level (2.43%) is roughly consistent with the data; due to the weak effect on the real exchange rate (when $\delta=\mathcal{D}=0$), the standard deviation of the nominal exchange rate is nearly identical to that of the price level.

In the nominal rigidities structure ($\delta=\mathcal{D}=0.75$), money shocks have a much stronger effect on real variables--predicted standard deviations of GDP and the real exchange rate: 1.77% and 3.07%, respectively (Col. 6); the standard deviation of the nominal exchange rate is also higher: 3.73% (compared to 2.43% when prices and wages are flexible). The predictions regarding the standard deviations of consumption, investment, net exports and the nominal interest rate also improve when $\delta=\mathcal{D}=0.75$ is assumed.

For the nominal rigidities model, Panel (a) in Figure 1 shows responses to a one-standard-deviation (1.70%) money supply innovation (the following responses represent relative deviations from pre-shock values). The shock induces a rise in the price level (impact effect: 0.45%), which increases however less rapidly than the money supply. As a result, there is a persistent increase in *real* money balances, which explains why the shock induces a reduction in the domestic nominal interest rate that lasts several periods. The expected *real* interest rate in terms of the final good also falls (not shown in Figure) as the expected inflation rate rises. This raises consumption and investment and, hence, GDP (by 1.47%, on impact).

On impact, a 1.70% money shock induces a 3.13% depreciation of the nominal exchange rate, in the nominal rigidities structure; the long-run effect is a 2.28% depreciation. Note that (18), (19) imply that uncovered interest parity holds (up to a certainty-equivalent approximation): $(1+i_t)\cong(1+i_t^*)E_t e_{t+1}/e_t$. The drop in the domestic interest rate hence requires a subsequent appreciation of the currency. On impact, the exchange rate thus overshoots its long run response (as in in Dornbusch (1976)). In contrast, there is no overshooting in the structure with flexible prices and wages.[6]

Due to the sluggishness of the domestic price level, the nominal exchange rate depreciation induces, on impact, a roughly equi-proportional *real* depreciation (subsequently the real exchange rate appreciates).

The foregoing explains why money shocks induce markedly higher standard deviations of the nominal and especially the *real* exchange rate, in the nominal rigidities structure (compared to flexible prices and wages), and a strong positive nominal-real exchange rate correlation, 0.92.

Fig. 1 also explains why the nominal rigidities model (with money shocks) predicts that GDP and exchange rates are positively autocorrelated, that consumption, investment, and money are procyclical, and that net exports are countercyclical, as is consistent with the data (the strong rise in consumption and investment triggered by a positive money shock drives down net exports (not shown in Fig. 1)). The model does not, however, capture the countercyclicality of the price level. Also, nominal and real exchange rates are predicted to be strongly procyclical while, empirically, G3 exchange rates are basically acyclical (see Table 1).

The prediction that positive money shocks lower the domestic interest rate, raise output and the price level, and induce a nominal and real currency depreciation is consistent with empirical evidence on the effect of monetary policy in G3 countries; see, e.g., Fung and Kasumovich (1998).

4.2. Other types of shocks

Under price-wage flexibility, *productivity* shocks have a stronger effect on real variables than money shocks, but a weaker effect on the nominal exchange rate (standard dev. of GDP and of real and nominal exchange rates: 0.97%, 1.21%, 0.65%, with just productivity shocks). Price-wage stickiness dampens the effect of productivity shocks on real variables (Cols. 2, 7).

Whether prices and wages are flexible or not, shocks to the *foreign expected real interest rate* have a sizable effect on nominal and real exchange rates (predicted standard deviations about 2%, when just these shocks are assumed), but only a weak effect on GDP (Cols. 3 and 8). Shocks to the *foreign price level* have a significant effect on the nominal exchange rate but little effect on the remaining variables (Cols. 4 and 9).

For the nominal rigidities structure, Panels (b) and (c) in Fig. 1 show the effects of shocks to domestic productivity and to the foreign expected real interest rate. A positive *productivity shock* causes a rise in GDP, a fall in the price level and a nominal and real currency depreciation. A positive shock to the *foreign real interest rate* similarly induces a nominal and real exchange rate depreciation.

