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Abstract

This paper examines the role of habit persistence in consumption in explaining persistent responses of inflation and output to money growth shocks. A MIU-model with a separable utility function is embedded into a stochastic DGE model with sticky prices. It is shown that for a high degree of habit persistence consumption displays a pronounced and hump-shaped response while the volatility falls short empirical estimates. The behavior of output and inflation does not change compared to a model without habit formation. Empirically plausible degrees of habit persistence still cause consumption to be persistent but do not improve the performance for other macroeconomic aggregates. Most variables are cyclical and too strongly correlated with output. Overall habit persistence in consumption cannot explain the observed reaction of the macroeconomic aggregates to monetary shocks.

JEL classification: E52
Keywords: Monetary Policy, New Neoclassical Synthesis, Sticky Prices, Persistency, Habit Persistence

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1 Introduction

Can money growth shocks generate persistent responses of inflation and output? This question has been addressed in a number of papers in the last few years. The most prominent paper is the one of [4, Chari/Kehoe/McGrattan (2000)] who conclude that standard models with staggered prices generate only a positive output reaction for the time of exogenous price stickiness. Several attempts have been made to challenge this result.

Recently [5, Christiano/Eichenbaum/Evans (2001)] have developed a stochastic DGE model that is capable of generating the observed persistence of monetary shocks in US data. With an average duration of two to three quarters wage contracts are the critical nominal friction, not price contracts. If inertia in inflation and output persistence is the main goal to match then they show that variable capacity utilization is most important. To explain the reaction of all variables they include habit persistence in consumption as well as adjustment costs in investment. It should be noted that these authors use a limited information econometric strategy that is not yet common in the literature so that the results are difficult to compare to existing studies.

The problem with this approach is that it is difficult to disentangle the specific role of several model components in generating persistent output responses. The authors do perform some sensitivity analysis but they do it by dropping only one or two model features. But it would also be interesting to study the implications of a simple sticky price model augmented by habit formation in consumption. This is done in this paper. The main result is that only the behavior of consumption after a monetary policy shock can be improved. Output and inflation responses are very strong on impact and are cyclical thereafter. The business cycle properties do not match well empirical estimates.

Very recently [2, Bouakez/Cardia/Ruge-Murcia (2002)] have estimated a similar model to the one presented here using US data. In addition to habit formation they consider the influence of adjustment costs to capital on the persistence of output after a money growth shock. They conclude that both features give rise to a hump-shaped response of output to a monetary shock. In light of the results obtained here the main reason for their success in matching empirical regularities must lie in the different modeling of the price adjustment process: While these authors consider Calvo-pricing I essentially assume Taylor-type price staggering.

[19, McCallum/Nelson (1999)] incorporate habit formation in an open economy model of nominal income targeting and find - contrary to the results obtained here - an important role for increasing the ability to match quarterly US data.

[1, Auray/Collard/Fève (2002)] consider habit formation in conjunction with a CIA model to explain the liquidity effect. They show that high enough habit persistence can generate a falling nominal interest rate after a positive money growth shock but that it leads also to real indeterminacy. In the model at hand the nominal rate rises. The difference may be due to the fact that these authors do not incorporate sticky prices.

The paper is organized as follows: Section 2 describes in detail the model, the steady state and the calibration. In section 3 impulse responses are discussed while section 4 gives results for the business cycle properties of the model. Section 5 concludes and gives some suggestions for future research.

2 The Model

2.1 The Household

The representative household is assumed to have preferences over consumption (c_t), leisure $(1 - n_t)$ (where n_t is labor) and real money balances M_t/P_t since they facilitate transactions. This money-in-the-utility-function specification was - among others - proposed by [20, Sidrauski (1967)]. Here I use the simplest specification in a separable form since the more complicated non-separable variant does not enhance much - if at all - the persistency effects of money growth shocks in standard sticky price models.

$$u\left(c_t, c_{t-1}, \frac{M_t}{P_t}, n_t\right) = \frac{1}{1-\sigma}\left[\left(\frac{c_t}{c_{t-1}^b}\right)^{1-\sigma} + \gamma\left(1-n_t\right)^{1-\sigma} + \left(\frac{M_t}{P_t}\right)^{1-\sigma}\right] \tag{1}$$

As usual σ governs the degree of risk aversion. γ is a positive parameter while b is a measure for the degree of habit persistence. Lagged consumption c_{t-1} is the habit reference level while b indexes the importance of this reference level relative to current consumption. With $b = 0$ the standard model with actual consumption c_t only results, but with $b = 1$ only consumption relative to previous consumption matters. This can be seen more clearly when rewriting the consumption term as

$$\left(\frac{c_t}{c_{t-1}^b}\right) = \left(\frac{c_t}{c_{t-1}} c_{t-1}^{1-b}\right) \tag{2}$$

Now with $b = 1$ the second term with lagged consumption has no influence any more so that the *level* of c_{t-1} does not matter. b cannot exceed 1 because otherwise steady state utility would be falling in consumption.[1]

This formulation of habit persistence neglects the possibility of memory in the habit reference level. [12, Fuhrer (2000)] considers the more general case introducing a new variable S_t for the reference level replacing c_{t-1} in (1). He assumes then that S_t evolves according to

$$S_t = \rho S_{t-1} + (1 - \rho)\, c_{t-1} \tag{3}$$

With $\rho = 0$ only last period's consumption matters while for higher ρ past period's consumption levels become more and more important. Using this formulation leads to a very complex Euler equation which will not be used in this paper (see e.g. [12, Fuhrer (2000)], p. 371).

