level is more negatively correlated with future output than with current output.⁸

In Figure 4 we extend this analysis to the nominal interest rate. We see that the nominal interest rate in general is somewhat positively correlated with output contemporaneously, but is strongly negatively correlated with future output, and positively correlated with past output. Although this dynamics of the nominal interest rate is well known for the U.S. economy (e.g., King and Watson, 1996), as in the case of the price level, it is striking that we observe the same empirical regularity also in other developed economies. In Subsection 6.3 we investigate, therefore, if the parsimonious international business cycle model can be

⁸Wang and Wen (2007) find that the lead-lag pattern of actual inflation rates, as opposed to cyclical components of fluctuations in prices, with output is also very similar across countries. Galí and Gertler (1999) were among first to point out a systematic lead-lag pattern between output and inflation. In addition, den Haan and Sumner (2004), using VAR analysis, find a similar dynamics of prices across G7 countries.

consistent with both, the high cross-country correlations of prices and nominal interest rates, as well as with the observed lead-lag patterns of these variables with respect to domestic output.

3 The model economy

A world economy consists of two countries, denoted 1 and 2, which are populated by equal measures of identical, infinitely lived consumers. Producers in each country use country-specific capital and labor to produce a single good, which we refer to as a “local” good. Production in each country is subject to technology shocks, which affect the productivity of capital and labor. These shocks are the only sources of uncertainty in the world economy. The good produced in country 1 is labelled by a , while that produced in country 2 is labelled by b . These are the only traded goods in the world economy. Within each country, goods a and b are combined to form a good that can be used for local consumption and investment, and which we refer to as an “expenditure” good. In order to purchase the expenditure good for consumption purposes, consumers have to incur a time cost, which depends positively on the amount of purchases made and negatively on the amount of real money balances held. In addition to domestic money balances, consumers in each country can accumulate capital, an internationally traded bond, and a domestically traded bond, whose nominal rate of return is controlled by a domestic central bank.

3.1 Preferences

Preferences of the representative consumer in country i are characterized by the utility function

$$E_0 \sum_{t=0}^{\infty} \beta^t U(c_{it}, 1 - n_{it} - s_{it}), \quad (1)$$

where $U(c, 1 - n - s) = [c^\mu (1 - n - s)^{1-\mu}]^{1-\gamma} / (1 - \gamma)$, with $0 < \mu < 1$ and $\gamma \geq 0$, and where c_{it} is consumption, n_{it} is time spent working, and s_{it} is time spent in transaction-

related activities. This “shopping time” is given by the following parametric representation

$$s_{it} = \kappa_1 \left(\frac{p_{it} c_{it}}{m_{it}} \right)^{\kappa_2}, \quad (2)$$

where $\kappa_1 > 0$, $\kappa_2 \geq 1$, p_{it} is the domestic price level (i.e., the price of country i 's expenditure good in terms of country i 's money), and m_{it} is domestic money.

3.2 Technology

We describe the production side of the economy following the three approaches to measuring aggregate output: the product approach, the income approach, and the expenditure approach.

3.2.1 Product approach to output

Consumers supply labor and capital to domestically located, perfectly competitive producers, who have access to an aggregate Cobb-Douglas production function $z_{it}H(k_{it}, n_{it}) = z_{it}k_{it}^\alpha n_{it}^{1-\alpha} = y_{it}$. Here, z_{it} is a country-specific technology level, k_{it} is capital, y_{it} is output of the local good (either a or b), and $0 < \alpha < 1$ is the capital share in production. Technologies in the two countries follow a joint first-order autoregressive process

$$\lambda_{t+1} = A_0 + A\lambda_t + \varepsilon_{t+1}, \quad \varepsilon_{t+1} \sim N(0, \Sigma), \quad (3)$$

where $\lambda_t = [\ln z_{1t}, \ln z_{2t}]'$. Market clearing for goods a and b requires

$$a_{1t} + a_{2t} = y_{1t}, \quad (4)$$

$$b_{1t} + b_{2t} = y_{2t}, \quad (5)$$

where a_{1t} is the amount of good a used by country 1, while a_{2t} is the amount used by country 2. Similarly, b_{1t} is the amount of good b used by country 1, while b_{2t} is the amount used by country 2.

Consumption and investment are composites of foreign and domestic goods. The device

for aggregating domestic and foreign goods used here is the Armington (1969) aggregator $G(\cdot, \cdot)$

$$c_{1t} + x_{1t} = G(a_{1t}, b_{1t}), \quad (6)$$

$$c_{2t} + x_{2t} = G(b_{2t}, a_{2t}), \quad (7)$$

where x_{it} is investment, and $G(a, b) = (\omega_1 a^{-\rho} + \omega_2 b^{-\rho})^{-(1/\rho)}$, with $0 < \omega_1 < 1$, $\omega_2 = 1 - \omega_1$, and $\rho \geq -1$. Here, ω_1 determines the extent to which there is a home bias in domestic expenditures and ρ controls the elasticity of substitution between domestic and foreign goods. This aggregator is a standard feature of general equilibrium models of trade. Investment is used for capital accumulation according to the law of motion

$$k_{i,t+1} = (1 - \delta) k_{it} + x_{it}, \quad (8)$$

where $0 < \delta < 1$ is a depreciation rate.

The prices of goods a and b in terms of the expenditure good of country 1 are determined competitively, and therefore given by the marginal products of these two goods

$$q_{1t}^a = \frac{\partial G(a_{1t}, b_{1t})}{\partial a_{1t}}, \quad q_{1t}^b = \frac{\partial G(a_{1t}, b_{1t})}{\partial b_{1t}}. \quad (9)$$

Similarly, the prices of the two goods in terms of country 2's expenditure good are given by

$$q_{2t}^a = \frac{\partial G(b_{2t}, a_{2t})}{\partial a_{2t}}, \quad q_{2t}^b = \frac{\partial G(b_{2t}, a_{2t})}{\partial b_{2t}}. \quad (10)$$

Using these prices, we can measure output of the two countries in terms of their respective expenditure goods as $q_{1t}^a z_{1t} H(k_{1t}, n_{1t}) = q_{1t}^a y_{1t}$ and $q_{2t}^b z_{2t} H(k_{2t}, n_{2t}) = q_{2t}^b y_{2t}$. This is the definition of real GDP employed in our model. We thus use the following notation $GDP_{1t} \equiv q_{1t}^a y_{1t}$ and $GDP_{2t} \equiv q_{2t}^b y_{2t}$. As the prices of the two goods fluctuate much less than y_{it} , none of our quantitative results significantly changes if we instead define GDP as measured in terms of the local good.

We in turn define the terms of trade e as the price of good b in terms of good a

$$e_t \equiv q_{1t}^b/q_{1t}^a = q_{2t}^b/q_{2t}^a, \quad (11)$$

where the equality holds in equilibrium. The real exchange rate, in contrast, is defined as the price of the expenditure good of country 2 relative to the price of the expenditure good of country 1, i.e. q_{2t}^a/q_{1t}^a , which, by applying relationship (11), is equal to q_{2t}^b/q_{1t}^b .

3.2.2 Income approach to output

Consumers derive income from selling capital and labor services to the domestically located producers at competitively determined rental and wage rates. Aggregate income measured in terms of the local good is thus

$$r_{it}^k k_{it} + w_{it} n_{it} = \frac{\partial H}{\partial k_{it}} k_{it} + \frac{\partial H}{\partial n_{it}} n_{it} = y_{it}, \quad (12)$$

where r_{it}^k is the rental rate for capital and w_{it} is the wage rate. Here, the first equality follows by assuming perfect competition, while the second equality follows from the constant-returns-to-scale property of the production function. Measured in terms of the expenditure good, aggregate income of country 1 is

$$q_{1t}^a \frac{\partial H}{\partial k_{1t}} k_{1t} + q_{1t}^a \frac{\partial H}{\partial n_{1t}} n_{1t} = GDP_{1t}. \quad (13)$$

Aggregate income of country 2 is measured similarly, evaluating its output of good b at the price q_{2t}^b .

3.2.3 Expenditure approach to output

Total expenditures in each country are related to GDP as

$$c_{1t} + x_{1t} + \left(q_{1t}^a a_{2t} - q_{1t}^b b_{1t} \right) = GDP_{1t}, \quad (14)$$

$$c_{2t} + x_{2t} + \left(q_{2t}^b b_{1t} - q_{2t}^a a_{2t} \right) = GDP_{2t}, \quad (15)$$

where the expressions in the parentheses are net exports, denoted by nx_{1t} and nx_{2t} , respectively. These equalities follow from combining the resource constraints (6) and (7) with the goods-market-clearing conditions (4) and (5), and from using the constant-returns-to-scale property of the Armington aggregator, together with the pricing functions (9) and (10). Each resulting equality is then pre-multiplied by the price of the local goods to obtain equations (14) and (15).