4.3. Combined effect of four types of shocks

In the nominal rigidities structure, money shocks induce larger standard deviations of endogenous variables than the other shocks. When simultaneously subjected to the four shocks, that structure generates predicted statistics that are, thus, largely similar to those reported when just money shocks are used; with the four shocks, the standard deviations of nominal and real exchange rates, 4.54% and 3.71%, are larger than those predicted under flexible prices and wages, 3.59% and 2.00% (Cols. (5) and (10)). The nominal rigidities model with four shocks captures 49% [41%] of the (average) standard deviation of post-Bretton Woods nominal [real]

G3/U.S. exchange rates. It also yields a predicted correlation between nominal and real exchange rates, 0.87, which is markedly higher than that under flexible prices and wages, 0.53 (historical correlation: 0.97).

4.4. Sensitivity analysis

The result that nominal rigidities raise the variability of output and of the nominal and (especially) the real exchange rate, as well as the nominal-real exchange rate correlation, is robust to changes in preference and technology parameters (sensitivity analysis available from author).

Here I discuss alternative assumptions about price and wage adjustment. A variant of the model was considered in which just wages are sticky, with a mean wage-change-interval of 4 periods (while prices are flexible; $\delta=0$, $\mathcal{D}=0.75$), as well as a variant with just sticky prices ($\delta=0.75$, $\mathcal{D}=0$). The key precondition for money shocks to have a noticeable effect on real activity (and to cause exchange rate overshooting) is sufficient domestic *price level* (P) sluggishness (the latter implies that a positive nominal money shock raises real balances, which triggers a fall in the interest rate and a rise in output; see Sect. 4.1). Wage stickiness dampens the response of P as wages are a key determinant of marginal cost (see (6)). Therefore, the structures with just sticky wages or just sticky prices generate higher output and exchange rate variability, and higher nominal-real exchange rate correlations than the structure with price-wage flexibility; however simultaneous price-wage stickiness generates higher variability than the structures with just sticky wages or prices.[7]

Increasing the average time lag between price and wage changes raises predicted output and exchange rate variability. For example, when that lag is set at 6 periods, the model with four shocks captures 59% [54%] of the historical standard deviations of nominal [real] G3/U.S. exchange rates. The average lag must be set at about 15 periods for the model to *exactly* match the historical standard deviations of nominal and real G3/U.S. exchange rates. Such a long lag lacks empirical plausibility.

5. Conclusion

This paper has examined a quantitative dynamic-optimizing business cycle model of a small open economy with nominal rigidities. Predicted exchange rate variability and correlations between nominal and real exchange rates are higher than in standard Real Business Cycle models that postulate flexible prices and wages. The nominal rigidities model, with an average interval between price and wage changes of 4 quarters, captures roughly 40%-50% of the volatility of the exchange rates of Japan, Germany, and the U.K. vis-à-vis the U.S., during the post-Bretton Woods era. Clearly, there is scope for exploring additional mechanisms that induce greater exchange rate variability. For example, the current model could be extended by assuming features that may generate multiple equilibria and permit "sunspot fluctuations" in the exchange rate (and in other variables)--in other words, movements that are not related to changes in the money stock and other fundamentals. Features of this type include production technologies with increasing returns (e.g., Guo and Sturzenegger (1998)) and "noise traders" in exchange markets (Jeanne and Rose (1999)). A key question for future work is whether incorporating these features into the nominal rigidities model would allow to capture *simultaneously* the high volatility of exchange rates and the other key macroeconomic facts considered here.

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Table 1. Historical statistics: Post-Bretton Woods era