Some authors (e.g. [5, Christiano/Eichenbaum/Evans (2001)]) consider the difference in consumption levels in the utility function, not the ratio. So the term corresponding to (2) looks like

$$c_t - hc_{t-1} \tag{4}$$

[7, Deaton (1992)] shows that this is a special case of the [12, Fuhrer (2000)] formulation where h captures both the influence of b and ρ. It is the result when setting $\rho = 1$ so that there is no "depreciation" of the habit reference level. In the model considered here persistence in habits does not have a great influence on the dynamics so it will not be used.[2]

The budget constraint is given by

$$c_t + i_t + \frac{M_t}{P_t} + \frac{B_t}{P_t} = w_t n_t + z_t k_{t-1} + \frac{M_{t-1}}{P_t} + (1 + R_{t-1})\,\frac{B_{t-1}}{P_t} + \frac{M_t^s}{P_t} \tag{5}$$

The household can invest i_t units of the final good to augment the capital stock k_t. Further it can decide how much to consume (c_t) and how much

[1] [19, McCallum/Nelson (1999)] also use this formulation for modeling habit persistence.

[2] See [7, Deaton (1992)], p. 30. Results for this model version are available from the author upon request.

real money balances M_t/P_t and real bonds B_t/P_t to hold. The household has a labor income $w_t n_t$ working in the market at the real wage rate w_t and can spend its money holdings carried over from the previous period (M_{t-1}/P_t). It also receives factor payments $z_t k_{t-1}$ for supplying capital to intermediate goods producing firms where z_t denotes the real return on capital. There are also previous period bond holdings including the interest on them $(1+R_{t-1})(B_{t-1}/P_t)$.[3] Finally the household receives a monetary transfer M_t^s from the government or the monetary authority, respectively. This transfer is equal to the change in money balances, i.e.

$$M_t^s = M_t - M_{t-1} \tag{6}$$

The capital stock increases according to the following law of motion:

$$k_t = (1-\delta)\, k_{t-1} + \phi\left(\frac{i_t}{k_{t-1}}\right) k_{t-1} \tag{7}$$

There are costs of adjusting the capital stock which are captured by the ϕ function. δ is the rate of depreciation. The detailed properties will be discussed in the calibration subsection.[4] Because this equation cannot be explicitly solved for i_t a second Lagrange multiplier (θ_t) has to be introduced into the optimization problem of the household. The Lagrangian is then given by:

$$\begin{aligned} L \;=\;& E_0\Bigg[\sum_{t=0}^{\infty}\beta^t u\left(c_t, c_{t-1}, m_t, n_t\right) \\ &+ \sum_{t=0}^{\infty}\beta^t\lambda_t\Bigg(z_t k_{t-1} + w_t n_t + m_{t-1}\frac{P_{t-1}}{P_t} + m_t^s \\ &+ (1+R_{t-1})\, b_{t-1}\frac{P_{t-1}}{P_t} - c_t - i_t - m_t - b_t\Bigg) \\ &+ \sum_{t=0}^{\infty}\beta^t\theta_t\left((1-\delta)\, k_{t-1} + \phi\left(\frac{i_t}{k_{t-1}}\right) k_{t-1} - k_t\right)\Bigg] \end{aligned} \tag{8}$$

[3] The household also receives profits from the intermediate goods firms. Since these profits will be zero in the equilibrium they are not explicitly included in the budget constraint here.

[4] [2, Bouakez/Cardia/Ruge-Murcia (2002)], p.4, assume a quadratic and strictly convex adjustment cost function.

Here small variables indicate real quantities, i.e. for example $m_t = M_t/P_t$. Households optimize over c_t, n_t, i_t, k_t, m_t and b_t taking prices and the initial values of the price level P_0 and the capital stock k_0 as well as the outstanding stocks of money M_0 and bonds B_0 as given. The first order conditions are reported below.

