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Endogenous monetary policy and the business cycle

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Abstract

The correlations and volatilities of real variables seem to be stable over time, but the relation between real and nominal variables is unstable. Presumably, one important factor behind this observation is the nature of money supply. In this paper, I look at a business cycle model where the central bank sets money supply to minimize the volatility of inflation and output. I find that small changes in the central bank's preferences can generate large changes in the derived money supply rule and in correlations between real and nominal variables. Although wages are assumed to be sticky, changes in the money supply rule do not generate any major changes in the behavior of real variables. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

It is widely acknowledged that money, inflation, and output are positively correlated over the business cycle. The behavior of real variables seems to be stable, but there is clear evidence that the relations between real and nominal variables change over time. In a large sample of countries, Backus and Kehoe

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(1992) find real variables to behave similarly in different subperiods while the behavior of money, inflation, and the price level is changing. Gavin and Kydland (1996) document these facts for U.S. post-war data.

Presumably, variations in the monetary policy is one important explanation to these observations. Even if money does not have any major real effects, changes in money supply certainly have a large impact on nominal variables. If the central bank takes real variables such as output and unemployment into consideration when deciding on money supply, nominal and real variables will be correlated just because of the central bank's reactions to changes in these variables, and if the money supply rule changes, so will correlations between real and nominal variables.

In the present paper, the central bank does indeed take the real economy into consideration when deciding on monetary policy. More precisely, I solve for the money supply rule that minimizes the central bank's loss function over inflation and output variability in a dynamic stochastic general equilibrium model. There are shocks both to productivity and in the money supply process. Wages have to be set before contemporaneous shocks and central bank decisions are observed. Hence, unanticipated changes in money supply have real effects.

I find, as did Gavin and Kydland (1996), that changes in the money supply rule can induce large changes in the business cycle behavior of nominal variables. The present paper adds to Gavin and Kydland's analysis by showing that money supply rules can change substantially when central bank preferences change. I find that the quantitative effects that monetary policy has on real variables are small but significant enough to make the optimal money supply rule change considerably when the central bank's weight put on output stability changes. The paper thus shows that sizeable variations in the central bank reaction function can be a reality.

The reason for the instability of the optimal money supply rule is that the central bank faces a trade-off between output and inflation stabilization. When the central bank puts much weight on output stability, its response to a negative productivity shock is as follows. The central bank observes the shock and increases money supply directly. Since nominal wages are assumed to be sticky, this action will decrease real wages and thus stimulate employment. Wage contracts will then be renegotiated, so the central bank cannot exploit the Phillips curve in later periods. Instead, the central bank contracts money supply in successive periods to decrease inflation. This leads to a temporary decrease in the distortionary effects from inflation and stimulates real activity. When, on the other hand, the central bank puts much weight on inflation stability its reactions are different. The central bank does not exploit the Phillips curve at all. Instead it contracts money supply in order to dampen the inflationary tendencies caused by the productivity shock. Compared to the first scenario, the central bank's willingness to use the timing of the inflation tax as an instrument to stabilize output has decreased.

The paper has implication both for empirical and theoretical research on the role of money in the business cycle. When trying to estimate, for example, a vector autoregression including both real and nominal shocks in the system, one must be careful in controlling for changes in monetary regimes. Ideally, one should use short time series for periods of stable monetary policy. Moreover, using high-frequency data (as do for example Bernanke and Mihov, 1995) is an advantage since then, arguably, the central bank cannot influence contemporaneous output. The main implication for theoretical modeling is that we should not expect there to be *one* business cycle behavior of nominal variables, but rather one behavior for each monetary regime.

Before going on to the model and its implications, I will shortly comment on earlier literature in this field. Methodologically, my approach is akin to the real business cycle framework. The model I work with is not purely 'real', though, since there are money supply shocks and wage rigidity.

My attempt to introduce money supply in this framework is not new, but until recently a common critique against real business cycle models was their absence or ignorance of monetary issues. Some articles allowed for money, in particular King and Plosser (1984), but the focus was still on the real economy and productivity shocks. Lately, though, several attempts to incorporate effects of monetary policy in dynamic general equilibrium models have been done, for example Cooley and Hansen (1989, 1995) and Huh (1993).[1] Cooley and Hansen (1995) assume that money supply is exogenous and follows an AR(1) process. In reality, however, the central bank reacts to changes in the economic environment when they decide on the monetary policy. This has been captured in the paper by Huh. He postulates a reaction function for the central bank, and this is fitted to actual data.

In a recent paper, Gavin and Kydland (1996) first document that the volatility and cross-correlations of real variables have been stable in post-war U.S. data but that the correlations between real and nominal variables have changed over time. They then look at a model with a transactions motive for holding money, and experiment with different money supply rules. As expected, they find that changes in the money supply rule have large effects on the correlations between real and nominal variables, but that the behavior of real variables is unaffected by the experiments.

To model monetary policy out of the general equilibrium framework has been typical for research in the real business cycle tradition so far. In this paper, I will assume that the central bank sets monetary policy to minimize a loss function over inflation and output. The central bank is assumed to dislike both inflation in itself and fluctuations in output and inflation. The main difference

[1] Surveys of this literature can be found in Van Els (1995), and Nelson (1997).

between my setup and earlier dynamic equilibrium models with money is that money growth was typically fitted to actual data in previous work, whereas I let monetary policy be the equilibrium outcome of the model used. Since the model is only a simplification of the true economy it will be more relevant to relate monetary policy to the model than to data, if we want to learn anything about how monetary policy works and how it (at least theoretically) drives the business cycle. A limitation of the approach is that the central bank's preferences are not derived from the preferences of the agents in the economy.

The paper is organized as follows. In Section 2, I present the model used in the paper. Then, in Section 3, I calibrate the model and look at its business cycle properties. In Section 4, I look at how changes in central bank preferences affect the bank's behavior and the business cycle properties of the simulated economy. Section 5 concludes.