3.3 Monetary policy

A central bank in each country controls the nominal rate of return R_{it} on a one-period domestically traded bond, which pays one unit of country i 's money in all states of the world in period $t + 1$. The central bank sets the rate of return according to a feedback rule

$$R_{it} = (1 - \phi) [R + \nu_y (\ln GDP_{it} - \ln GDP) + \nu_\pi (\pi_{it} - \pi)] + \phi R_{i,t-1}, \quad (16)$$

where $\pi_{it} \equiv \ln p_{it} - \ln p_{i,t-1}$ is the inflation rate, and a variable's symbol without a time subscript represents the variable's steady-state value. In line with the literature we also assume that the central bank "smooths" the nominal interest rate by putting a weight $0 < \phi < 1$ on the past interest rate. The central bank then supplies, through lump-sum transfers v_{it} to the consumers, whatever amount of money balances consumers demand at that nominal interest rate. The money stock in the economy thus evolves as

$$m_{it} = m_{i,t-1} + v_{it}. \quad (17)$$

We do not attempt to justify this monetary policy rule in terms of its welfare implications. We simply take it as an empirically plausible approximation of central banks' behavior in a number of industrialized countries, as suggested by the literature, and embed it into the international business cycle model.

3.4 Consumer's budget constraint and the balance of payments

Consumers hold money in order to economize on shopping time. In addition, they accumulate capital, a one-period internationally traded bond f_{it} , which pays one unit of good a in all states of the world in period $t + 1$, and the domestically traded bond, which we denote by d_{it} .⁹ Measured in terms of the domestic expenditure good, the consumer's budget constraint is

$$\frac{q_{it}^a f_{it}}{1 + r_t^f} + \frac{d_{it}}{p_{it}(1 + R_{it})} + \frac{m_{it}}{p_{it}} + c_{it} + x_{it} = q_{it}^\zeta (r_{it}^k k_{it} + w_{it} n_{it}) + q_{it}^a f_{i,t-1} + \frac{d_{i,t-1}}{p_{it}} + \frac{m_{i,t-1}}{p_{it}} + \frac{v_{it}}{p_{it}}, \quad (18)$$

where r_t^f is the real rate of return (in terms of good a) on the internationally traded bond, and q_{it}^ζ is equal to q_{1t}^a in the case of country 1, and to q_{2t}^b in the case of country 2.

The domestic nominal bond is in zero net supply. Therefore, in equilibrium, $d_{it} = 0$. Furthermore, substituting into the budget constraint v_{it} from equation (17), and using equations (12) and (13), we obtain economy i 's balance of payments constraint

$$\frac{q_{it}^a f_{it}}{1 + r_t^f} + c_{it} + x_{it} = q_{it}^\zeta z_{it} H(k_{it}, n_{it}) + q_{it}^a f_{i,t-1}. \quad (19)$$

Notice, that equation (19), together with (14) or (15), implies that $q_{it}^a f_{it}/(1 + r_t^f) - q_{it}^a f_{i,t-1} = nx_{it}$.

3.5 Recursive competitive equilibrium

In each country, the consumer chooses state-contingent plans for c_{it} , x_{it} , $k_{i,t+1}$, m_{it} , d_{it} , f_{it} , n_{it} , and s_{it} in order to maximize (1) subject to (2), (8), and (18), taking all prices as given. In all states of the world, the prices of capital and labor services, and of the two local goods a and b , are given by their respective marginal products. In period t the state of the world economy is defined by the vector of technology levels λ , a vector of domestic endogenous

⁹The denomination of the internationally traded bond has only second-order effects on equilibrium, which are not captured by our computational method. The denomination of the bond thus does not affect the computed equilibrium allocations and prices. We could also extend the model to allow consumers in country i to hold the nominal bond of country j , but this would only clutter the model without affecting the computed equilibrium – a nominal exchange rate would exist that would support the equilibrium of the current economy.

state variables $\Upsilon_i = (p_{i,t-1}, R_{i,t-1}, k_{it}, \vartheta_{i,t-1}, f_{i,t-1})$, and a vector of foreign state variables $\Upsilon_j = (p_{j,t-1}, R_{j,t-1}, k_{jt}, \vartheta_{j,t-1}, f_{j,t-1})$, where $\vartheta_{i,t-1} \equiv d_{i,t-1} + m_{i,t-1}$, and similarly for $\vartheta_{j,t-1}$.

The equilibrium of the world economy is then characterized by a set of pricing functions for each country $\{r_i^k(\lambda, \Upsilon_i, \Upsilon_j), w_i(\lambda, \Upsilon_i, \Upsilon_j), q_i^a(\lambda, \Upsilon_i, \Upsilon_j), q_i^b(\lambda, \Upsilon_i, \Upsilon_j), p_i(\lambda, \Upsilon_i, \Upsilon_j), R_i(\lambda, \Upsilon_i, \Upsilon_j)\}$, a set of aggregate decision rules for each country $\{n_i(\lambda, \Upsilon_i, \Upsilon_j), k_i(\lambda, \Upsilon_i, \Upsilon_j), m_i(\lambda, \Upsilon_i, \Upsilon_j), d_i(\lambda, \Upsilon_i, \Upsilon_j), f_i(\lambda, \Upsilon_i, \Upsilon_j)\}$, and a pricing function for the rate of return on the internationally traded bond $r^f(\lambda, \Upsilon_i, \Upsilon_j)$, such that the allocations and prices generated by these functions satisfy the consumer's optimization problem, the resource constraints (6) and (7), the goods-market-clearing conditions (4) and (5), a market-clearing condition for domestically traded bonds $d_{it} = 0$, a market-clearing condition for the internationally traded bond $f_1 + f_2 = 0$, and the monetary policy rule (16). Each country's balance of payments constraint (19) is then satisfied by Walras' Law.

Because the state space is large, we compute log-linear approximations to the equilibrium decision rules and pricing functions in the neighborhood of the model's non-stochastic steady-state. In particular, we use the linear-quadratic approximation method developed by Kydland (1989) (see also Hansen and Prescott, 1995). Before computing the equilibrium, all nominal variables are transformed so that they are stationary. Following Heathcote and Perri (2002) we also impose a tiny quadratic cost of adjusting holdings of the internationally traded bond in the consumer's optimization problem in order to ensure stationarity of international bond holdings.

4 Calibration

Table 7 summarizes the parameter values for our benchmark experiment. In Section 6 we study the sensitivity of our results to parameter values that are calibrated with considerable uncertainty. The calibration is largely based on empirical estimates of steady-state relations among the model's variables. To start, a period in the model is set equal to one quarter. As preferences and technology in our model are the same as those used by Backus et al. (1994), the parameters of the utility function, the production function, the Armington aggregator,

and of the stochastic process for technology shocks are either the same as in their paper, or are calibrated to the same targets.

In particular, we set the risk aversion parameter γ equal to 2, capital's share in production α equal to 0.36, and the elasticity of substitution between domestic and foreign goods $\sigma \equiv 1/(1 + \rho)$ equal to 1.5. The share of locally produced goods in the Armington aggregator ω_1 is set equal to 0.761, which implies that in a symmetric steady state (one characterized by $y_1 = y_2$, $b_1 = a_2$, and $e = 1$) the ratio of imports to output b_1/y_1 is equal to 0.15. The depreciation rate δ is set equal to 0.025. Given a share of investment in GDP equal to 0.25, this depreciation rate is consistent with a steady-state capital-output ratio of 10. The capital-output ratio and the depreciation rate then imply a discount factor β equal to 0.989. The weight on consumption in utility μ is determined by the first-order condition for labor input

$$\frac{U_c}{U_l} = \left(\frac{\mu}{1 - \mu} \right) \frac{1 - n - s}{c},$$

where c is equal to 0.75, n is equal to 0.3, and s is determined by the calibration of the shopping-time parameters described below. The weight on consumption implied by this condition is then 0.34. Finally, the diagonal elements of the transition matrix for technology shocks A are set equal to 0.906, the off-diagonal elements, which measure the degree of spillovers of technology shocks across countries, are set equal to 0.088, the standard deviations of the ε 's are set equal to 0.00852, and their correlation is set equal to 0.258. The values of A_0 are chosen so that output of the locally produced good is equal to 1 in steady state, which is a convenient normalization.

The parameters of the shopping time function (2) are chosen so that the money demand function in the model has the same interest rate elasticity and implies the same average velocity of money as its empirical counterpart estimated for the United States. The money demand function in the model is given implicitly by the consumer's first-order condition for money holdings. In steady state this optimality condition has the form

$$\kappa_1 \kappa_2 \left(\frac{pc}{m} \right)^{\kappa_2} \frac{p}{m} = \frac{1}{w} \left(\frac{R}{1 + R} \right). \quad (20)$$

Setting the curvature parameter κ_2 equal to 1, the money demand function has the form

$$\frac{m}{p} = \left[\kappa_1 c w \left(1 + \frac{1}{R} \right) \right]^{0.5}, \quad (21)$$

which has interest elasticity equal to -0.5 , in line with a number of empirical studies (see Lucas, 2000). We set the level parameter κ_1 equal to 0.0054, which implies annual velocity of money equal to 6.08 – the average U.S. annual velocity of M1 in the period 1959-2006.

The estimates of the parameters of the monetary policy rule (16) vary greatly in the literature, depending on the countries considered, periods covered, and the exact specification of the rule (e.g., whether the central bank responds to actual inflation and output or their expected values). For our benchmark experiment we set the weight on inflation ν_π equal to 1.5 and the weight on output ν_y equal to 0.125 – the values used by Taylor (1993).¹⁰ In addition, we set the steady-state inflation rate π equal to 0.0091 – the average quarterly inflation rate in the United States between 1959 and 2006 – and the smoothing coefficient ϕ equal to 0.75, which is within the range of estimates obtained in the literature (e.g., Clarida et al., 2000; Sack and Wieland, 2000).