$$\frac{\partial L}{\partial c_t} = \beta^t \frac{\partial u\left(c_t, c_{t-1}, m_t, n_t\right)}{\partial c_t} + \beta^{t+1} \frac{\partial u\left(c_{t+1}, c_t, m_{t+1}, n_{t+1}\right)}{\partial c_t} - \beta^t \lambda_t = 0 \tag{9}$$

$$\frac{\partial L}{\partial n_t} = \beta^t \frac{\partial u\left(c_t, c_{t-1}, m_t, n_t\right)}{\partial n_t} + \beta^t \lambda_t w_t = 0 \tag{10}$$

$$\frac{\partial L}{\partial i_t} = -\beta^t \lambda_t + \beta^t \theta_t \phi' \left(\frac{i_t}{k_{t-1}}\right) \left(\frac{1}{k_{t-1}}\right) k_{t-1} = 0 \tag{11}$$

$$\begin{aligned} \frac{\partial L}{\partial k_t} &= E_t \beta^{t+1} \lambda_{t+1} z_{t+1} - \beta^t \theta_t + E_t \beta^{t+1} \theta_{t+1} \Bigg[(1-\delta) \\ & +\phi\left(\frac{i_{t+1}}{k_t}\right) + \phi'\left(\frac{i_{t+1}}{k_t}\right)\left(-\frac{i_{t+1}}{k_t^2}\right) k_t \Bigg] = 0 \end{aligned} \tag{12}$$

$$\frac{\partial L}{\partial m_t} = \beta^t \frac{\partial u\left(c_t, c_{t-1}, m_t, n_t\right)}{\partial m_t} - \beta^t \lambda_t + E_t \beta^{t+1} \lambda_{t+1} \frac{P_t}{P_{t+1}} = 0 \tag{13}$$

$$\frac{\partial L}{\partial b_t} = -\beta^t \lambda_t + E_t \beta^{t+1} \lambda_{t+1} \left(1 + R_t\right) \frac{P_t}{P_{t+1}} = 0 \tag{14}$$

The derivative with respect to λ_t is omitted since it is equal to the intertemporal budget constraint. The derivative with respect to θ_t is not reported again since it is given by the capital accumulation condition stated above. ϕ' denotes the derivative of the ϕ-function with respect to the investment to capital ratio which is regarded as one argument. Note the different consumption Euler equation. Due to habit formation the marginal utility of consumption enters two times indicating the influence of last period's consumption on today's utility. In addition the household's optimal choices must also satisfy the transversality conditions:

$$\lim_{t\to\infty} \beta^t \lambda_t x_t = 0 \qquad \text{for } x = m, b, k \tag{15}$$

The familiar result that the first two efficiency conditions imply the equality of the marginal rate of substitution between consumption and labor and the real wage is altered here through the influence of habit formation in consumption. The real wage is now given by

$$w_t = -\frac{\frac{\partial u(c_t,c_{t-1},m_t,n_t)}{\partial n_t}}{\frac{\partial u(c_t,c_{t-1},m_t,n_t)}{\partial c_t} + \beta\frac{\partial u(c_{t+1},c_t,m_{t+1},n_{t+1})}{\partial c_t}} \tag{16}$$

Note that the marginal utility of consumption enters twice in the denominator which alters the dynamic evolution of w_t.
The efficiency condition for bond holdings establishes a relation between the nominal interest rate and the price level. Rearranging terms yields

$$(1+R_t) = \frac{\lambda_t}{\lambda_{t+1}}\frac{1}{\beta}\frac{P_{t+1}}{P_t} \tag{17}$$

Supposed the Fisher equation is valid the real interest rate r_t is implicitly defined as

$$(1+r_t) = \frac{\lambda_t}{\lambda_{t+1}}\frac{1}{\beta} \tag{18}$$

because P_{t+1}/P_t equals one plus the rate of expected inflation which is approximated by the ex-post-inflation rate.

In the efficiency condition for money the marginal utility of real balances has to be considered. This derivative determines the endogenous money demand function. Combining the optimum conditions for consumption, bonds and money yields the following equation:

$$\begin{aligned}\frac{\partial u\left(c_t, c_{t-1}, m_t, n_t\right)}{\partial m_t} &= \left[\frac{\partial u\left(c_t, c_{t-1}, m_t, n_t\right)}{\partial c_t}\right.\\ &\left. +\beta\frac{\partial u\left(c_{t+1}, c_t, m_{t+1}, n_{t+1}\right)}{\partial c_t}\right]\frac{R_t}{1+R_t}\end{aligned} \tag{19}$$

In principal this specification allows to estimate an empirical money demand function. But this approach will not be pursued here since the dynamic structure involves consumption at three different points in time, a specification normally not considered to be appropriate for the estimation of an empirical money demand function.