2. Model

The model I use builds on the cash-in-advance model with nominal wage rigidities described in Cooley and Hansen (1995). Here, I extend that model to incorporate endogenous monetary policy. The central bank is assumed to minimize a loss function over output and inflation. I assume that the central bank can commit to follow a policy rule which, under some restrictions, is optimal ex ante. Since the basic setup of the model is the same as Cooley and Hansen's, I will only give a brief description of it here.

Aggregate production is given by

$$Y_t = e^{z_t} K_t^{\theta} H_t^{1-\theta},$$

where z is the level of productivity, K is the aggregate capital stock and H is the aggregate labor supply. When relevant, lower-case letters denote individual holdings and capital letters denote aggregate holdings.

Productivity is assumed to follow an autoregressive process,

$$z_{t+1} = \rho z_t + \varepsilon_{t+1},$$

where ε is Gaussian white noise.

Letting X denote investment and δ the depreciation rate of physical capital, the capital stock evolves according to

$$K_{t+1} = (1-\delta)K_t + X_t.$$

There are two consumption goods, c_1 which requires cash, and c_2 which can be bought on credit. Previously accumulated cash balances are thus needed to purchase the 'cash good'. Purchases of the cash good must then fulfill

$$P_t c_{1t} \le m_t + (1 + R_{t-1})b_t + T_t - b_{t+1}, \tag{1}$$

where P is the nominal price level, m is money holdings in the beginning of the period, b is bond holdings, R is the nominal interest rate on bonds and T is a lump sum transfer from the government to the households.

Agents also have to fulfill the budget constraint

$$c_{1t} + c_{2t} + x_t + \frac{m_{t+1} + b_{t+1}}{P_t} \leq w_t h_t + r_t k_t + \frac{m_t + (1 + R_{t-1}) b_t + T_t}{P_t}, \tag{2}$$

where w is the real wage rate and r is the real return on capital. These factor returns are determined by the firms' profit maximization and are

$$w_t = (1 - \theta) \mathrm{e}^{z_t} \left(\frac{K_t}{H_t} \right)^{\theta}$$

and

$$r_t = \theta \mathrm{e}^{z_t} \left(\frac{H_t}{K_t} \right)^{1-\theta}.$$

The government's budget constraint is

$$T_t = M_{t+1} - M_t + B_{t+1} - (1 + R_{t-1}) B_t.$$

To simplify, we assume that the government does not issue any bonds, $B_t \equiv 0$.[2] We then get

$$T_t = M_{t+1} - M_t.$$

Agents have preferences for both consumption goods and for leisure. Each agent's labor input is assumed to be indivisible as in Hansen (1985). The representative agent's utility function is

$$u(c_1, c_2, h) = \alpha \ln c_1 + (1 - \alpha) \ln c_2 - \gamma h.$$

Money evolves according to

$$M_{t+1} = \mathrm{e}^{\mu_t} M_t \equiv g_t M_t.$$

The money stock is controlled by the central bank, which decides μ_t, perfectly or imperfectly.

[2] The reason for introducing bonds into the model is that they enable us to solve for the nominal interest rate.

2.1. The agents' problem

If nominal interest rates are positive, the cash-in-advance constraint (1) will bind. The budget constraint (2) will also bind. From these two equations we get

$$Pc_1 = m + M' - M = m + (g-1)M \tag{3}$$

and

$$c_1 + c_2 + x + \frac{m'}{P} = wh + rk + \frac{m}{P} + \frac{(g-1)M}{P}. \tag{4}$$

Time subindices have been suppressed to simplify notation. Primes denote next period's variables. The money stock and the price level are non-stationary variables. We introduce two new stationary transformations of them,

$$\hat{m} \equiv \frac{m}{M}$$

and

$$\hat{P} \equiv \frac{P}{M'} = \frac{P}{gM}.$$

From Eq. (3), we then get

$$c_1 = \frac{\hat{m}M + (g-1)M}{\hat{P}gM} = \frac{\hat{m} + g - 1}{g\hat{P}}. \tag{5}$$

We can then substitute for c_1 in Eq. (4) and get

$$\begin{aligned} c_2 &= wh + rk - x + \frac{\hat{m}M}{\hat{P}gM} + \frac{(g-1)M}{P} - \frac{\hat{m} + g - 1}{g\hat{P}} - \frac{\hat{m}'gM}{\hat{P}gM} \\ &= wh + rk - x - \frac{\hat{m}'}{\hat{P}}. \end{aligned} \tag{6}$$

From now on, I will disregard of the 'hats' and use m and P instead of $\hat{m}$ and $\hat{P}$ respectively.

Now, the agents' problem can be specified as the dynamic optimization problem

$$v(\tilde{z}, K, k, m) = \max_{\{d, m'\}} \{u(c_1, c_2, h) + \beta \mathrm{E} v(\tilde{z}', K', k', m')\} \tag{7}$$

subject to

$$u(c_1, c_2, h) = \alpha \ln c_1 + (1-\alpha) \ln c_2 - \gamma h,$$

Eqs. (5) and (6), where, if we temporarily ignore the money growth process, the exogenous state variables are $\tilde{z} = [1 \;\, z]'$, the endogenous state variable is k, and the decision variables are $d = [x \;\, h]'$. The dynamics of this economy are given by

$$\tilde{z}' = \begin{bmatrix} 1 & 0 \\ 0 & \rho \end{bmatrix} \tilde{z}$$

and

$$k' = B(k, x) \equiv (1-\delta)k + x.$$

2.2. Nominal rigidities

In order to get interesting effects of monetary policy, I introduce a nominal rigidity. More specifically, I assume that nominal wages are set before contemporaneous productivity shocks are observed. The nominal wage, W^c, is set equal to the expected marginal product of labor (in nominal terms), i.e.