5 Findings

5.1 International business cycle

Table 8 reports the cross-country correlations of the price level, the nominal interest rate, and output generated by the model for our baseline calibration, and compares them with the data. As in the case of the data, the artificial series produced by the model are filtered with the Christiano and Fitzgerald (2003) filter. The statistics for the model are averages for 100 runs of the length of 188 periods each – the same as the length of the data series in the sample that goes back to 1960:Q1.

We see that the model generates the main feature of the international nominal business cycle: The cross-country correlations for the price level and the nominal interest rate are sub-

¹⁰Taylor uses the weight on output equal to 0.5. This value is scaled down by four in our calibration in order to make it consistent with GDP in our model, which is measured at a quarterly rate.

stantially higher than that for output. In addition, in line with the data, the cross-country correlations for the price level and the nominal interest rate are similar. Furthermore, the model's *quantitative* predictions are reasonably close to the data as well. In particular, in the model the cross-country correlations of the price level and the nominal interest rate are 0.69 and 0.68, respectively, while the cross-country correlation of real GDP is only 0.23. In the data the mean values of these correlations are, respectively, 0.52, 0.57, and 0.27 for the six country sample (covering the period 1960.Q1-2006.Q4), and 0.59, 0.59, and 0.43 for the eight-country sample (covering the period 1970.Q1-2006.Q4). Given the rather parsimonious nature of our model economy, and that it has only one source of shocks, it accounts for the observed cross-country correlations for these variables surprisingly well.¹¹ Recall from the previous section that none of the parameter values was chosen in order to generate this result.

5.2 Domestic business cycle

In Table 9 we report the domestic business cycle properties of the model economy and compare them with those of the U.S. economy. In particular, we report the standard deviations of key domestic variables, relative to that of GDP, and their correlations with GDP at various leads and lags. Although the characteristics of domestic business cycles differ across developed economies, the statistics reported in Table 9 for the U.S. economy are fairly representative (see, for example, Zimmermann, 1997; Agresti and Mojon, 2001). We also report the J-curve – a dynamic relationship between net exports and the terms of trade – for the United States. As documented by Backus et al. (1994), in a number of industrialized economies net exports are negatively correlated with future terms of trade, and positively correlated with past terms of trade.

The behavior of real variables in an international business cycle model has been thoroughly analyzed by Backus et al. (1994) and Backus, Kehoe and Kydland (1995). Here we therefore point out only some of the key properties of the cyclical behavior of the real side

¹¹However, as most other international business cycle models, and in contrast to the data, the model generates a higher cross-country correlation of consumption than of output.

of the model economy. In particular, the model accounts for about 80 percent of GDP fluctuations and, in line with the data, produces consumption about half as volatile as GDP, investment about three times as volatile as GDP, and net exports about 25 percent as volatile as GDP. Hours, however, are somewhat less volatile in the model than in the data. In addition, in line with the data, consumption, investment, and hours are procyclical, while net exports are countercyclical. Furthermore, the model generates a J-curve.

As for the two nominal variables, the model correctly generates countercyclical price level and produces standard deviations of the price level and the nominal interest rate, relative to that of GDP, similar to those for the U.S. economy. However, the model fails to produce the empirical lead-lag pattern of the price level and the comovement between output and the nominal interest rate observed in the U.S. economy, as well as in the other economies in our sample. While in the data the price level leads output negatively, in the model it lags output negatively. In addition, the nominal interest rate is negatively correlated with output contemporaneously in the model, while in the data the contemporaneous correlation is positive and the nominal interest rate leads output negatively.

The failure of the model to generate the empirical dynamics of the price level and the nominal interest rate in relation to domestic output is not surprising – these are well known anomalies and therefore we would not expect our relatively simple model to be able to account for them.¹² However, in Subsection 6.3 we extend the model in a way that allows it to be consistent with the key features of both, international, as well as the domestic nominal business cycles.

5.3 The mechanism

We can gain intuition for our main result by plotting the responses of the model's variables to a 1% positive technology shock. These responses are contained in Figure 5. As the focus of the paper is on nominal variables, we describe the responses of the real variables only briefly and refer the reader to Backus et al. (1994) and Heathcote and Perri (2002)

¹²See Backus, Routledge and Zin (2007) for a recent attempt to account for the lead-lag pattern of the nominal interest rate, and Wang and Wen (2007) for an attempt to account for a lead-lag pattern of inflation.

for a more detailed analysis. In the following discussion it is useful to abstract from the effects of nominal variables on the real economy, which in our model occur only due to an inflation tax on real money balances held by the consumer between periods, and thus on shopping time and the time available for leisure and work. These effects are small for our baseline calibration and taking them into account would only clutter the description of the mechanism without providing much insight into the main result.

5.3.1 Responses of real variables

Because the shocks in the two countries are correlated, a 1% increase in technology in country 1 leads, on impact, to an increase in technology in country 2 by 0.258%, where 0.258 is the correlation coefficient of the ε 's. In addition, due to spillovers, technology in country 2 gradually catches up with technology in country 1. As a result of a higher current and expected future technology level, consumption in both countries increases, but it increases by less in country 2 than in country 1. There are two reasons for this. First, the net present value of country 2's future income is smaller than that of country 1. This is because technology in country 2 does not reach the level of technology in country 1 for a while. Second, there is intertemporal trade between the two countries: in order to take advantage of higher total factor productivity, country 1 increases investment by borrowing from country 2. Country 2 is thus giving up some of its current consumption in return for higher future consumption. This intertemporal trade is reflected in the decline of net exports of country 1, and the increase in the real return on the internationally traded bond.

Because of the initially higher technology level in country 1, GDP is initially higher in country 1 than in country 2. However, as technology in country 2 catches up with technology in country 1, GDP in country 2 catches up with GDP in country 1. As a result of initially higher output in country 1, the price of good a falls, reflecting its abundance in the world market relative to good b . The terms of trade of country 1 therefore worsen, following the technology shock.

5.3.2 Responses of nominal variables

The dynamics of the price level and the nominal interest rate can be understood by deriving the pricing functions for these variables. The first-order conditions for the accumulation of capital, and domestic and foreign bonds in country i are, respectively,

$$\begin{aligned} E_t \left[Q_{it} \left(1 + r_{i,t+1}^k - \delta \right) \right] &= 1, \\ (1 + R_{it}) E_t \left[Q_{it} \left(\frac{1}{1 + \pi_{i,t+1}} \right) \right] &= 1, \\ (1 + r_t^f) E_t \left[Q_{it} \left(\frac{q_{i,t+1}^a}{q_{i,t}^a} \right) \right] &= 1, \end{aligned}$$

where $Q_{it} \equiv \beta(U_{c,t+1} - U_{l,t+1}s_{c,t+1})/(U_{ct} - U_{lt}s_{ct})$ is country i 's stochastic discount factor. For the following discussion it is convenient to log-linearize these conditions around the model's non-stochastic steady state

$$E_t \widehat{Q}_{it} + E_t \widehat{r}_{i,t+1}^k = 0, \quad (22)$$

$$\widehat{R}_{it} + E_t \widehat{Q}_{it} - E_t \widehat{\pi}_{i,t+1} = 0, \quad (23)$$

$$\widehat{r}_t^f + E_t \widehat{Q}_{it} + E_t \widehat{q}_{i,t+1}^a - \widehat{q}_{it}^a = 0, \quad (24)$$

where $\widehat{r}_{i,t+1}^k \equiv (r_{i,t+1}^k - r^k)/(1 + r^k - \delta)$, $\widehat{R}_{it} \equiv (R_{it} - R)/(1 + R)$, $\widehat{\pi}_{it} \equiv (\pi_{it} - \pi)/(1 + \pi)$, $\widehat{r}_t^f \equiv (r_t^f - r^f)/(1 + r^f)$ are percentage deviations of the gross rates from steady state, and $\widehat{Q}_{it} \equiv \log Q_{it} - \log Q_i$ is the percentage deviation of the stochastic discount factor. Combining equations (22) and (23), and (22) and (24), then gives, respectively, a no-arbitrage condition for domestic real and nominal assets, and for real domestic and international assets

$$E_t \widehat{r}_{i,t+1}^k = \widehat{R}_{it} - E_t \widehat{\pi}_{i,t+1}, \quad (25)$$

$$E_t \widehat{r}_{i,t+1}^k = \widehat{r}_t^f + E_t \widehat{q}_{i,t+1}^a - \widehat{q}_{it}^a. \quad (26)$$

In addition, combining equation (26) for country 1 with that for country 2 gives a relationship between the return to capital in the two countries

$$E_t \widehat{r}_{1,t+1}^k + E_t (\widehat{q}_{2,t+1}^a - \widehat{q}_{1,t+1}^a) - (\widehat{q}_{2t}^a - \widehat{q}_{1t}^a) = E_t \widehat{r}_{2,t+1}^k, \quad (27)$$

where $E_t (\widehat{q}_{2,t+1}^a - \widehat{q}_{1,t+1}^a) - (\widehat{q}_{2t}^a - \widehat{q}_{1t}^a)$ is the expected change in the real exchange rate. Notice, that due to the expected changes in the real exchange rate, the expected real interest rates in the two countries do not need to be equalized.