Statistic	Country: Japan	Germany	U.K.	Average
	(1)	(2)	(3)	(4)
Standard deviation (in %)				
GDP	1.28 (.16)	1.57 (.15)	1.70 (.15)	1.52
Consumption	1.19 (.16)	1.27 (.14)	1.88 (.19)	1.45
Investment	3.37 (.28)	6.46 (.78)	6.85 (.72)	5.55
Net exports	6.82 (1.0)	2.63 (.35)	3.57 (.39)	4.34
Price level	1.92 (.49)	1.09 (.06)	2.27 (.22)	1.75
Money	1.97 (.20)	2.50 (.26)	2.87 (.46)	2.45
Nominal interest rate	0.45 (.06)	0.43 (.06)	0.51 (.06)	0.46
Nominal $ exchange rate	9.14 (1.0)	9.02 (1.2)	9.23 (.92)	9.13
Real $ exchange rate	9.16 (1.1)	8.63 (1.1)	8.89 (.96)	8.89
Correlation with domestic GDP				
Consumption	0.64 (.04)	0.60 (.08)	0.81 (.05)	0.69
Investment	0.81 (.02)	0.83 (.04)	0.75 (.04)	0.80
Net exports	-0.30 (.10)	-0.30 (.15)	-0.26 (.12)	-0.29
Price level	-0.39 (.24)	-0.53 (.14)	-0.58 (.08)	-0.50
Money	0.01 (.15)	0.31 (.16)	0.44 (.11)	0.25
Nominal interest rate	0.02 (.28)	0.32 (.09)	0.08 (.10)	0.14
Nominal $ exchange rate	0.06 (.18)	-0.21 (.17)	-0.06 (.10)	-0.07
Real $ exchange rate	0.15 (.14)	-0.18 (.17)	-0.01 (.11)	-0.01

Table 1.-- continued

Autocorrelation				
GDP	0.79 (.03)	0.80 (.05)	0.76 (.06)	0.78
Nominal $ exchange rate	0.82 (.02)	0.79 (.05)	0.78 (.05)	0.80
Real $ exchange rate	0.81 (.02)	0.78 (.05)	0.75 (.04)	0.78
Correlation between nominal & real $ exchange rate	0.97 (.01)	0.98 (.00)	0.97 (.01)	0.97

Notes: The figures in parentheses are standard errors (obtained by GMM, assuming tenth-order serial correlation in residuals). All series were logged (with exception of interest rates) and HP filtered.

Col. (4): arithmetic average of the statistics, across the 3 countries.

The **data** are quarterly; unless otherwise indicated, data are from OECD Main Economic Indicators [MEI] and cover 1973Q1-1994Q4. **GDP:** real GDP (for Germany: GNP) from International Financial Statistics [IFS]. **Consumption:** total private consumption, in constant prices. **Investment:** gross fixed capital formation plus inventory change, in constant prices. **Net exports**: *exp/imp*, where *exp* (*imp*) is volume index of exports (imports) of goods and services. **Price level**: CPI. **Money supply**: M1 (German M1 series: 1973Q1-1990Q1). **Nominal interest rate**: short-term rates from Citibase (series FYGECM, FYJPCM, FYGBBB), expressed on a quarterly basis. **Nominal $ exchange rate:** from IFS. **Real $ exchange rate**: based on relative CPIs. Exchange rates are measured as domestic currency prices of the U.S. dollar. German series pertain to *West* Germany.

Table 2. Predictions: model *without* nominal rigidities and nominal rigidities model.

	Model without nominal rigidities					Nominal rigidities model					
	Shocks to:					Shocks to:					
	M	θ	r^*	P^*	$r, P^*, M\&\theta$	M	θ	r^*	P^*	$r, P^*, M\&\theta$	Data
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Standard deviation (in %)											
GDP	0.06	0.97	0.09	0.00	**0.97**	1.77	0.53	0.05	0.05	**1.83**	**1.52**
C	0.10	0.54	0.30	0.00	**0.61**	1.34	0.34	0.14	0.02	**1.37**	**1.45**
I	0.04	2.32	1.29	0.00	**2.64**	6.70	1.38	0.59	0.02	**6.79**	**5.55**
NX	0.10	0.90	2.61	0.00	**2.78**	1.77	0.36	0.84	0.33	**2.02**	**4.34**
P	2.43	0.57	0.35	0.00	**2.53**	1.48	0.29	0.12	0.01	**1.51**	**1.75**
M	2.36	0.00	0.00	0.00	**2.36**	2.36	0.00	0.00	0.00	**2.36**	**2.45**
i	0.06	0.08	0.04	0.00	**0.11**	0.19	0.05	0.02	0.08	**0.20**	**0.46**
e	2.43	0.65	1.92	1.65	**3.59**	3.73	0.57	2.01	1.62	**4.54**	**9.13**
RER	0.01	1.21	1.57	0.00	**2.00**	3.07	0.84	1.93	0.05	**3.71**	**8.89**
Correlation with GDP											
C	0.99	0.99	-0.98	u	**0.82**	0.99	0.99	0.68	-0.92	**0.99**	**0.69**
I	-0.99	0.99	-0.99	u	**0.81**	0.99	0.99	0.70	-0.36	**0.98**	**0.80**
NX	-0.99	0.98	0.99	u	**0.40**	-0.90	0.59	-0.50	0.99	**-0.72**	**-0.29**
P	-0.42	-0.99	0.98	u	**-0.24**	0.21	-0.98	-0.47	0.97	**0.16**	**-0.50**
M	0.34	u	u	u	**0.01**	0.31	u	u	u	**0.30**	**0.25**
i	-0.99	-0.99	0.98	u	**-0.68**	-0.98	-0.99	-0.62	0.90	**-0.98**	**0.14**
e	-0.43	0.98	0.99	u	**0.20**	0.91	0.95	-0.94	-0.71	**0.71**	**-0.07**
RER	-0.95	0.99	0.99	u	**0.67**	0.99	0.98	-0.95	0.81	**0.83**	**-0.01**