$$W^c = \mathrm{E}\left\{P(1-\theta)\,\mathrm{e}^z\left(\frac{K}{H^{\mathrm{e}}}\right)^{\theta}\right\},$$

where H^{e} is the expected labor demand. After the shocks have been revealed firms decide on labor demand. Now W^c is given, so the labor input chosen by firms is that which makes the marginal product of labor equal to the real wage, i.e. firms choose H such that

$$\frac{W^c}{P} = (1-\theta)\,\mathrm{e}^z\left(\frac{K}{H}\right)^{\theta}.$$

Combining these two equations, taking logs, approximating the logs of expected values with expected values of logs, and solving for H results in

$$\ln H = \mathrm{E}\ln H + \frac{1}{\theta}(\ln P - \mathrm{E}\ln P) + \frac{1}{\theta}(z - \mathrm{E}z). \tag{8}$$

As earlier, we work with transformed prices, $\hat{P} = P/M'$. To be able to reformulate (8) in terms of transformed prices we note that, $\ln P = \ln \hat{P} + \ln M'$, and $\ln M' = \ln M + \mu$. Now,

$$\ln M' - \mathrm{E}\ln M' = \mu - \mathrm{E}\mu.$$

We also know that $z - \mathrm{E}z = \varepsilon$. From this we get

$$\ln H = \mathrm{E}\ln H + \frac{1}{\theta}(\ln \hat{P} - \mathrm{E}\ln \hat{P}) + \frac{1}{\theta}\varepsilon + \frac{1}{\theta}(\mu - \mathrm{E}\mu). \tag{9}$$

2.3. Central bank behavior and money supply

I assume that the central bank can commit to follow a rule which is linear in the state variables, and which is decided before any realizations of the state variables are observed. When deciding on the rule, the central bank takes into account the effects its decision has on the behavior of the agents in the economy. The bank also uses its knowledge of the probability distribution for the future state variables and how these depend on the policy rule it chooses. Given the linear approximation of the agents' decision rules, and the approximation $\ln(1+\pi) \approx \pi$, the quadratic loss function implies that the optimal money supply rule under commitment would be linear in the state variables if the central bank did not take into account the effects its actions have on agents' decision rules. Here, however, the central bank does consider changes in agents' decision rules when deciding on the policy rule. Therefore, the optimal linear rule need not be the same as the rule chosen when the central bank can commit to follow *any* rule.

A natural question to ask at this point is if this kind of rule realistically captures the actual behavior of central banks. I will not claim that it does. My rationale for using it is that it is simpler to model. I also believe that the linear rule is a good approximation of the optimal rule with no linearity restriction. Moreover, as suggested e.g. in Currie and Levine (1993), it is difficult for the public to monitor the central bank's fulfillment of a complex rule. If that is the case, committing to follow the complex rule might be impossible. When information is incomplete and learning is important, a simple rule might outperform a more complex rule.

As mentioned earlier, the central bank is assumed to have preferences for inflation and output stability. It conducts monetary policy to minimize a weighted sum of the unconditional variances of inflation and output,

$$L = \tfrac{1}{2}\mathrm{E}\,[(\pi_t - \pi^*)^2 + \lambda(y_t - y^*)^2], \tag{10}$$

where π^* is the central bank's inflation target, y_t is log output, and y^* its output target. The output target is assumed to be the logarithm of output in the steady state where $\pi = \pi^*$. Inflation is given by

$$\pi_t = \frac{P_t}{P_{t-1}} - 1 = \frac{\hat{P}_t M_{t+1}}{\hat{P}_{t-1} M_t} - 1 = \mathrm{e}^{\mu_t} \frac{\hat{P}_t}{\hat{P}_{t-1}} - 1.$$

The central bank's loss function is not motivated by maximization of agents' utility. In particular, nothing in the model can rationalize positive nominal interest rates or inflation. Also, the desire to stabilize output around the steady state might look like a strange objective. However, agents prefer a smooth level of consumption, and for a given average level of inflation, all the central bank will do to stabilize output is to shift inflation over time. Due to the wage rigidity, hours worked will overreact to productivity shocks. The central bank will mitigate these overreactions and it will shift the distortions from the inflation tax to times when consumption is high. This will not influence the average level of output or consumption. Simulations show that the agents' average utility is slightly increasing in λ, at least for $\lambda \in [0, 0.5]$.

The central bank sets the money growth rate, μ_t^{CB}, after observing the productivity shock, ε_t. We also assume that the bank does not have perfect control over the money growth rate, so realized money growth is given by

$$\mu_t = \mu_t^{\mathrm{CB}} + \xi_t,$$

where ξ is Gaussian white noise with variance σ_ξ^2.[3] This setup results in the following decision rule for the money growth rate:[4]

$$\mu_t^{CB} = \beta_1 + \beta_2 z_{t-1} + \beta_3 \varepsilon_t + \beta_4 \ln K_t + \beta_5 \ln \hat{P}_{t-1}. \tag{11}$$

I thus assume that the central bank sets money supply at time t after having observed the contemporaneous productivity shock, ε_t, but not the money growth shock, ξ_t. Agents on the other hand observe both shocks and thereby also μ_t before they have to make their decisions for hours worked and consumption.