Abstracting from the small inflation tax effects, we can think of the real variables as being determined independently of the nominal variables. Thus, given the equilibrium real quantities and prices, the equilibrium nominal interest rate and the price level in country i are determined by the no-arbitrage condition for real and nominal assets (25) and the (log-linearized) Taylor rule

$$\widehat{R}_{it} = \widetilde{\nu}_\pi \widehat{\pi}_{it} + \widetilde{\nu}_y \widehat{Y}_{it}, \quad (28)$$

where $\widetilde{\nu}_\pi \equiv \nu_\pi(1 + \pi)/(1 + R)$, $\widetilde{\nu}_y \equiv \nu_y/(1 + R)$, and $\widehat{Y}_{it} \equiv \log GDP_{it} - \log GDP$, and where for simplicity of the exposition we set ϕ equal to zero. These two conditions state that in each period, in equilibrium, the nominal interest rate has to be at a level that makes consumers indifferent between holding capital and nominal bonds, and inflation has to be such that the central bank wants to hold the nominal interest rate at that level.

Combining these two equilibrium conditions gives us a first-order difference equation in inflation

$$E_t \widehat{r}_{i,t+1}^k + E_t \widehat{\pi}_{i,t+1} = \widetilde{\nu}_\pi \widehat{\pi}_{it} + \widetilde{\nu}_y \widehat{Y}_{it}, \quad (29)$$

where inflation in period t depends on output in period t , and expectations of the return to capital and inflation in period $t + 1$. Solving equation (29) by forward substitution, and, in line with the literature, excluding equilibria with hyperinflations or hyperdeflations, we obtain the price level in period t as a sum of two terms: the price level in period $t - 1$ and a difference between the expected discounted sum of future real returns to capital and the

expected discounted sum of current and future output

$$\widehat{p}_{it} = \widehat{p}_{i,t-1} + E_t \left[\sum_{j=1}^{\infty} \left(\frac{1}{\widetilde{\nu}_\pi} \right)^j \widehat{r}_{i,t+j}^k \right] - \widetilde{\nu}_y E_t \left[\sum_{j=1}^{\infty} \left(\frac{1}{\widetilde{\nu}_\pi} \right)^j \widehat{Y}_{i,t+j-1} \right]. \quad (30)$$

Substituting the price level from equation (30) into the Taylor rule (28) then gives the nominal interest rate in period t as a difference between the expected discounted sum of future real returns to capital and the expected discounted sum of future output

$$\widehat{R}_{it} = E_t \left[\sum_{j=1}^{\infty} \left(\frac{1}{\widetilde{\nu}_\pi} \right)^{j-1} \widehat{r}_{i,t+j}^k \right] - \widetilde{\nu}_y E_t \left[\sum_{j=1}^{\infty} \left(\frac{1}{\widetilde{\nu}_\pi} \right)^j \widehat{Y}_{i,t+j} \right]. \quad (31)$$

The degree of comovement of the two nominal variables across the two countries is thus determined by the extent to which the expected discounted sums of returns to capital and output in the two countries move together.

As follows from equation (27), due to real exchange rate changes, cross-country borrowing and lending does not necessarily equate the returns to capital in the two economies. This is indeed the case in our benchmark experiment, as we see in Figure 5: The return to capital in country 1 increases on impact, while the return to capital in country 2 increases only gradually as technology in country 2 catches up with technology in country 1. The expected discounted sums of the rates of return in the two countries nevertheless increase on impact, as in both countries the return to capital is expected to stay above its steady-state level for much of the duration of the technology shock. A similar argument also applies to the expected discounted sums of output. Thus, although output differs across the two countries between the impact period and the time when country 2 catches up with country 1, the discounted sums increase on impact in both countries.

Because the price level and the nominal interest rate depend on the *difference* between the expected discounted sums of returns to capital and GDP, the sign of their responses depends on the relative weight on GDP in the Taylor rule. It turns out that, for our benchmark experiment, the weight on GDP is sufficiently large, leading to a fall in prices and nominal interest rates in the two countries following the technology shock in country

1.

5.3.3 Discussion

It is well known that models of the type used here generate much lower real exchange rate volatility than what is observed in the data. This is because, through equations (27) and (22), the real exchange rate is tightly linked with the countries' stochastic discount factors, which, for standard utility functions, display little volatility. However, as the equilibrium condition for international capital flows (27) is not used to derive the solutions for the price level and the nominal interest rate, (30) and (31), whether this condition holds or not is not crucial for the mechanism in our model generating the strong comovement of nominal variables across countries. In fact, the model predicts substantially higher cross-country correlations of the two nominal variables than that of output even when we shut down the international asset market (i.e., we let the countries trade in the goods market, but we prevent them from lending to each other). In this case, for our baseline calibration, $\text{corr}(y_1, y_2) = 0.43$, $\text{corr}(p_1, p_2) = 0.84$, and $\text{corr}(R_1, R_2) = 0.86$.

In contrast, the equilibrium condition for domestic bonds (23) is used in the derivation of the equilibrium price level and the nominal interest rate. It is well known (e.g., Hansen and Singleton, 1983) that this Euler equation does not price financial assets well.¹³ To some extent this is reflected in the failure of our model to generate the observed dynamics of the nominal interest rate and prices in relation to output. In Subsection 6.3 we introduce into the current model a tax that distorts this Euler equation. As we will see, this extension helps bring the model closer to the observed features of the domestic nominal business cycles, but does not change our main result regarding the cross-country movements of nominal variables.

¹³Canzoneri, Cumby and Diba (2007) show that the Euler equation fails to price short-term debt for a variety of specifications of the utility function.

6 Sensitivity analysis

In order to check the robustness of our quantitative findings, we conduct sensitivity analysis for those parameters that are not estimated precisely in the literature, or whose estimates vary significantly across countries. We report results for the parameters of the monetary policy rule (ν_π, ν_y, ϕ) , the degree of spillovers (A_{12}) , and the extension that allows the model to be consistent with the observed features of the domestic nominal business cycle. We have also examined the quantitative properties of the model for alternative values of the elasticity of substitution between home and foreign goods (σ) , the steady-state import share of GDP (b_1/y_1) , steady-state inflation rate (π) , and the shopping-time parameters (κ_1, κ_2) . However, as our main finding is not particularly sensitive to alternative values of these parameters, we do not report the results of these experiments.

6.1 Parameters of the Taylor rule

6.1.1 Weight on output

Figure 6 plots the cross-country correlations for output and the two nominal variables for alternative values of ν_y , which we vary between -0.05 and 0.25 – a range that covers most of the estimates found in the literature.¹⁴ We see that except for a small interval between 0.025 and 0.06, the cross-country correlations of the price level and the nominal interest rate are higher than that of real GDP.

Figure 7 provides intuition for the sharp fall in the cross-country correlations for the two nominal variables, and for the nominal interest rate in particular, in the interval 0.025-0.06. It plots the responses of the nominal interest rates in the two countries for three alternative values of ν_y : 0.125 (our baseline value), 0, and 0.03, the value at which the cross-country correlation for the nominal interest rate is the lowest. As mentioned in the previous section, for our baseline value of ν_y , the negative effect of the expected discounted sum of future output on prices and the nominal interest rate is stronger than the positive effect on these variables of the expected discounted sum of future returns to capital. The nominal interest

¹⁴The values mentioned here are the values reported in the literature, divided by four in order to make them consistent with the measure of GDP in the model, which is expressed at a quarterly rate.

rate, as well as the price level, therefore fall in both countries following a positive technology shock in country 1.

In contrast, when ν_y is equal to zero, the two variables are determined only by the expected discounted sum of future returns to capital. The nominal interest rate and prices therefore increase in both countries after the shock. In the intermediate case, when ν_y is equal to 0.03, during the first 10 to 15 quarters after the shock, the response of the nominal interest rate in country 1 looks more like that for our benchmark weight on output, whereas that for country 2 looks more like the one for a zero weight on output. This is because the expected discounted sum of future output in country 2 is smaller than that in country 1 (see the output responses in Figure 5). The negative effect of this sum on prices and the interest rate is thus smaller in country 2 than in country 1, leading to an increase in the nominal interest rate in country 2, while the nominal interest rate falls in country 1.

6.1.2 Weight on inflation

In the top panels of Figure 8 we plot the international correlations for alternative weights on inflation. We plot these correlations for two alternative weights on output: our benchmark weight of 0.125, and a zero weight. In empirical Taylor rules, ν_π is usually in the range from 0.8 to 2.5. In our model, however, when ν_π is too close to one, the equilibrium becomes indeterminate. This is a common feature of most general equilibrium models with interest rate monetary policy rules. We therefore restrict ν_π to be in the interval from 1.05 to 2.5. We see that except for the case of a zero weight on output and the weight on inflation being close to our lower bound, the cross-country correlations of the two nominal variables are higher than that of output.¹⁵

Interestingly, the model predicts higher cross-country correlations of the two nominal variables than that of output even when the central bank puts a large weight on stabilizing inflation and no weight on stabilizing output. By increasing the weight on inflation and putting zero weight on output, the central bank minimizes the volatility of the two nominal

¹⁵The large increase in the cross-country correlation of output in the right-hand panel is due to substantial inflation tax effects that occur with a relatively large weight on output and a small weight on inflation in the Taylor rule.

variables, relative to that of output. In particular, for the upper-bound weight on inflation of 2.5, the central bank reduces the standard deviations of the price level and the nominal interest rate, relative to that of output, to 0.11 and 0.17, respectively – well below the values observed for the post-war period (for example, the average relative standard deviations of these two variables for the U.S. economy are 0.82 and 0.73, respectively; see Table 9). This finding is consistent with the observation that the cross-country correlations of the two nominal variables remained substantially higher than that of output even during the Great Moderation period.