Table 2.-- continued

Autocorrelation

GDP	0.04	0.60	0.56	u	**0.60**	0.61	0.81	0.51	0.89	**0.62**	**0.78**
e	0.69	0.51	0.56	0.92	**0.69**	0.64	0.66	0.55	0.92	**0.65**	**0.80**
RER	0.10	0.60	0.56	u	**0.58**	0.57	0.74	0.53	0.64	**0.57**	**0.78**
Correlation between nominal & real exchange rate											
	0.16	0.99	0.99	u	**0.53**	0.92	0.98	0.99	-0.63	**0.87**	**0.97**

Notes: **C**: consumption; **I**: Investment; **P**: price level; **M**: money supply; **i**: nominal interest rate; **e/RER**: nominal/real exchange rate; **NX**: net exports (defined as Q_t^x/Q_t^m, where Q_t^x $[Q_t^m]$ is quantity index of exports [imports]; see (1), (8)).

u: correlation not defined (series with zero variance).

Cols. labelled "Shocks to M", "Shocks to θ" etc. pertain to cases in which shocks to just *one* of the exogenous variables are assumed (θ: domestic productivity; P^*: foreign price level; r^*: foreign real interest rate). Cols. labelled "Shocks to r^*,P^*,M&θ": four types of shocks used simultaneously.

"Data" Col. (11): average of historical statistics across G3 countries (from Table 1).

The theoretical statistics (Cols. (1)-(10)) are averages of moments computed over 1000 simulation runs with a length of 88 periods each (which corresponds to the length of the historical time series used in Table 1). All series were logged (with exception of interest rates) and HP filtered.

[1] In the Obstfeld-Rogoff model, with prices set one period in advance, nominal exchange rate volatility (due to money shocks) is lower (for plausible parameter values) than if prices were flexible.

[2] The basic structure here was developed before I became aware of these studies (Kollmann (1993, 1996)). The present study is, thus, an independent and complementary analysis. Betts and Devereux (1998) focus on the international transmission of monetary and fiscal policy shocks. The Chari et al. model can generate more real exchange rate volatility than standard RBC models, provided highly risk averse households are postulated, but it assumes longer periods of price stickiness than the paper here.