2.4. Equilibrium and solution

I solve the model by making a linear quadratic approximation around the steady state. The equilibirum then consists of a matrix $\boldsymbol{\alpha}$ describing the dynamics of capital, labor supply, and prices, and a decision rule for money supply, $\boldsymbol{\beta}$. More specifically the dynamics of the economy are determined by the following two equations in addition to the exogenous process for productivity:

$$\begin{bmatrix} \ln K_{t+1} \\ \ln H_t \\ \ln P_t \end{bmatrix} = \boldsymbol{\alpha} \begin{bmatrix} 1 \\ z_{t-1} \\ \varepsilon_t \\ \xi_t \\ \ln K_t \\ \ln \hat{P}_{t-1} \end{bmatrix},$$

$$\mu_t = \boldsymbol{\beta} \begin{bmatrix} 1 \\ z_{t-1} \\ \varepsilon_t \\ \ln K_t \\ \ln \hat{P}_{t-1} \end{bmatrix} + \xi_t.$$

[3] Cooley and Hansen assume that ξ is log-normally distributed in order to ensure that money growth is always positive. They thereby guarantee that the cash-in-advance restriction binds. There is no point for me to make the same assumption since the derived money supply rule (11) will allow money growth to be negative anyway. I assume that the cash-in-advance restriction binds and disregard the problem.

[4] With exogenous money supply, the state variables for agents would be z_{t-1}, ε_t, $\ln K_t$, ξ_t, and possibly previous realizations of money growth. Here, the central bank does not observe ξ_t when deciding on μ_t^{CB}. Moreover, $\ln \hat{P}_{t-1}$ is needed as a state variable to calculate inflation in the loss function.

The equilibrium conditions are:

- For a given $\boldsymbol{\beta}$, $\boldsymbol{\alpha}$ is consistent with optimization of firms and individuals. Hence, $\boldsymbol{\alpha}$ can be thought of as a function of $\boldsymbol{\beta}$.
- The money supply rule $\boldsymbol{\beta}$ solves the central bank's optimization problem, i.e. $\boldsymbol{\beta}$ is the solution to

$$\min_{\boldsymbol{\beta}} L(\boldsymbol{\alpha}(\boldsymbol{\beta}), \boldsymbol{\beta}).$$

To solve this problem in practice, I rely on numerical methods. The algorithm is as follows. First, guess some $\boldsymbol{\beta}$ and solve for $\boldsymbol{\alpha}$. I describe below how to solve that problem. Then evaluate the central bank's loss function for this money supply rule. Next (numerically), differentiate the loss function with respect to the elements in the vector $\boldsymbol{\beta}$. Finally, use some minimization algorithm to update the candidate solution to the minimization problem. The problem appears to be very non-linear, and at least for high values of λ, the solution is sensitive to the initial guess of $\boldsymbol{\beta}$. I have therefore experimented with a variety of initial values.

To solve the representative agent's problem for a given money supply rule I do as follows.[5] First, solve the problem without wage rigidities. This is a standard real business cycle exercise. Let $\tilde{\boldsymbol{\alpha}}$ denote the decision rules then obtained, i.e.

$$\begin{bmatrix} \ln \tilde{K}_{t+1} \\ \ln \tilde{H}_t \\ \ln \tilde{P}_t \end{bmatrix} = \tilde{\boldsymbol{\alpha}} \begin{bmatrix} 1 \\ z_{t-1} \\ \varepsilon_t \\ \xi_t \\ \ln \tilde{K}_t \\ \ln \tilde{P}_{t-1} \end{bmatrix}.$$

Next, note that the linear quadratic approximation used in obtaining the above solution imposes certainty equivalence on the problem. Therefore $\mathrm{E} \ln H = \mathrm{E} \ln \tilde{H}$, and $\mathrm{E} \ln \hat{P} = \mathrm{E} \ln \tilde{P}$. By using these equalitites in (9), I can solve for hours actually worked to get the actual $\boldsymbol{\alpha}$. The money supply rule is implicit in the solution to the agent's problem. The state variable $\ln \hat{P}_{t-1}$ together with the other state variables provide sufficient information for agents to make the best prediction of money growth at t. To solve this economy I also use μ as a state variable, even though it will not appear in the decision rules. It is needed to calculate hours actually worked from Eq. (9).

[5] This exactly follows Cooley and Hansen (1995).

3. Business cycle properties of the model

In this section, the general business cycle behavior of the model is discussed and evaluated. The main conclusion is that the model captures many, but not all, features of the business cycle, and that it behaves at least as good as other models in the field.

As far as possible, the model is calibrated with values from Cooley and Hansen (1995). In addition to those values, we must specify the standard deviation of the money supply shocks, σ_ξ, and the weight on output stability in the central bank's loss function, λ. It turns out that letting $\sigma_\xi = 0.0089$, the same value as in Cooley and Hansen, yields a standard deviation of μ which is close to 0.0089 even though Cooley and Hansen's money growth process is totally different from the one used in this model. Rather arbitrarily, I first let $\lambda = 0.1$ and $\lambda = 0.5$. Those values make the central bank's average loss from output fluctuations approximately of the same size as the average loss from inflation fluctuations. The parameter values used are summarized below:

$$\alpha = 0.84, \quad \beta = 0.989, \quad \gamma = 2.53, \quad \delta = 0.019,$$

$$\theta = 0.40, \quad \rho = 0.95, \quad \sigma_\varepsilon = 0.007.$$

The business cycle properties of the real variables in the U.S. economy are well known. All of them are highly procyclical, except the capital stock which is acyclical. Investment is much more volatile than output and hours worked, which in turn are more volatile than consumption and the capital stock. Productivity leads the business cycle slightly while all other real variables peek at the same time as production. The most important feature of the nominal variables is that prices are countercyclical while inflation and money are procyclical. Inflation lags the business cycle but prices and money lead the cycle. Tables 1 and 2 summarize the business cycle statistics for the U.S. economy and for simulated economies with $\lambda = 0.1$ and 0.5. All statistics reported, both for the U.S. economy and for the model economies, are calculated on detrended variables.[6]

Responses to productivity shocks in the simulated economies are reported in Fig. 1. The solid lines in these graphs show impulse responses for an economy where money supply is exogenously specified to be autocorrelated and stochastic (Cooley and Hansen's model), while the dashed lines show the impulse-responses for economies with $\lambda = 0.1$ and 0.5. Tables 1–3 report volatilities and correlations of the variables in these economies. We see that the model generates

[6] The variables were detrended with an H-P filter with $\lambda = 1600$, except data on the real interest which Stock and Watson (1998) detrended with a bandpass filter.