2.2 The Finished Goods Producing Firm

The firm producing the final good y_t in the economy uses $y_{j,t}$ units of each intermediate good $j \in [0,1]$ purchased at price $P_{j,t}$ to produce y_t units of the finished good. The production function is assumed to be a CES aggregator as in [8, Dixit/Stiglitz (1977)] with $\epsilon > 1$.

$$y_t = \left(\int_0^1 y_{j,t}^{(\epsilon-1)/\epsilon} dj \right)^{\epsilon/(\epsilon-1)} \tag{20}$$

The firm maximizes its profits over $y_{j,t}$ given the above production function and given the price P_t. So the problem can be written as

$$\max_{y_{j,t}} \left[P_t y_t - \int_0^1 P_{j,t} y_{j,t} dj \right] \text{ s.t. } \quad y_t = \left(\int_0^1 y_{j,t}^{(\epsilon-1)/\epsilon} dj \right)^{\epsilon/(\epsilon-1)} \tag{21}$$

The first order conditions for each good j imply

$$y_{j,t} = \left(\frac{P_{j,t}}{P_t} \right)^{-\epsilon} y_t \tag{22}$$

where $-\epsilon$ measures the constant price elasticity of demand for each good j. Since the firm operates under perfect competition it does not make any profits. Inserting the demand function into the profit function and imposing the zero profit condition reveals that the only price P_t that is consistent with this requirement is given by

$$P_t = \left(\int_0^1 P_{j,t}^{(1-\epsilon)} dj \right)^{1/(1-\epsilon)} \tag{23}$$

In case that prices are fixed for just two periods and assuming that all price adjusting producers in a given period choose the same price the consumption aggregate can be written as

$$y_t = y\left(y_{0,t}, y_{1,t}\right) = \left(\frac{1}{2} y_{0,t}^{(\epsilon-1)/\epsilon} + \frac{1}{2} y_{1,t}^{(\epsilon-1)/\epsilon} \right)^{\epsilon/(\epsilon-1)} \tag{24}$$

where $y_{j,t}$ can then be interpreted as the quantity of a good produced in period t whose price was set in period $t-j$. Similarly in the two period price setting case to be explored in detail in the next section the price equation simplifies. With prices set for two periods half of the firms adjust their price in period t and half do not. Moreover all adjusting firms choose the same price. Then $P_{j,t}$ is the nominal price at time t of any good whose price was set j periods ago and P_t is the price index at time t and is given by

$$P_t = \left(\frac{1}{2}P_{0,t}^{1-\epsilon} + \frac{1}{2}P_{1,t}^{1-\epsilon}\right)^{1/(1-\epsilon)} \tag{25}$$

2.3 The Intermediate Goods Producing Firm

Intermediate good firms can be considered to consist of a producing and a pricing unit. The producing unit operates under a Cobb-Douglas-technology which is subject to an aggregate random productivity shock a_t.

$$y_{j,t} = a_t n_{j,t}^{\alpha} k_{j,t-1}^{1-\alpha} \tag{26}$$

Here $n_{j,t}$ is the labor input employed in period t by a firm who set the price in period $t-j$, similarly $k_{j,t-1}$ is the capital stock, and $0 < \alpha < 1$ is labor's share. Those who do not adjust their prices in a given period can be interpreted as passive while those who do adjust do so optimally.

The pricing unit sets prices to maximize the present discounted value of profits.[5] This can only be done after the producing unit has determined the cost function. In models with capital the problem is given by

$$\begin{aligned} &\min_{n_{j,t},k_{j,t-1}} \left[P_{j,t}w_{j,t}n_{j,t} + P_{j,t}z_{j,t}k_{j,t-1}\right] \\ &\text{s.t.} \quad y_{j,t} = a_t n_{j,t}^{\alpha} k_{j,t-1}^{1-\alpha} \end{aligned} \tag{27}$$

It is useful for further calculations to define nominal marginal cost as $\Psi_{j,t}$ which is equal to the Lagrange multiplier in the cost minimization problem stated above. The efficiency conditions are the following:

$$P_{j,t}w_{j,t} = \Psi_{j,t}\alpha a_t n_{j,t}^{\alpha-1} k_{j,t-1}^{1-\alpha} \tag{28}$$

$$P_{j,t}z_{j,t} = \Psi_{j,t}\left(1-\alpha\right) a_t n_{j,t}^{\alpha} k_{j,t-1}^{-\alpha} \tag{29}$$

[5] The model deviates in this respect from the standard textbook model in which profits are maximized over the quantity.

In a symmetric equilibrium all choices of the producing unit of the firms are the same so that

$$P_{j,t} = P_t, w_{j,t} = w_t, z_{j,t} = z_t, n_{j,t} = n_t, k_{j,t-1} = k_{t-1} \text{ for all } t \tag{30}$$

So (28) and (29) hold with all j's eliminated.