6.1.3 Interest rate smoothing

Some specifications of Taylor rules have no smoothing coefficient (e.g., Taylor, 1999). Often, however, a smoothing coefficient is included and is usually found to be in the range between 0.5 and 0.9 (see Woodford, 2003, chapter 1). In the mid-panels of Figure 8 we therefore report how the cross-country correlations change as we vary ϕ between 0 and 0.99. We see that our main result is robust to alternative values of this parameter.

6.2 Spillovers

The estimates of the spillover term in the transition matrix A vary substantially in the literature. Backus et al. (1992) estimate this term to be 0.088, our benchmark value, while Heathcote and Perri (2002) obtain an estimate of 0.025. Yet, Baxter and Crucini (1995) find little evidence for non-zero spillovers. We therefore vary A_{12} between 0 and 0.1. In all these experiments we adjust the diagonal elements of A so that its highest eigenvalue is the same as in our benchmark experiment. We see in the bottom panels of Figure 8 that except for the case of no spillovers, nominal variables are correlated more strongly across countries than output. Furthermore, the gap between the cross-country correlations of the two nominal variables and that of GDP increases rapidly as we move away from the case of no spillovers. For example, even for a modest degree of spillovers, such as that found by Heathcote and Perri (2002), the model generates a gap between the cross-country correlations of the two nominal variables and real GDP close to that observed in the data

(for example, in the case of prices, a gap of about 0.35, when $\nu_y = 0$, and a gap of about 0.2, when $\nu_y = 0.125$).

6.3 Domestic nominal business cycle

As noted above, in its current form the model does not generate the lead-lag pattern between domestic output and the domestic price level, and between domestic output and the domestic nominal interest rate, as in the data. Although this is not surprising, as these are well known anomalies, we would have more confidence in the answer the model gives to our question regarding the international nominal business cycle if it were consistent with the key features of the domestic nominal business cycle.

Providing a quantitative-theoretical account of the domestic nominal business cycle from first principles is, however, beyond the scope of this paper. Instead, we proceed as follows. Using an extended version of the business cycle accounting method of Chari, Kehoe and McGrattan (2007), Sustek (2008) shows that fluctuations in two “wedges” in a prototype monetary business cycle model are necessary, and to a large extent also sufficient, for generating the observed lead-lag pattern of prices and interest rates with respect to output. These two wedges look like total factor productivity and a tax on adjusting the holdings of nominal bonds. The tax captures various asset market distortions, such as limited participation or frictions leading to time-varying risk premia, while Chari et al. (2007) provide various interpretations of total factor productivity. Movements in these two wedges over the business cycle are then interpreted as resulting from the propagation of primitive shocks through the frictions embedded in them.

Based on Šustek’s result, we introduce such a tax τ_{it} into each country in the current model and choose its stochastic process so as to replicate the lead-lag pattern of the nominal interest rate. Given this calibration, we then ask if the model generates both the observed lead-lag pattern of the price level and higher cross-country correlations for the two nominal variables than that for output.

In this extended model, the budget constraint of the representative consumer in country

i becomes

$$\frac{q_{it}^a f_{it}}{1 + r_t^f} + (1 + \tau_{it}) \left[\frac{d_{it}}{p_{it}(1 + R_{it})} - \frac{d_{i,t-1}}{p_{it}} \right] + \frac{m_{it}}{p_{it}} + c_{it} + x_{it} =$$

$$q_{it}^s (r_{it}^k k_{it} + w_{it} n_{it}) + q_{it}^a f_{i,t-1} + \frac{m_{i,t-1}}{p_{it}} + \frac{v_{it}}{p_{it}} + T_{it},$$

where T_{it} is the proceeds from taxing the accumulation of domestic bonds, which are rebated back to the consumer in a lump sum way. Notice that the tax distorts the Euler equation for domestic bonds, which now becomes

$$(1 + R_{it}) E_t \left[Q_{it} \left(\frac{1 + \tau_{i,t+1}}{1 + \tau_{it}} \right) \left(\frac{1}{1 + \pi_{i,t+1}} \right) \right] = 1.$$

We postulate a joint stochastic process for the tax and technology shocks

$$\begin{bmatrix} \ln z_{1,t+1} \\ \tau_{1,t+1} \\ \ln z_{2,t+1} \\ \tau_{2,t+1} \end{bmatrix} = \Lambda_0 + \begin{bmatrix} \Lambda_{11} & \Lambda_{12} & \Lambda_{13} & \Lambda_{14} \\ \Lambda_{21} & \Lambda_{22} & \Lambda_{23} & \Lambda_{24} \\ \Lambda_{13} & \Lambda_{14} & \Lambda_{11} & \Lambda_{12} \\ \Lambda_{23} & \Lambda_{24} & \Lambda_{21} & \Lambda_{22} \end{bmatrix} \begin{bmatrix} \ln z_{1t} \\ \tau_{1t} \\ \ln z_{2t} \\ \tau_{2t} \end{bmatrix} + \varepsilon_{t+1}, \quad (32)$$

where we have imposed symmetry across the two countries, set the steady-state value of τ_{it} equal to zero, and let $\varepsilon_{t+1} \sim N(0, \Omega)$, with the elements of Ω related to the innovations in technology the same as those in Σ (the covariance matrix in the stochastic process (3)), and those related to the innovations in the tax set equal to zero. In light of the above discussion about the interpretation of the wedges, the innovations in technology are the only primitive shocks in this economy.

This stochastic process has eight parameters that need to be calibrated: Λ_{11} , Λ_{12} , Λ_{13} , Λ_{14} , Λ_{21} , Λ_{22} , Λ_{23} , and Λ_{24} . We choose their values by minimizing the distance between eight moments in the data and the same moments in the model: $\text{corr}(R_{1t}, R_{1,t-1})$, $\text{corr}(R_{1,t-1}, y_{1t})$, $\text{corr}(R_{1,t-3}, y_{1t})$, $\text{corr}(R_{1,t+1}, y_{1t})$, $\text{corr}(R_{1,t+3}, y_{1t})$, $\text{corr}(\ln z_{1t}, \ln z_{1,t-1})$, $\text{corr}(\ln z_{1t}, \ln z_{2,t-1})$, and $\text{corr}(\ln z_{1t}, \ln z_{2,t-3})$. Our choice of the leads and lags of the nominal interest rate with respect to GDP means that we try to match every other cross-

correlation in the row for the nominal interest rate in Table 9, panel B. Notice also that matching $\text{corr}(\ln z_{1t}, \ln z_{1,t-1})$, $\text{corr}(\ln z_{1t}, \ln z_{2,t-1})$, and $\text{corr}(\ln z_{1t}, \ln z_{2,t-3})$ ensures that technology shocks in the extended model have approximately the same persistence and spillovers as in our baseline calibration of the benchmark model; i.e., estimating the stochastic process for technology shocks (3) on time series for $\ln z_{1t}$ and $\ln z_{2t}$ generated by the stochastic process (32), we find approximately the same autocorrelations and spillovers of these shocks as those found by Backus et al. (1994). The resulting values of the eight parameters are contained in Table 10.

Table 11 then reports the domestic and international nominal business cycle properties of this extended economy. Recall that in the benchmark economy, the price level was lagging output negatively, while in the data it leads output negatively. As we can see from Table 11, the extended model generates the correct phase shift of the price level. In addition, it still produces higher cross-country correlations of the two nominal variables than that of output. It is also important to realize that because this tax affects only the two nominal variables (it shows up only in the Euler equation for bonds), and in our calibration we match the observed autocorrelation and cross-country correlations of the technology shocks, the desirable business cycle properties of real variables in the benchmark economy are also present in the extended economy.

7 Concluding remarks

This study adds to the literature that investigates cross-country movements in key macroeconomic variables. Our empirical contribution lies in documenting that, at business cycle frequencies, fluctuations in prices and nominal interest rates are substantially more synchronized across countries than fluctuations in output. This observation is based on a sample of six major industrialized economies for the period 1960.Q1-2006.Q4. Adding more economies as the required data become available, or splitting the sample into subsamples to control for the Bretton Woods and the Great Moderation periods, does not alter this empirical regularity. This is an intriguing finding both from a theoretical point of view, as

well as from the perspective of the current policy debate about how inflation, and nominal variables in general, are determined in an international environment.

We then ask if a parsimonious international business cycle model, augmented to include nominal assets and a monetary authority in each country, following a simple, empirically plausible rule, can account for this feature of international aggregate fluctuations. We find that it can. For a benchmark calibration, the cross-country correlation of output is slightly lower than that in the data, while the cross-country correlations of prices and nominal interest rates are slightly higher. Due to spillovers of technology shocks across countries, expected future responses of national central banks to fluctuations in domestic output and inflation generate movements in current prices and interest rates that strongly co-move across countries even when output does not. International nominal business cycles are thus highly synchronized even when national monetary policies focus squarely on stabilizing domestic output and inflation. A key element of our findings is that even a modest degree of spillovers, in the range of the smaller estimates found in the literature, is sufficient to generate correlations such as those in the data.

We show also that introducing a tax on bonds into our model, and choosing its stochastic process appropriately, makes the model consistent with both, international as well as domestic nominal business cycles. We interpret the tax as capturing various distortions in asset markets or time-varying risk premia. Future research should focus on exploring which specific mechanisms can distort the Euler equation for bonds over the business cycle in a similar way as the tax on bonds in our model. Having such mechanisms would improve our understanding of the dynamics of domestic nominal variables in relation to domestic output.