Table 1
Volatility

Variable	U.S.	$\lambda = 0.1$	$\lambda = 0.5$
Output	1.72	2.09	1.87
Consumption	0.86	0.43	0.43
Investment	8.24	7.50	6.58
Capital stock	0.63	0.39	0.34
Hours	1.59	2.44	2.27
Productivity	0.90	0.93	1.04
Prices[a]	1.43	1.10	1.62
Inflation	0.57	0.88	1.09
Nominal interest rate[b]	1.29	0.50	0.43
Real interest rate	n.a.	0.04	0.04
Money[c]	0.84	0.85	0.93
Velocity[d]	1.94	1.79	1.57
Money growth	0.009	0.009	0.012

Notes: U.S. data adapted from Cooley and Prescott (1995), Cooley and Hansen (1995) and Hansen (1985). Volatility is measured as the standard deviation of percentual fluctuations around trend.
[a] CPI for U.S. data.
[b] TB1MO for U.S. data.
[c] Monetary base for U.S. data.
[d] Velocity of M1 for U.S. data.

procyclical inflation. Prices are countercyclical when λ is high but almost acyclical when λ is low. The nominal interest rate is acyclical. The correlation between consumption and output is close to that in the U.S. economy and consumption and output are not as volatile as in Cooley and Hansen's model. In contrast, Huh's (1993) model generates a counterfactually high correlation between output and consumption (0.98). Also, the behavior of the nominal interest rate and the leads and lags of nominal variables are more satisfactory than in Huh's model.

The impulse-responses in Fig. 2 show that money supply shocks have transitory effects both on real and on nominal variables. A positive shock to money supply leads to increased output and inflation in the period following the shock, but most variables have returned to the equilibrium levels two periods after the shock. The very transitory nature of these responses is not compatible with the evidence from vector autoregressions on U.S. data. For example, Christiano et al. (1998a, b) find that the largest output effect of a monetary policy shock comes six to eight quarters after the shock, while inflation responds somewhat earlier.

These transitory effects of money are also in line with Nelson's (1997) finding that most equilibrium models with money fail to capture two properties of the U.S. economy, namely that inflation reacts to money shocks with a lag and that inflation is persistent. The statistics in Table 3 show that this critique certainly

Table 2
Correlations with output

Variable x	Cross-correlation of output (t) with								
	$x(t-2)$			$x(t)$			$x(t+2)$		
	U.S.	$\lambda_{0.1}$	$\lambda_{0.5}$	U.S.	$\lambda_{0.1}$	$\lambda_{0.5}$	U.S.	$\lambda_{0.1}$	$\lambda_{0.5}$
Output	0.63	0.26	0.28	1.00	1.00	1.00	0.63	0.26	0.28
Consumption	0.68	0.14	0.31	0.77	0.75	0.76	0.47	0.50	0.44
Investment	0.59	0.26	0.26	0.91	0.99	0.99	0.50	0.20	0.23
Capital stock	n.a.	– 0.31	– 0.34	0.04	– 0.05	– 0.08	n.a.	0.46	0.45
Hours	0.53	0.18	0.12	0.86	0.93	0.89	0.69	0.10	0.15
Productivity	0.30	0.10	0.25	0.41	– 0.19	– 0.16	0.00	0.31	0.18
Prices[a]	– 0.72	– 0.28	– 0.50	– 0.52	– 0.06	– 0.39	– 0.17	– 0.02	– 0.18
Inflation	0.01	– 0.18	– 0.29	0.34	0.31	0.31	0.44	0.08	0.22
Nom. int. rate[b]	– 0.03	0.01	– 0.05	0.40	0.04	0.05	0.44	0.04	0.12
Real int. rate[c]	– 0.38	0.34	0.21	– 0.28	0.57	– 0.19	– 0.12	0.37	0.09
Money[d]	0.42	– 0.04	– 0.18	0.30	0.61	0.55	0.15	– 0.04	0.10
Velocity[e]	– 0.08	0.27	0.25	0.37	0.99	0.99	0.33	0.18	0.22

Notes: U.S. data adapted from Cooley and Prescott (1995), Cooley and Hansen (1995), Hansen (1985), and Stock and Watson (1998). $\lambda_{0.1}$ = model with $\lambda = 0.1$, $\lambda_{0.5}$ = model with $\lambda = 0.5$
[a]CPI for U.S. data.
[b]TB1MO for U.S. data.
[c]Real TB3MO for U.S. data.
[d]Monetary base for U.S. data.
[e]Velocity of M1 for U.S. data.

applies to the current model when λ is low. When λ is high, nominal variables become more serially correlated since the central bank then uses intertemporal changes in the inflation tax to stimulate the economy in recessions and to depress it in booms. However, inflation still reacts to money growth shock without delay.