The pricing unit of the firm maximizes profits by choosing the optimal price. Define the relative price by $p_{j,t} = P_{j,t}/P_t$. Because the production functions are homogenous of degree one real profit $\xi_{j,t}$ for a firm of type j is equal to

$$\xi_{j,t} = \xi\left(p_{j,t}, y_t, \psi_t\right) = p_{j,t}y_{j,t} - \psi_t y_{j,t} \tag{31}$$

Using the demand function for the intermediate goods $\left(y_{j,t} = p_{j,t}^{-\epsilon} y_t\right)$ the profit function can be rewritten as

$$\xi_{j,t} = \xi\left(p_{j,t}, y_t, \psi_t\right) = y_{j,t}\left(p_{j,t} - \psi_t\right) = p_{j,t}^{-\epsilon} y_t\left(p_{j,t} - \psi_t\right) \tag{32}$$

In the case in which prices are not sticky the firm can just set prices on a period by period basis optimizing the profit function (32) with respect to $p_{j,t}$. The result of this exercise would be that relative prices will have to be set according to

$$p_{j,t} = \frac{\epsilon}{\epsilon - 1}\psi_t \tag{33}$$

But when prices are fixed for two periods the firm has to take into account the effect of the price chosen in period t on current and future profits. The price in period $t+1$ will be affected by the gross inflation rate Π_{t+1} between t and $t+1$ $(\Pi_{t+1} = P_{t+1}/P_t)$.

$$p_{1,t+1} = \frac{p_{0,t}}{\Pi_{t+1}} \tag{34}$$

If there is positive inflation, $p_{1,t+1}$ will fall because nominal prices are fixed for two periods. As the nominal price in period t is defined by $P_{0,t}$ and in period $t+1$ by $P_{1,t+1}$, one has $P_{0,t} = P_{1,t+1}$, so that $p_{0,t} = P_{0,t}/P_t$ and $p_{1,t+1} = P_{1,t+1}/P_{t+1} = \left(P_{0,t}/P_t\right)\left(P_t/P_{t+1}\right)$ which is what is stated in (34). So the optimal relative price has to balance the effects due to inflation between profits today and tomorrow. This intertemporal maximization problem is formally given by

$$\max_{p_{0,t}} E_t \left[\xi\left(p_{0,t}, y_t, \psi_t\right) + \beta \frac{\lambda_{t+1}}{\lambda_t} \xi\left(p_{1,t+1}, y_{t+1}, \psi_{t+1}\right) \right]$$
$$\text{s.t.} \quad p_{1,t+1} = \frac{p_{0,t}}{\Pi_{t+1}} \tag{35}$$

The term λ_{t+1}/λ_t is equal to the ratio of future to current marginal utility of labor and the respective real wage ratio (derived in the household's optimization problem) and considered to be - in conjunction with β - the appropriate discount factor for real profits. This is a consequence of the assumption that households own the production factors labor and capital and rent them to the firms. They also own a diversified portfolio of claims to the profits earned by the firms. λ_t can be used to determine the present value of profits.[6] The efficiency condition for this problem is given by

$$0 = \frac{\partial \xi\left(p_{0,t}, y_t, \psi_t\right)}{\partial p_{0,t}} + \beta E_t \left(\frac{\lambda_{t+1}}{\lambda_t} \frac{\partial \xi\left(p_{1,t+1}, y_{t+1}, \psi_{t+1}\right)}{\partial p_{1,t+1}} \frac{1}{\Pi_{t+1}} \right) \tag{36}$$

Multiplying this equation by $p_{0,t}$ and λ_t produces a more symmetric form of the efficiency condition that will be more convenient to derive the model solution later.

$$0 = \lambda_t p_{0,t} \frac{\partial \xi\left(p_{0,t}, y_t, \psi_t\right)}{\partial p_{0,t}} + \beta E_t \left(\lambda_{t+1} p_{1,t+1} \frac{\partial \xi\left(p_{1,t+1}, y_{t+1}, \psi_{t+1}\right)}{\partial p_{1,t+1}} \right) \tag{37}$$

Using (32) one can solve this condition for the optimal price to be set in period t which corresponds to the optimal price in case that prices are flexible derived before. This yields a forward-looking form of the price equation and is in that respect similar to the one in [21, Taylor (1980)].

$$p_{0,t} = \frac{\epsilon}{\epsilon - 1} \frac{\lambda_t y_t \psi_t + \beta E_t \lambda_{t+1} \left(P_{t+1}/P_t\right)^{\epsilon} y_{t+1} \psi_{t+1}}{\lambda_t y_t + \beta E_t \lambda_{t+1} \left(P_{t+1}/P_t\right)^{\epsilon - 1} y_{t+1}} \tag{38}$$

The optimal relative price $p_{0,t}$ depends upon the current and future real marginal costs, the gross inflation rate, current and future consumption as well as today's and tomorrow's interest rates (through the influence of the

[6] More details on this can be found in [10, Dotsey/King/Wolman (1999)], p. 659-665 as well as in [9, Dotsey/King/Wolman (1997)], p. 9-13.