We view the model presented in this paper as a natural starting point for providing understanding of the observed cross-country movements in nominal variables. It is, of course, possible that various mechanisms from which we have abstracted can also contribute to account for the same phenomenon. For instance, international monetary policy coordination (modelled, for example, by Canzoneri and Henderson, 1992), or various goods market rigidities and exchange-rate pass-through mechanisms (surveyed, for instance, by

Taylor, 2000), may play a role. We believe, however, that before moving on to more complex environments, it is necessary to understand to what extent a parsimonious international business cycle model can account for the data. As we have demonstrated, such a model can go a long way.

8 Appendix: Data sources

For all countries, data on real GDP and the price level (consumer price index) come from the International Financial Statistics (IFS) database. For Germany, the consumer price index for the period 1960.Q1-1991.Q4 is for West Germany only. Wherever possible, the nominal interest rate is the yield on a 3-month government bond. For Austria we use the yield on a 1-year government bond, and for France and Japan we use a money market rate. The interest rate data for Japan, the United Kingdom, and the United States come from the IFS database; for Australia, Canada, and Germany from the Global Financial Data database; for Austria from Datastream; and for France from the IFS database for the period 1970.Q1-1999.Q1, and from Datastream for the period 1999.Q2-2006.Q4.

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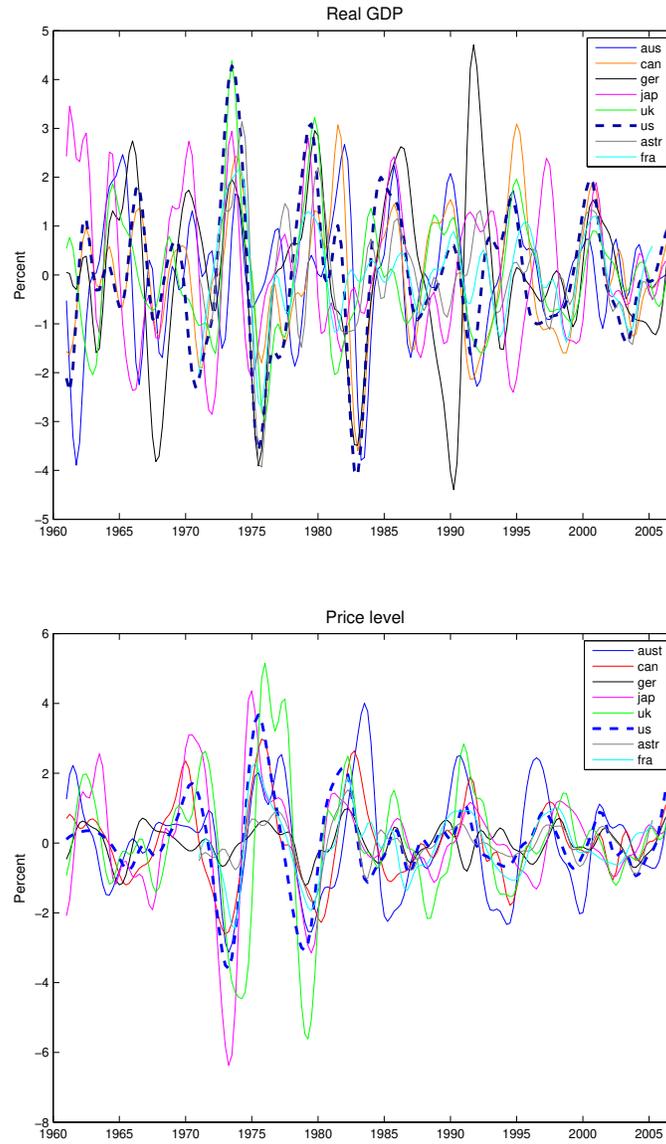


Figure 1: Business-cycle-frequency fluctuations in output and the price level.

Table 1: Cross-country correlations of real GDP, 1960.Q1-2006.Q4

	aus	can	ger	jap	uk	us
aus	1.00					
can	0.53	1.00				
ger	-0.02	0.16	1.00			
jap	-0.12	-0.06	0.39	1.00		
uk	0.19	0.45	0.21	0.18	1.00	
us	0.23	0.72	0.42	0.21	0.56	1.00
mean = 0.27 CV = 0.89						
Excluding Bretton Woods period						
mean = 0.25 CV = 1.21						
pre-1984			post-1984			
mean = 0.34			mean = 0.16			
CV = 0.71			CV = 3.00			

Table 2: Cross-country correlations of short-term nominal interest rates, 1960.Q1-2006.Q4

	aus	can	ger	jap	uk	us
aus	1.00					
can	0.61	1.00				
ger	0.52	0.62	1.00			
jap	0.39	0.39	0.47	1.00		
uk	0.58	0.56	0.63	0.63	1.00	
us	0.55	0.84	0.72	0.43	0.57	1.00
mean = 0.57 CV = 0.22						
Excluding Bretton Woods period						
mean = 0.57 CV = 0.26						
pre-1984			post-1984			
mean = 0.61			mean = 0.53			
CV = 0.20			CV = 0.37			

Table 3: Cross-country correlations of price levels, 1960.Q1-2006.Q4

	aus	can	ger	jap	uk	us
aus	1.00					
can	0.68	1.00				
ger	0.25	0.43	1.00			
jap	0.33	0.63	0.41	1.00		
uk	0.50	0.52	0.42	0.58	1.00	
us	0.47	0.71	0.51	0.76	0.61	1.00
mean = 0.52		CV = 0.28				
Excluding Bretton Woods period						
mean = 0.50		CV = 0.29				
pre-1984			post-1984 ^a			
mean = 0.60			mean = 0.30 (0.40)			
CV = 0.17			CV = 1.03 (0.77)			

^aThe values in the brackets are for a sample that excludes Germany, whose price level was affected by the unification in 1990.

Table 4: Eight-country sample, cross-country correlations of real GDP, 1970.Q1-2006.Q4

	aus	aut	can	fra	ger	jap	uk	us
aus	1.00							
aut	0.05	1.00						
can	0.74	0.35	1.00					
fra	0.21	0.70	0.53	1.00				
ger	-0.10	0.68	0.18	0.47	1.00			
jap	0.03	0.39	0.12	0.50	0.55	1.00		
uk	0.26	0.48	0.56	0.74	0.24	0.40	1.00	
us	0.39	0.56	0.69	0.67	0.53	0.52	0.65	1.00
mean = 0.43		CV = 0.54						
Excluding Bretton Woods period								
mean = 0.34		CV = 0.76						
post-1984								
mean = 0.19		CV = 2.07						

Table 5: Eight-country sample, cross-country correlations of short-term nominal interest rates, 1970.Q1-2006.Q4

	aus	aut	can	fra	ger	jap	uk	us
aus	1.00							
aut	0.63	1.00						
can	0.65	0.64	1.00					
fra	0.48	0.57	0.49	1.00				
ger	0.58	0.73	0.70	0.77	1.00			
jap	0.44	0.55	0.37	0.47	0.61	1.00		
uk	0.59	0.45	0.57	0.47	0.74	0.68	1.00	
us	0.58	0.61	0.85	0.57	0.77	0.46	0.58	1.00
mean = 0.59		CV = 0.20						
Excluding Bretton Woods period								
mean = 0.55		CV = 0.25						
post-1984								
mean = 0.46		CV = 0.48						

Table 6: Eight-country sample, cross-country correlations of price levels, 1970.Q1-2006.Q4

	aus	aut	can	fra	ger	jap	uk	us
aus	1.00							
aut	0.43	1.00						
can	0.71	0.59	1.00					
fra	0.66	0.72	0.82	1.00				
ger	0.23	0.69	0.54	0.57	1.00			
jap	0.36	0.57	0.62	0.78	0.52	1.00		
uk	0.50	0.65	0.53	0.71	0.43	0.54	1.00	
us	0.44	0.69	0.67	0.76	0.59	0.77	0.57	1.00
mean = 0.59		CV = 0.23						
Excluding Bretton Woods period								
mean = 0.59		CV = 0.24						
post-1984								
mean = 0.45		CV = 0.56						

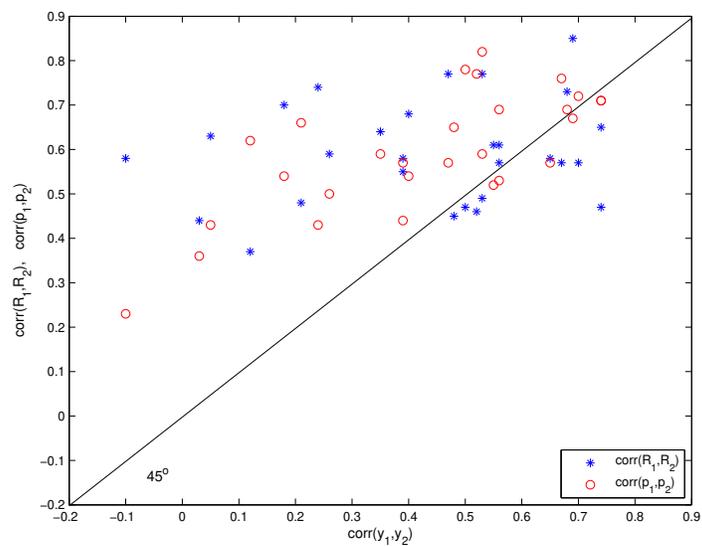


Figure 2: Cross-country comovement of nominal variables vs cross-country comovement of real GDP – the eight-country sample, 1970.Q1-2006.Q4.