There are several explanations for the low persistence of money shocks in the current paper. When comparing simulated effects of monetary policy shocks with those in the data, it is necessary to consider the nature of the shocks. The money shocks I have allowed for in the model are control errors made by the central bank when implementing monetary policy. These are by nature uncorrelated over time, and we have seen that the effects they have are transitory. A main theme in this paper has been the instability of central bank objectives and preferences. Such changes also constitute monetary policy shocks and these shocks may certainly be persistent and have long-lasting effects. Indeed, Christiano et al. (1998a) find evidence that the U.S. monetary policy shock process can be approximated by a second-order moving average

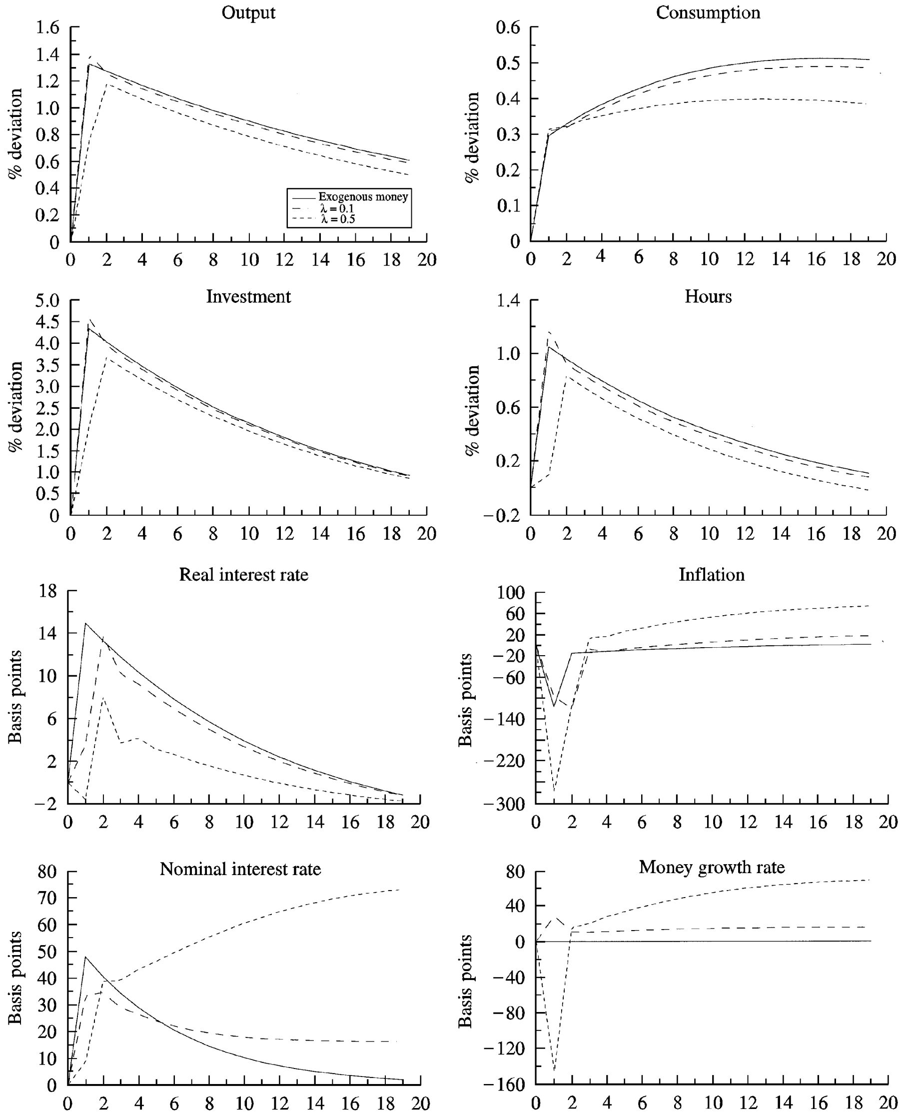

Fig. 1. Impulse response to productivity shock.

process, i.e. that shocks are not independent over time. One interpretation they give for the monetary policy shock process identified is that it 'reflects exogenous shocks to the preferences of the monetary authority, perhaps due to stochastic shifts in the relative weight given to unemployment and inflation' (Christiano et al., 1998b).

Table 3
Auto-correlations and cross-correlations of nominal variables

	$k=0$			$k=1$			$k=2$			$k=4$		
	U.S.	$\lambda_{0.1}$	$\lambda_{0.5}$	U.S.	$\lambda_{0.1}$	$\lambda_{0.5}$	U.S.	$\lambda_{0.1}$	$\lambda_{0.5}$	U.S.	$\lambda_{0.1}$	$\lambda_{0.5}$
$\rho(\mu_t, \mu_{t-k})$	1.00	1.00	1.00	0.54	0.04	0.37	0.50	− 0.06	0.34	0.27	0.14	0.45
$\rho(\pi_t, \pi_{t-k})$	1.00	1.00	1.00	0.84	0.13	0.50	0.78	0.00	0.39	0.76	0.20	0.45
$\rho(\pi_t, \mu_{t-k})$	0.34	0.86	0.95	0.36	− 0.02	0.47	0.38	− 0.07	0.37	0.32	0.22	0.52

Notes: U.S. data adapted from Nelson (1997) and own calculations. $\lambda_{0.1} =$ model with $\lambda = 0.1$, $\lambda_{0.5} =$ model with $\lambda = 0.50$. ρ denotes correlations, μ_t is money growth, and π_t is inflation.

Most economists would also agree that there have been a number of changes in the Fed's preferences in the post-war era, in particular connected to the entry of chairman Volcker. The existence of structural changes in the Federal Reserve's behavior is supported empirically by e.g. Bernanke and Mihov (1995), Gavin and Kydland (1996), and Clarida et al. (1997). By introducing an inflation target that shifts over time into the model, money growth and inflation would become more autocorrelated, and money would have more persistent effects.

Another explanation for the long-lasting effects of money shocks in the data could be that the central bank's loss function is fundamentally different from the one used in this paper. If, for example, there are costs for the society associated with changes in the inflation rate in addition to changes in the price level, the central bank will not restore inflation to the normal level immediately after having reacted to a shock.

Finally, the nominal rigidity only lasts for one period in the model. Consequently, there is no reason for the central bank to pursue an expansionary policy in response to a negative productivity shock even if the shock has long-lasting effects on real variables. It could be more realistic to allow wage contracts to last for more than one-quarter. By doing so, we would also derive money supply rules with more serial correlation.