λ-terms). It is thus fundamentally different from the one derived under fully flexible prices on a period-by-period basis (see (33)). (38) can be manipulated in a way that yields a form which is exactly equal to the one studied in [22, Walsh (1998)], p. 197, when using (17) for the interest rate factor. To derive the Taylor approximation in the Appendix it is useful to write (38) as

$$P_{0,t} = \frac{\epsilon}{\epsilon - 1} \frac{\lambda_t P_t^{\epsilon} y_t \psi_t + \beta E_t \lambda_{t+1} P_{t+1}^{\epsilon} y_{t+1} \psi_{t+1}}{\lambda_t P_t^{\epsilon-1} y_t + \beta E_t \lambda_{t+1} P_{t+1}^{\epsilon-1} y_{t+1}} \tag{39}$$

[2, Bouakez/Cardia/Ruge-Murcia (2002)] essentially use a New Keynesian Phillips curve which can be derived by combining their optimum condition for price setting with their price level equation. Remember that they consider Calvo-pricing so that the probability of price adjustment appears as a further parameter in their Phillips curve.

2.4 Market Clearing Conditions and Other Equations

The aggregate resource constraint is derived using the resource constraint of households, firms, the government and the monetary authority. Since there are neither government expenditures nor taxes in this model, this condition is given by

$$y_t = c_t + i_t \tag{40}$$

It is well known that models like the one at hand imply multiple equilibria and sunspots because bonds are not determined. To escape this problem the household budget constraint is dropped and bonds are set to zero: $b_t = 0$ for all t.[7]

The markup μ_t is just the reciprocal of real marginal cost so that

$$\mu_t = \frac{1}{\psi_t} \tag{41}$$

Note that the optimal price $P_{0,t}$ is left in the model as a variable. It is not eliminated and combined with the price level to obtain a New Keynesian Phillips-curve as in some papers in the literature (see for example [3, Brückner/Schabert (2001)]). This makes it possible to analyze the behavior of optimal prices, the price level and inflation separately.

[7] See [11, Flodén (2000)], p. 1413. He argues that bonds are introduced to determine the nominal interest rate.

2.5 The Monetary Authority

The model is closed by adding a monetary policy rule. Therefore an exogenous process for the money growth rate is assumed. To achieve persistent but non permanent effects the level of money follows an AR(2)-process which implies that the growth rate follows an AR(1)-process. That means for the level of money

$$\widehat{M}_t = (1 + \rho_{M_2})\,\widehat{M}_{t-1} - \rho_{M_2}\widehat{M}_{t-2} + \epsilon_{M_t} \tag{42}$$

whereas for the growth rate one gets

$$\widehat{M}_t - \widehat{M}_{t-1} = \rho_{M_2}\left(\widehat{M}_{t-1} - \widehat{M}_{t-2}\right) + \epsilon_{M_t} \tag{43}$$

A hat ($\widehat{\ }$) represents the relative deviation of the respective variable from its steady state (see the Appendix). ϵ_{M_t} is an i.i.d. sequence of shocks that hit the growth rate.

This formulation is equivalent to the standard assumption that money grows at a factor g_t:

$$M_t = g_t M_{t-1} \tag{44}$$

Suppose $\widehat{g}_t$ follows an AR(1)-process $\widehat{g}_t = \rho_{M_2}\widehat{g}_{t-1} + \epsilon_{M_t}$ then it is easy to show that (43) is valid. Note that inflation is zero in the steady state so also money growth is zero there ($g = 1$, see the next Section).

There is another shock in the model, namely the productivity shock a_t. So one can easily analyze the model's impulse responses to a productivity shock. Under these circumstances $\widehat{a}_t$ follows an AR(1)-process

$$\widehat{a}_t = \rho_a \widehat{a}_{t-1} + \epsilon_{a_t} \tag{45}$$

with ϵ_{a_t} white noise.

2.6 The Steady State

Imposing the condition of constancy of the price level in the steady state ($P_t = P_{t-1} = P$) on the nominal interest rate equation reveals the familiar condition from RBC models that $\beta = 1/(1 + R)$. In addition, as there is no steady state inflation, $R = r$. The two period price setting of the firms implies $P_0 = P_1$. Using this in the price index reveals that $P_0 = P_1 = P$. The capital accumulation equation tells us that $\phi\left(i/k\right)=\delta$ at the steady state. It is assumed that $\phi'=1$ in steady state to ensure that Tobin's q is equal to one ($q=1/\phi'$). As a consequence of the requirement that the model with adjustment costs of capital should display the same steady state as the model without them i/k is equal to $\phi\left(i/k\right)$. Using this in the efficiency condition for capital it can be shown that the rental rate on capital is $z=r+\delta$ as in a standard RBC model. With the help of (28) and the steady state for z it is possible to pin down k/n which amounts to

$$\frac{k}{n}=\left(\frac{r+\delta}{a}\frac{1}{1-\alpha}\frac{1}{\psi}\right)^{-1/\alpha} \tag{46}$$