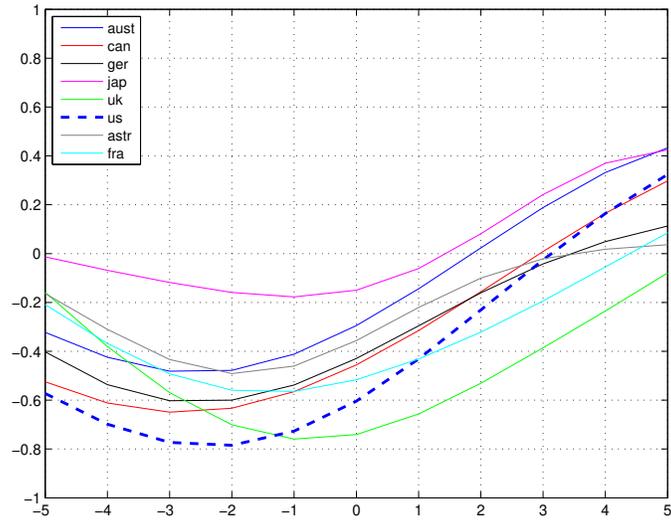


Figure 3: Correlations of the price level in period $t + j$ with real GDP in period t .

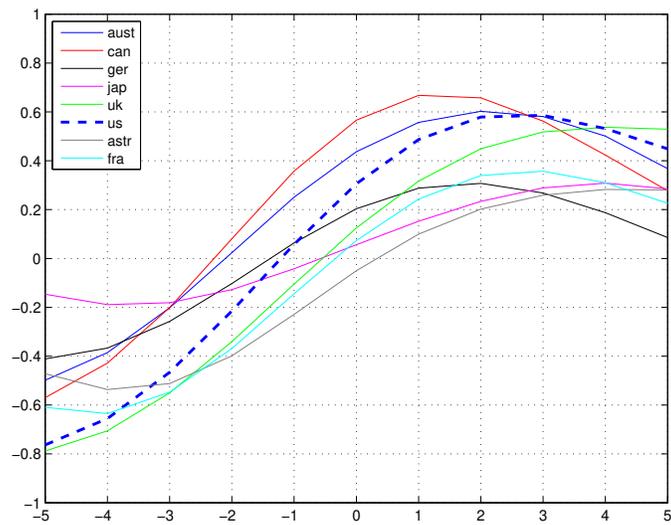


Figure 4: Correlations of a short-term nominal interest rate in period $t + j$ with real GDP in period t .

Table 7: Baseline calibration

Symbol	Value	Definition
Preferences		
γ	2.0	Relative risk aversion
μ	0.34	Consumption share in utility
β	0.989	Discount factor
Technology		
δ	0.025	Depreciation rate
α	0.36	Capital share in production
ω_1	0.761	Weight on domestic good
ω_2	0.239	Weight on foreign good
$\sigma = 1/(1 + \rho)$	1.5	Elasticity of substitution
Shopping time		
κ_1	0.0054	Level parameter
κ_2	1.0	Curvature parameter
Monetary policy rule		
π	0.0091	Steady-state inflation rate
ν_y	0.125	Weight on GDP
ν_π	1.5	Weight on inflation
ϕ	0.75	Smoothing coefficient
Process for technology shocks		
$A_0 =$	[0.00072 0.00072]	
$A =$	[0.906 0.088] [0.088 0.906]	
$\text{Var } \varepsilon_1 = \text{Var } \varepsilon_2 =$	0.00852 ²	
$\text{Corr}(\varepsilon_1, \varepsilon_2) =$	0.258	

Table 8: International business cycle^a

	Correlation		
	(p_1, p_2)	(R_1, R_2)	(GDP_1, GDP_2)
Model economy	0.69	0.68	0.23
Six-country sample, 1960.Q1-2006.Q4	0.52	0.57	0.27
Eight-country sample, 1970.Q1-2006.Q4	0.59	0.59	0.43

^a The entries for the model are averages for 100 runs of the length of 188 periods each. As in the case of the data, the series for output and prices in the model are in logs and all series are filtered with the Christiano-Fitzgerald (2003) band-pass filter.

Table 9: Domestic business cycle

A. Model economy ^a										
v_{t+j}	Relative std. dev. ^b	Correlations of GDP in period t with variable v in period $t + j$:								
		$j = -4$	-3	-2	-1	0	1	2	3	4
GDP (qy)	1.21	0.02	0.29	0.62	0.89	1.00	0.89	0.62	0.29	0.02
Consumption (c)	0.53	-0.06	0.20	0.51	0.80	0.95	0.90	0.69	0.42	0.17
Investment (x)	3.35	0.04	0.29	0.60	0.85	0.93	0.79	0.51	0.18	-0.08
Hours (n)	0.43	0.08	0.34	0.66	0.90	0.97	0.82	0.52	0.17	-0.10
Net exports (nx)	0.25	0.05	-0.13	-0.35	-0.54	-0.61	-0.53	-0.33	-0.11	0.06
Price level (p)	1.00	0.47	0.34	0.12	-0.13	-0.37	-0.52	-0.57	-0.54	-0.46
Nominal interest rate (R)	0.67	0.02	-0.24	-0.55	-0.82	-0.95	-0.88	-0.66	-0.37	-0.12
Correlations of terms of trade (e_t) with net exports (nx_{t+j})										
J -curve		-0.50	-0.64	-0.75	-0.73	-0.57	-0.27	0.08	0.37	0.54
B. U.S. economy ^c										
v_{t+j}	Relative std. dev. ^b	Correlations of GDP in period t with variable v in period $t + j$:								
		$j = -4$	-3	-2	-1	0	1	2	3	4
GDP	1.48	0.22	0.50	0.75	0.93	1.00	0.93	0.75	0.50	0.22
Consumption	0.52	0.15	0.37	0.58	0.73	0.80	0.78	0.68	0.53	0.34
Investment	2.99	0.35	0.58	0.78	0.91	0.94	0.86	0.68	0.43	0.17
Hours	0.90	-0.07	0.19	0.46	0.71	0.88	0.95	0.91	0.76	0.55
Net exports	0.25	-0.48	-0.52	-0.56	-0.58	-0.58	-0.52	-0.39	-0.21	-0.01
Price level	0.82	-0.70	-0.77	-0.78	-0.73	-0.60	-0.43	-0.23	-0.03	0.16
Nominal interest rate	0.73	-0.66	-0.47	-0.22	0.06	0.31	0.49	0.58	0.59	0.53
Correlations of terms of trade (e_t) with net exports (nx_{t+j})										
J -curve		-0.09	-0.12	-0.16	-0.14	-0.03	0.17	0.39	0.55	0.60

^a The entries are averages for 100 runs of the length of 188 periods each. Except for net exports and the nominal interest rate, all artificial series are in logs; the nominal interest rate is expressed at annual rates. Before computing the statistics, the artificial series were filtered with the Christiano-Fitzgerald (2003) band-pass filter.

^b Standard deviations are measured relative to that of GDP; the standard deviation of GDP is in absolute terms.

^c Except for net exports and the nominal interest rate, all data series are in logs; net exports are measured as a fraction of trend GDP and the nominal interest rate is expressed at annual rates. All statistics are based on series filtered with the Christiano-Fitzgerald (2003) band-pass filter. Consumption is measured as the sum of nondurables, services, and government expenditures; investment as the sum of fixed private investment and consumer durables; hours as total hours in nonagricultural establishments; and terms of trade as the ratio of import and export price deflators.

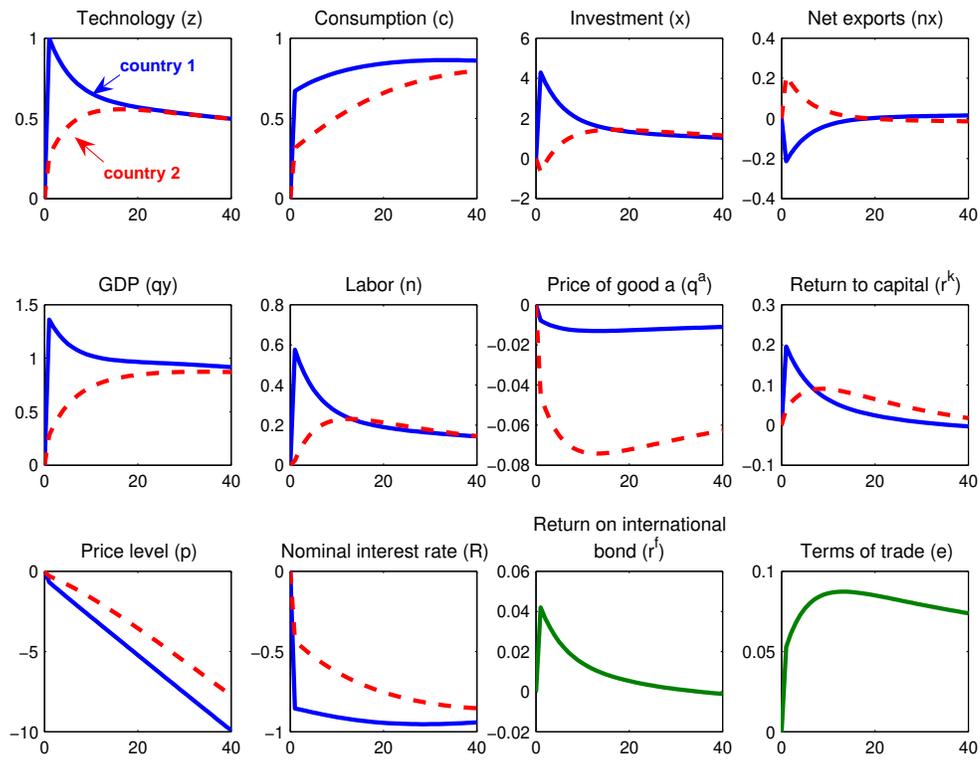


Figure 5: Responses to a 1% technology shock in country 1 for the baseline calibration; rates of return are measured as percentage point deviations from steady state at annual rates; all other variables as percentage deviations.