To sum up, I claim that the model replicates many important features of the U.S. business cycle, at least concerning real variables. An important message in the paper, and which will be stressed in the next section, is that central bank preferences may vary over time and that these variations can affect the behavior of nominal variables. Since these fluctuations in preferences are not modelled explicitly here, the model *should not* capture all fluctuations in nominal variables.

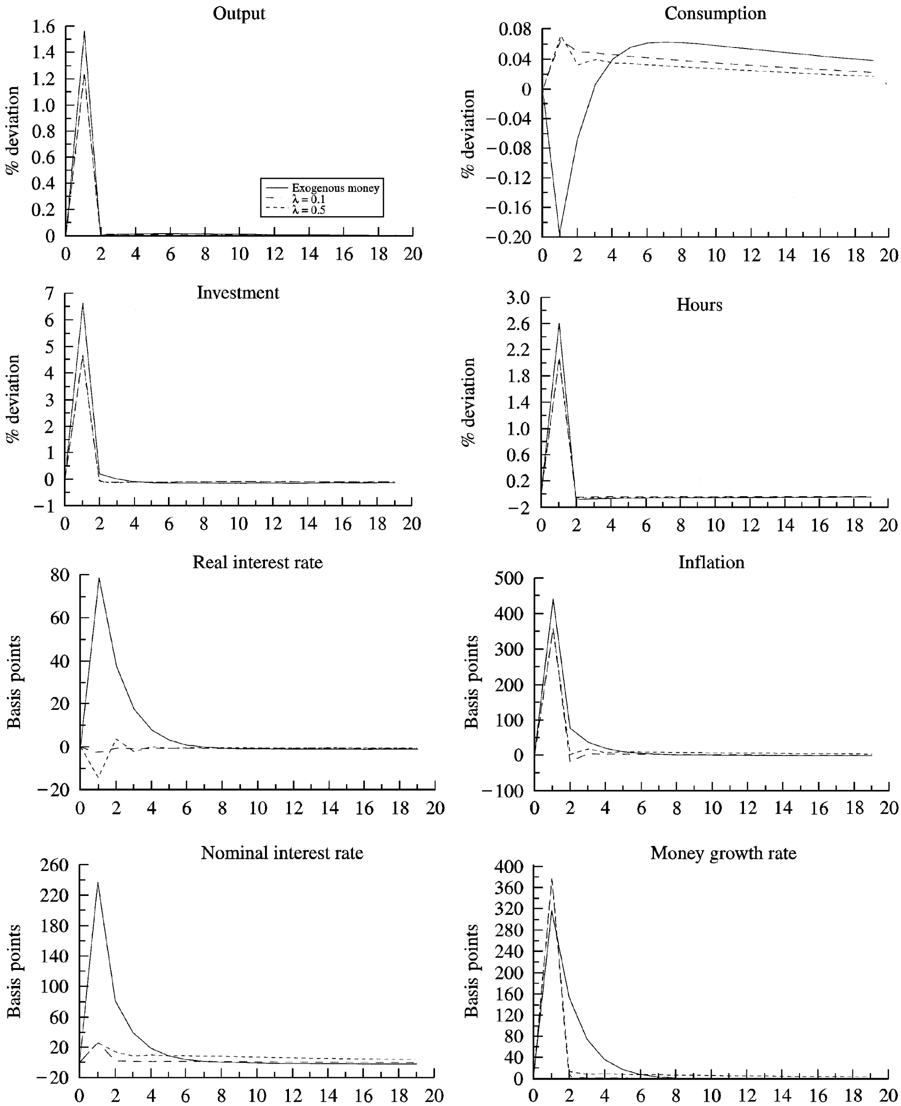

Fig. 2. Impulse response to money supply shock.

4. Effects of changes in central bank preferences

In this section, I examine the effects that changes in the central bank's preferences have on its own policy rule, on the agents' decision rules, and on the properties of the resulting economies. I first look at changes in the weight the central bank puts on inflation stability relative to output stability. The central bank's inflation target, π^*, is assumed to be 1.5% per quarter.

Table 1 shows that the central bank does have *some* control over the two components in its loss function – the volatility of output and inflation. As the weight put on output stability increases from 0.1 to 0.5, the coefficient of variation for output falls from 2.09 to 1.87 and the coefficient of variation for inflation increases from 0.88 to 1.09. In general, however, the volatility of variables does not change much when λ changes. The correlations between output and some nominal variables reported in Table 2 change considerably when λ change. This holds in particular for the correlation between output and prices, but also for the leads and lags of money and inflation.

In Tables 4 and 5, I report optimal decision rules for different values of the weight λ. With the numerical methods used to solve for the decision rules, some of the parameters are difficult to solve for with good precision. This holds in particular for β_1 and β_4 (the constant term and capital).[7]

The most interesting finding of these tables is the central bank's response to productivity shocks. When the central bank puts much weight on inflation stability, it increases money supply in response to positive productivity shocks. This is because these shocks tend to drive inflation down. But positive productivity shocks also tend to increase output. Therefore, the central bank will contract money supply and exploit the short run Phillips curve when it puts more weight on output stability. In Fig. 1, we see the results that these different money supply rules have on the agents' behavior. When λ is low, hours worked increases in response to positive productivity shocks, but when λ is high, the initial response of hours worked to these shocks is small. With the exception of hours worked, the impulse-response graphs also confirm that the money supply process is not important for the behavior of real variables, but that nominal variables behave differently under different monetary regimes.

Money supply shocks have roughly the same effects under all monetary regimes. Since wages are set before money growth shocks are observed, output, hours worked, and investment increase significantly in response to positive shocks, and so do inflation and nominal interest rates. As can be seen in Fig. 2, though, the effects are very transitory. In the second period after the shock, most variables are back to their trend levels, so money supply shocks cannot account for the cyclical behavior we observe in real variables.