For the markup μ it follows $\mu=1/\psi$ while ψ is determined by the steady state of the efficiency condition for maximizing profits, (38). This amounts to $\psi=(\epsilon-1)/\epsilon$. This can be used to calculate w as well:

$$w=\psi a\alpha\left(\frac{k}{n}\right)^{1-\alpha} \tag{47}$$

The calculation of the steady state value of consumption is quite tedious because it takes quite a lot of steps. From the production function one knows that labor productivity is given by

$$\frac{y}{n}=a\left(\frac{k}{n}\right)^{1-\alpha} \tag{48}$$

This productivity can be combined with the investment to capital ratio to calculate the investment share:

$$\frac{i}{y}=\left(\frac{i}{k}\frac{k}{n}\right)/\left(\frac{y}{n}\right) \tag{49}$$

Now one can derive the consumption share using the aggregate resource constraint.

$$\frac{c}{y}=-\frac{i}{y}+1 \tag{50}$$

To get the level of c the level of y and i have to be determined: $y=n\cdot y/n$, $i=y\cdot i/y$. Finally $c=y-i$ is the consumption steady state value.

The marginal rate of substitution (16) between consumption and labor can also be used to calculate the preference parameter γ.

$$\gamma = (1-\beta b)\, c^{\sigma b-\sigma-b} w\,(1-n)^{\sigma} \tag{51}$$

Using the efficiency condition for money m depends only upon β, b, c and σ and can be written as

$$m = (1-\beta)^{-\frac{1}{\sigma}}\,(1-\beta b)^{-\frac{1}{\sigma}}\, c^{\frac{\sigma+b-\sigma b}{b}} \tag{52}$$

2.7 Calibration

To compute impulse responses the parameters of the model have to be calibrated.

It is possible to either specify β or r exogenously. Here β will be set to 0.99 implying a value of r of about 0.0101 per quarter which is in line with other values used for the real interest rate in the literature. ψ and μ can be determined by fixing a value for the elasticity of the demand functions for the differentiated products. This elasticity being equal to 4 causes the static markup $\mu = \epsilon/(\epsilon-1)$ to be 1.33 which is in line with the study of [18, Linnemann (1999)] about average markups. In order to determine the steady state real wage w the productivity shock a has to be specified, along with calculating k/n, see below. As there is no information available about that parameter it is arbitrarily set at 10.[8] n is specified to be equal to 0.25 implying that agents work 25 % of their non-sleeping time.

In the benchmark case, σ, the parameter governing the degree of risk aversion, is set to 2. The value of b which measures the degree of habit persistence is set to 0.8 as in [19, McCallum/Nelson (1999)] in the benchmark case, implying a value for γ of 0.1483.

As this model considers the role of capital accumulation several other technological parameters have to be calibrated. The most common one is the depreciation rate δ which is set to 0.025 implying 10% depreciation per year. Labor's share α is 0.64 whereas the elasticity of Tobin's q with respect to i/k is set to -0.5.[9] This value is also used in [17, King/Wolman (1996)]. The presence of adjustment costs of capital dampens the volatility of investment

[8] In contrast to the well known basic neoclassical model of [13, King/Plosser/Rebelo (1988)] there is no escape from specifying parameters such as a at the steady state. The system cannot be reduced until only deep parameters remain to be calibrated.

[9] It can be shown that this elasticity is given by $-[\phi''/\phi' \cdot (i/k)]$.

and is a common feature in equilibrium business cycle models. Using r, δ, a, α and ψ the ratio k/n can be determined.

For the exogenous money growth process $\rho_{M_2} = 0.5$ is used. As the focus of the paper is on persistency of money shocks productivity shocks will not be considered. But they can be used to check whether the model displays reasonable impulse responses to technology shocks.

3 Impulse Response Functions

The solution is conducted using an extended version of the algorithm of [14, King/Plosser/Rebelo (2002)] which allows for singularities in the system matrix of the reduced model. The theoretical background of this algorithm is developed in [15, King/Watson (1999)] whereas computational aspects and the implementation are discussed in [16, King/Watson (2002)].

Figure 1 shows the reaction of output, investment, consumption and labor hours to a one percent shock to the money growth rate. The immediate impression is the cyclical responses of $\widehat{y}_t, \widehat{n}_t$ and $\widehat{i}_t$. They display almost no persistence at all. But consumption displays quite a persistent response although the magnitude is very small. Nevertheless the effects last for more than five periods. This is due to the habit formation in consumption. With the respective parameter b equal to 0.8 there is a sizeable influence of past period's consumption on today's utility so that households smooth their consumption expenditures. Figure 2 mirrors the response of the real wage, the real interest rate, the markup and the nominal interest rate. Counterfactually the nominal rate rises so the model does not generate the liquidity effect. But this variable is quite persistent as opposed to the other three which are again cyclical. The strong rise in real marginal costs displayed in Figure 3 causes firms to raise prices very strongly. They overshoot their new equilibrium value considerably. This rise is stronger than the rise in money so real balances even fall and approach the steady state from below. The capital stock is hump-shaped but the magnitude of the increase is very small while nevertheless the effects are longlasting. Inflation does not show a hump but peaks in the first period, as shown in Figure 4. It can be concluded that habit persistence improves only the response of consumption to a money growth shock.