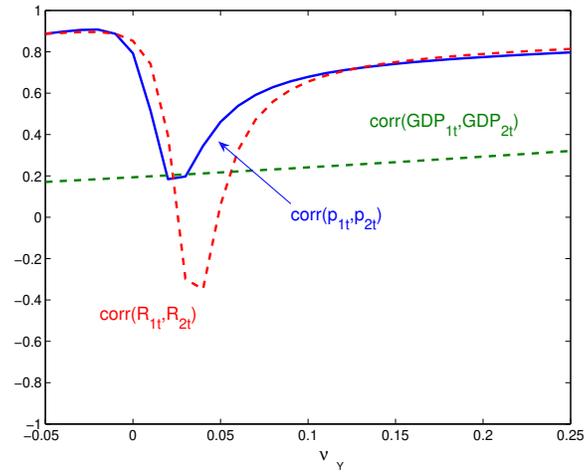


Figure 6: Sensitivity analysis: varying the weight on GDP in the Taylor rule.

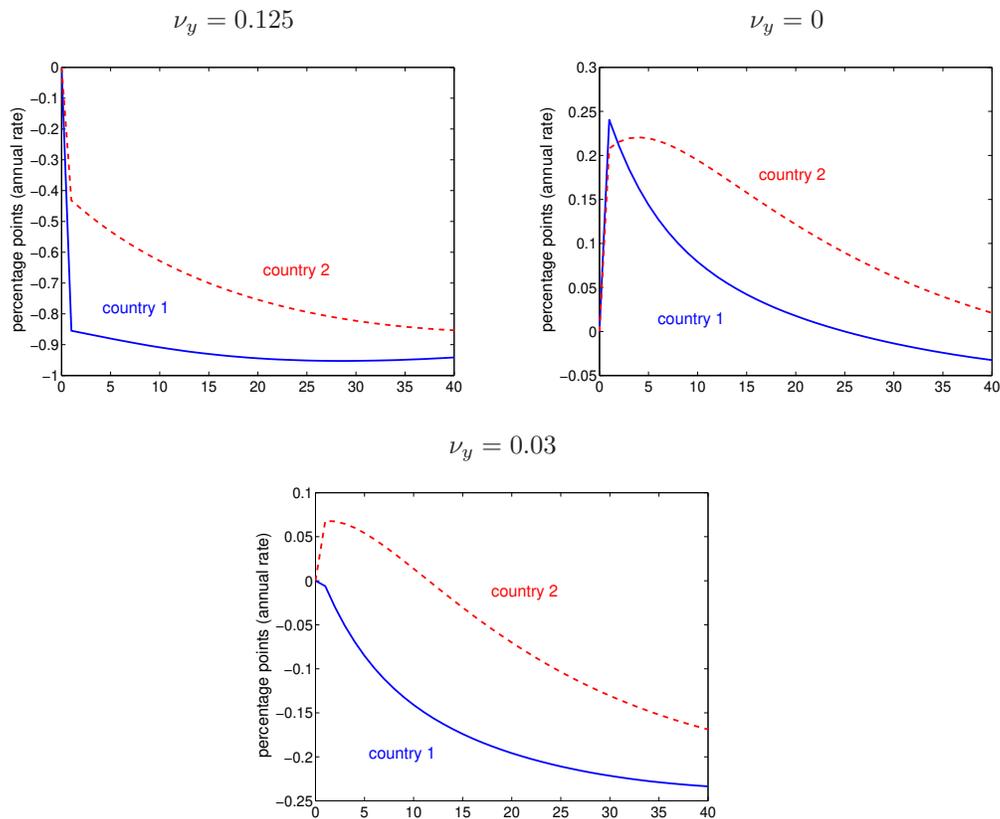
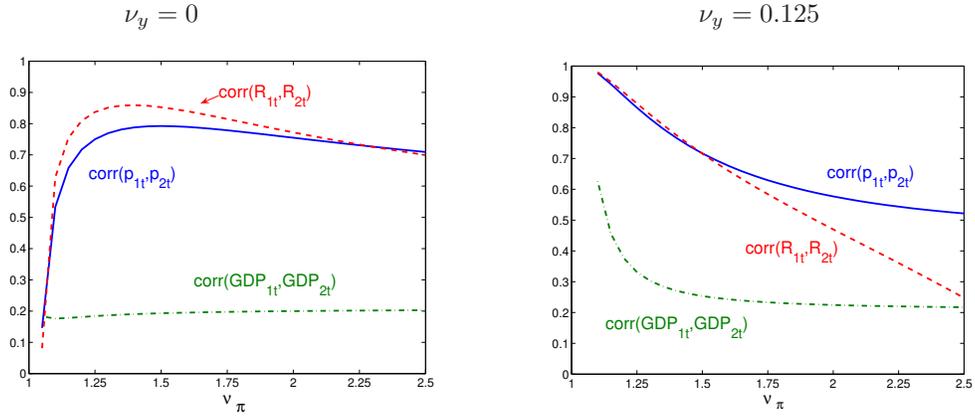
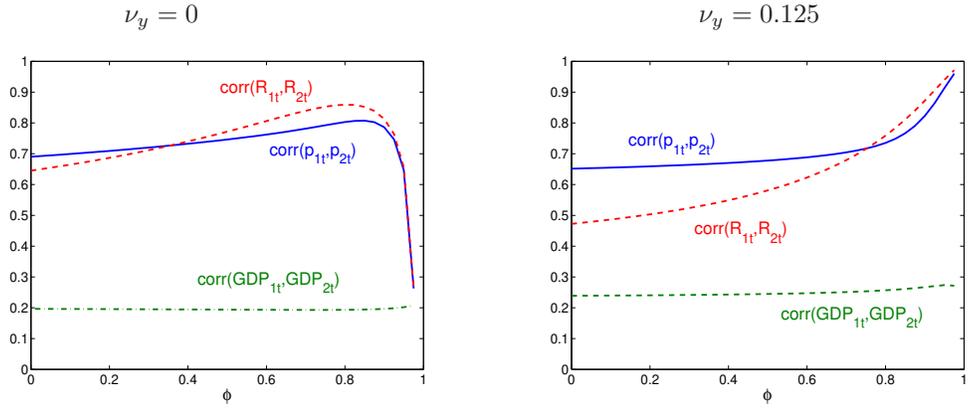


Figure 7: Responses of the nominal interest rate to a 1% productivity shock in country 1; alternative weights on GDP in the Taylor rule.

Weight on inflation in the Taylor rule



Interest rate smoothing



Spillovers

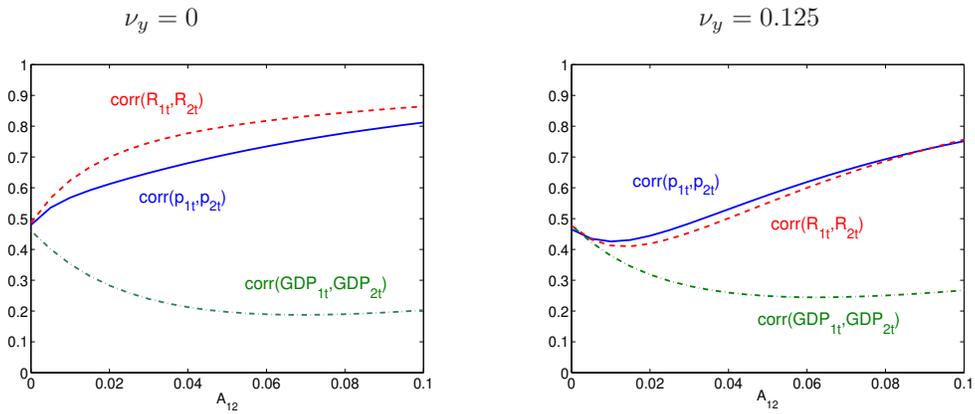


Figure 8: Sensitivity analysis

Table 10: Parameters of the transition matrix in the joint stochastic process for technology and taxes

Λ_{11}	Λ_{12}	Λ_{13}	Λ_{14}	Λ_{21}	Λ_{22}	Λ_{23}	Λ_{24}
0.075	0.642	0.18	-0.44	0.808	-0.112	0.999	0.496

Table 11: Extended model with a tax on bonds

v_{t+j}	Relative std. dev.	Correlations of GDP in period t with variable v in period $t + j$:								
		$j = -4$	-3	-2	-1	0	1	2	3	4
p	0.50	0.06	-0.17	-0.38	-0.43	-0.32	-0.05	0.25	0.41	0.41
R	0.85	-0.16	-0.29	-0.33	-0.19	0.10	0.44	0.67	0.68	0.48

Cross-country correlations		
(p_1, p_2)	(R_1, R_2)	(GDP_1, GDP_2)
0.73	0.91	0.41