So far, I have assumed that the public has perfect information about the central bank's preferences and that agents immediately understand what policy rule the central bank will use. In reality, central bank preferences might change

[7] The source of this problem is probably that the capital stock does not fluctuate much. Hence, it is difficult to separate it from the constant term.

Table 4
Central bank decision rules and resulting economies $\mu_t^{CB} = \beta_1 + \beta_2 z_{t-1} + \beta_3 \varepsilon_t + \beta_4 \ln K_t + \beta_5 \ln \hat{P}_{t-1}$

λ	Const.	z_-	ε	$\ln K$	$\ln \hat{P}_-$	Properties of the economy		
						SD (Y)	SD (π)	Corr (μ)
0.0	0.338	− 0.001	0.422	− 0.107	− 0.140	2.25	0.86	0.00
0.1	0.204	− 0.035	0.099	− 0.065	− 0.189	2.09	0.88	0.04
0.2	0.112	− 0.065	− 0.130	− 0.038	− 0.259	1.99	0.94	0.12
0.5	− 0.391	− 0.105	− 0.501	0.120	− 0.342	1.87	1.09	0.37
1.0	− 1.342	− 0.038	− 0.738	0.425	− 0.258	1.80	1.25	0.55

Notes: SD% is the standard deviation of a variable's percentual fluctuations relative to its trend. Y is output and π is inflation. Corr (μ) is the autocorrelation of money growth.

Table 5
Decision rules for agents $x_{i,t} = \alpha_{i,1} + \alpha_{i,2} z_{t-1} + \alpha_{i,3} \varepsilon_t + \alpha_{i,4} \xi_t + \alpha_{i,5} \ln K_t + \alpha_{i,6} \ln \hat{P}_{t-1}$

x	λ	Const.	z_-	ε	ξ	$\ln K$	$\ln \hat{P}_-$
$\ln \hat{P}$	0.0	2.05	− 0.38	− 0.43	− 0.06	− 0.68	− 0.137
	0.1	1.97	− 0.43	− 0.43	− 0.06	− 0.66	− 0.185
	0.2	1.93	− 0.48	− 0.43	− 0.07	− 0.65	− 0.253
	0.5	1.57	− 0.56	− 0.45	− 0.07	− 0.54	− 0.335
	1.0	0.81	− 0.55	− 0.49	− 0.08	− 0.29	− 0.251
$\ln K'$	0.0	0.15	0.11	0.16	0.10	0.95	− 0.006
	0.1	0.15	0.11	0.13	0.10	0.95	− 0.008
	0.2	0.15	0.11	0.10	0.10	0.95	− 0.011
	0.5	0.15	0.10	0.06	0.10	0.95	− 0.015
	1.0	0.14	0.09	0.02	0.10	0.95	− 0.011
$\ln H$	0.0	0.23	1.42	2.48	2.34	− 0.46	0.008
	0.1	0.36	1.38	1.68	2.34	− 0.49	0.011
	0.2	0.48	1.34	1.11	2.34	− 0.53	0.014
	0.5	0.83	1.24	0.13	2.33	− 0.64	0.019
	1.0	1.34	1.08	− 0.57	2.31	− 0.80	0.016

over time and it is possible that these changes are not immediately noticed or understood by the public. Moreover, even if the new preferences are taken into account immediately, agents might be afraid that the central bank's preferences will change again. The Volcker era is arguably a period with considerable uncertainty about monetary policy, for instance whether the shift to low inflation was persistent or not. If we allow for mechanisms like these, monetary policy can cause cyclicality in real variables since agents' misapprehensions or mistrust will be serially correlated in itself.

The model I use here provides a tool for thinking about central bank preferences in a business cycle framework, but the complexity of the model does not allow us to explicitly introduce a new dimension of uncertainty. To get an upper limit of the quantitative effects that this uncertainty can induce, I have looked at changes in the central bank's preferences which are not noticed by the agents. I find that if $\lambda = 0.1$ and the central bank's inflation target falls from 1.5 to 0.75 percent per quarter, and if this change is not perceived by the agents, output falls immediately to approximately 1% below trend, hours to 1.5% below trend, and investment to 4% below trend. Consumption does not react much initially.[8]

5. Concluding remarks

The effects of anticipated and unanticipated monetary policy have for a long time been a controversial issue in economics. The observation that correlations between real and nominal variables are significant in magnitude is not enough to conclude a causality from money to output or vice versa. Theoretically, these correlations can, for example, be due to nominal rigidities, i.e. that money causes output. It could also be the case that money demand responds to real activity, i.e. that real variables cause fluctuations in nominal variables. In models trying to explain the money–output correlations, money supply has often been neglected. In this paper, I have worked from the starting point that the money supply process is the most important source of fluctuations in nominal variables. Therefore, money supply will also be an important factor behind the relationship between real and nominal variables if, which seems to be the case, the central bank takes the real economy into account when deciding on money supply.

In order to study these issues, this paper has endogenized the central bank's money supply decisions in a dynamic general equilibrium model of macroeconomic fluctuations. The central bank has some power to stabilize inflation and output in the model. To achieve this stabilization it has to react to changes in the real and nominal environment. I find that the money supply process, as expected, is an important determinant of the joint behavior of real and nominal variables. I also find that small changes in the central bank's desire to stabilize output relative to inflation cause large changes in the implied money supply rule and in the behavior of nominal variables, but real variables are mostly unaffected.

[8] It is worth noting that if the central bank's preference change were noticed by the public, all these variables would increase by approximately 1% since the distorting effect of inflation would decrease.

An interesting next step on this research agenda would be to explicitly model the stochastic nature of central bank preferences. Empirical research has indicated that preferences or objectives actually do change and this paper has shown that such changes can have important effects on the conduct of monetary policy. My presumption is that preference shocks are more important than other monetary policy shocks, and that such shocks will be a necessary ingredient in a succesful theoretical model of the co-fluctuations of money and output.

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