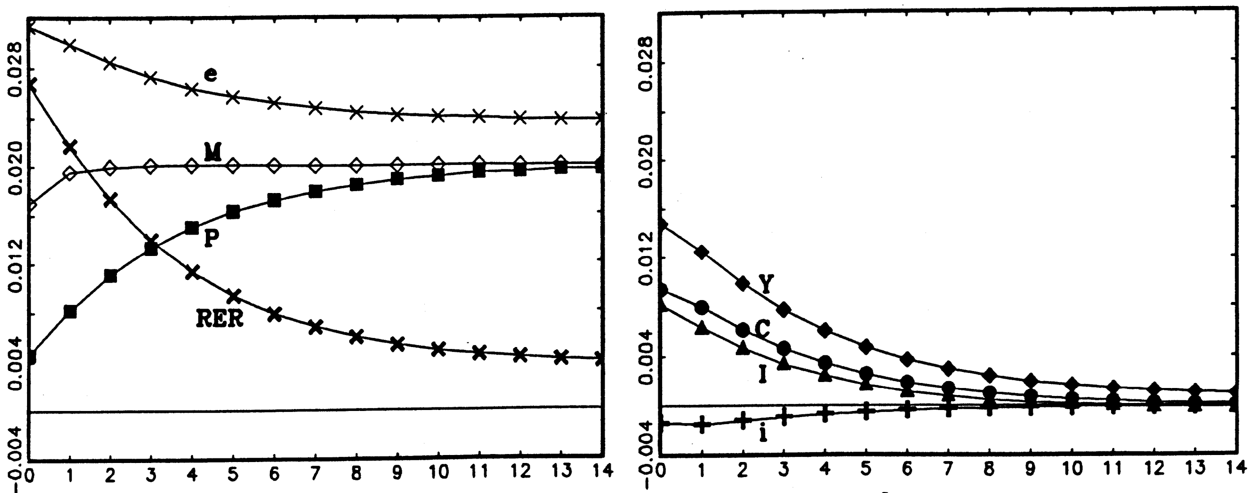
[3] Linearizing the model yields equations in aggregate variables that do not depend on γ (see (5)); thus, no value needs to be assigned to γ.

[4] For the M1 money series in Table 1 and Kollmann's (1998) linearly detrended log total factor productivity series (75Q1-91Q3), the following estimates are obtained (by OLS; an intercept was included in empirical regressions): ρ^m=0.14, 0.12, 0.19; σ^m=0.015, 0.017, 0.018; ρ^θ=0.82, 0.85, 0.80; σ^θ=0.012, 0.014, 0.009 for Japan, Germany, and the UK, respectively.

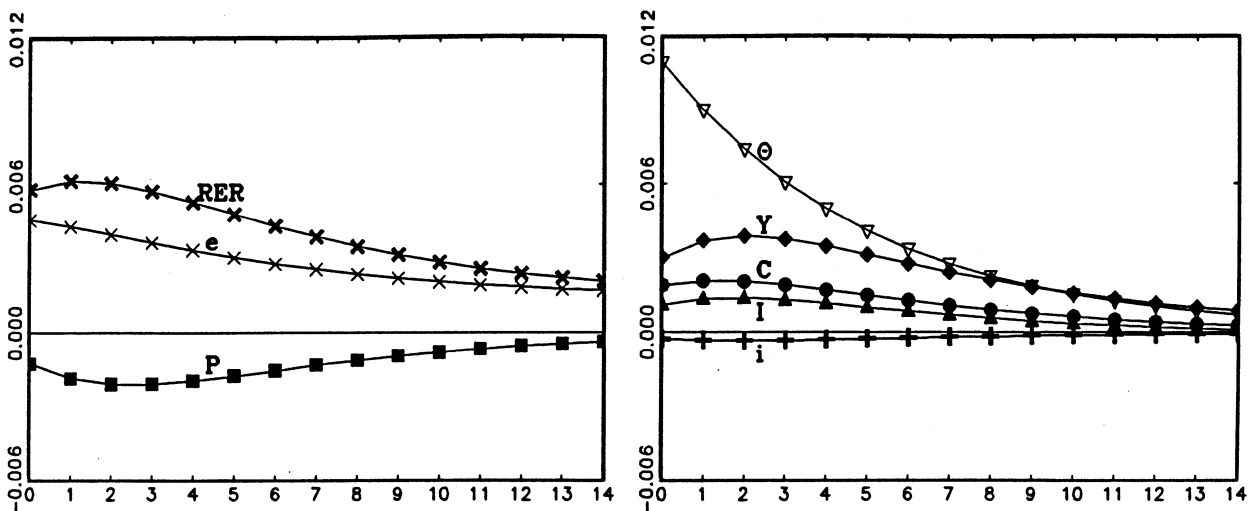
[5] Constructing a series for r_t^* using the formula $r_t^* \cong i_t^* - \rho^P \ln(P_t^*/P_{t-1}^*)$, with ρ^P=0.80, and fitting an AR(1) process to r_t^* yields ρ^r=0.76, σ^r=0.005.

[6] In that structure the expected *real* interest rate is hardly affected by money shocks, and a positive money shock raises the nominal interest rate, as the shock raises the expected inflation rate (due to positive serial correlation of money growth)--thus, no nominal exchange rate overshooting.

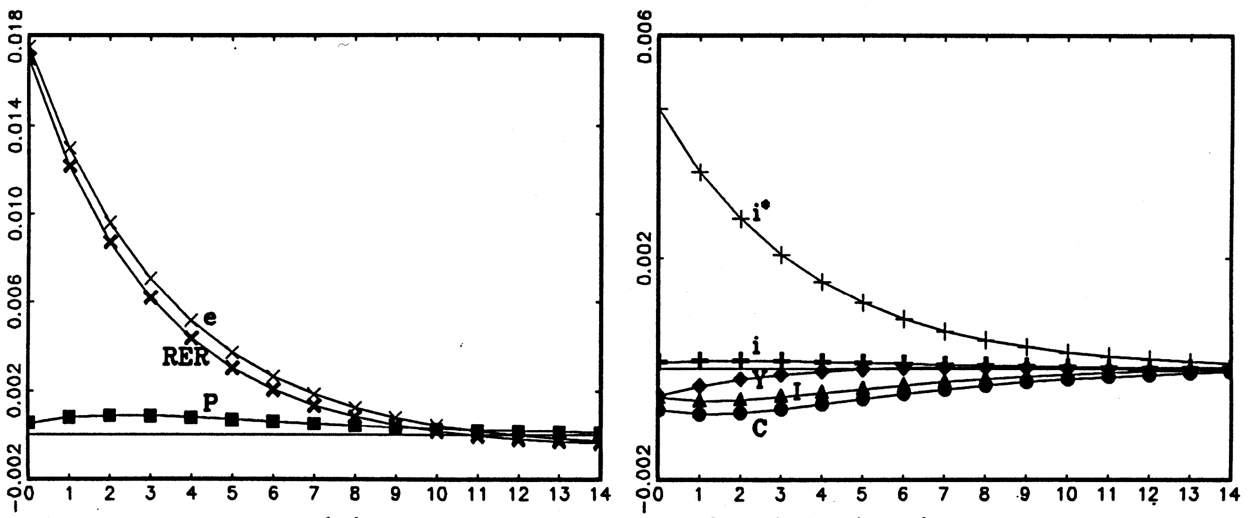
[7] When there are solely money shocks, the standard deviations of GDP, of nominal and real exchange rates, and the nominal-real exchange rate correlation are 1.06%, 2.95%, 1.33%, 0.87 with just sticky wages, and 1.31%, 3.26%, 2.35%, 0.87 with just sticky prices--compared to 0.06%, 2.43%, 0.01%, 0.16 without nominal rigidities, and to 1.77%, 3.73%, 3.07%, 0.92 with sticky prices *and* wages. With the four shocks, the corresponding statistics are 1.60%, 3.93%, 2.46%, 0.74 with just sticky wages; 1.40%, 4.22%, 3.15%, 0.83 with just sticky prices; 0.97%, 3.59%, 2.00%, 0.53 without nominal rigidities; 1.83%, 4.54%, 3.71%, 0.87 with sticky prices *and* wages.



(a) Shock to domestic money supply



(b) Shock to domestic productivity



(c) Shock to foreign real interest rate

Figure 1.-- continued on next page

Figure 1 Nominal rigidities model

Dynamic responses to 1 standard deviation innovations to domestic money supply, domestic productivity and foreign expected real interest rate. Interest rate responses expressed as differences from initial position; consumption and investment responses shown in units of initial GDP; responses of other variables shown as relative deviations from initial position. Period t money stock response pertains to end of period money stock (M_{t+1}). Abscissa: periods after shock.

◇: money, M; ▽: productivity, θ; +: foreign nominal interest rate, i^*;

■: price level, P; ×: nominal exchange rate, e; ✖: real exchange rate, RER;

●: consumption, C; ▲: investment, I; ◆: real GDP, Y;

✚: domestic nominal interest rate, i.