To see this Figure 5 displays the results when setting $b = 0.1$ so that the influence of the habit reference level c_{t-1} is quite small. Now consumption responds in a similar way as investment and output rising strongly in the first period while falling below steady state immediately afterwards. All other variables react in a similar way as in the benchmark case.

Assigning b the highest possible value of 1 so that only the ratio of current to past consumption matters (see the discussion of the utility function above) allows consumption to be hump-shaped reaching a peak 12 periods after the shock. But note the very small value of the reaction: $\widehat{c}_t$ deviates only about 0.01 percent from steady state due to a 1 percent shock to money growth. To evaluate the model along this dimension see the next section.

4 Business Cycle Properties

In order to explore the implications for the business cycle properties one has to specify the standard deviation of the AR(1)-process for money growth. Here the value estimated in [6, Cooley/Hansen (1995)], p.201, is used.[10] It implies a value of 0.0000792 for the variance σ_M^2. Table 1 shows the results for the benchmark model with $b = 0.8$ after HP-filtering with $\lambda = 1600$.

Table 1
Moments of Selected Variables in the Benchmark Model[11]

			autocorrelation		cross correlation of $\widehat{x}_t$ with $\widehat{y}$ in				
$\widehat{x}_t$	$\sigma_{\widehat{x}}$	$\sigma_{\widehat{x}}/\sigma_{\widehat{y}}$	1	2	$t-2$	$t-1$	t	$t+1$	$t+2$
$\widehat{y}_t$	0.34	1.00	-0.14	-0.02	-0.02	-0.14	1.00	-0.14	-0.02
$\widehat{i}_t$	1.42	4.14	-0.23	-0.04	-0.06	-0.25	0.99	-0.12	-0.01
$\widehat{c}_t$	0.10	0.29	0.28	0.06	0.10	0.26	0.90	-0.18	-0.08
$\widehat{n}_t$	0.54	1.59	-0.15	-0.03	-0.04	-0.16	0.99	-0.13	-0.01
$\widehat{w}_t$	1.09	3.19	-0.20	-0.04	-0.05	-0.22	0.99	-0.13	-0.01
$\widehat{\mu}_t$	1.29	3.78	-0.20	-0.04	0.05	0.21	-0.99	0.12	0.01
$\widehat{R}_t$	1.30	3.79	0.60	0.12	0.17	0.62	0.62	-0.13	-0.07
$\widehat{\psi}_t$	1.29	3.78	-0.20	-0.04	-0.05	-0.21	0.99	-0.12	-0.01
$\widehat{\Pi}_t$	1.26	3.67	0.35	-0.20	-0.21	0.61	0.69	-0.11	-0.04
$\widehat{P}_t$	2.17	6.33	0.83	0.54	0.31	0.43	0.07	-0.32	-0.26

[10] It is not intended to take the model explicitly to the data because of its overwhelming simplicity. This justifies the use of Cooley and Hansen's parameter values.

[11] $\sigma_{\widehat{x}}$ denotes the percentage standard deviation of $\widehat{x}$ whereas $\sigma_{\widehat{x}}/\sigma_{\widehat{y}}$ measures the respective standard deviation relative to that of output $\widehat{y}$. The next two columns report the autocorrelations for one and two lags of the respective aggregate.

This table strenghtens the insights from the impulse response functions. First, the cyclical character of most variables is displayed in their negative autocorrelations, see e.g. output and investment. Second, investment, labor, the real wage and real marginal cost are nearly perfectly correlated with output whereas the correlations at leads and lags are negative. Third, the relative variability of consumption (0.29) is very low while also most absolute volatilities of the real variables are too small compared to empirical estimates. This applies especially to output and investment giving support to the claim that money growth shocks cannot account for the observed volatilities of real aggregates. The opposite is true for nominal variables such as the inflation rate which is by far too volatile. The same result concerns the price level. Fourth, only consumption and the nominal interest rate show a small portion of persistence since their autocorrelations are positive and well above 0.25 at the first lag.

In the limiting case with $b = 1$ the relative variability of consumption falls to 0.04 while the absolute value is only 0.01% (see also Figure 6). But the autocorrelations rise to 0.75 and 0.57 respectively. On the other hand investment is now 5.40 times as volatile as output which is by far too high. Labor's relative variability does not change. Finally considering $b = 0.1$ worsens the performance of the model even more (compare Figure 5). Of course now consumption shows more variation, its relative volatility rises to 0.62. But the autocorrelations as well as the lead/lag correlations get negative while the contemporaneous correlation with output is perfect.

5 Conclusions

Adding habit persistence in consumption to a stochastic DGE model with sticky prices does not enhance very much the ability to account for persistent effects of money growth shocks. It is only the behavior of consumption that can be improved.

This stands in contrast to results in [2, Bouakez/Cardia/Ruge-Murcia (2002)] who consider a similar model. But these authors estimate their model using a Kalman-filter to explain US data. They also use a different way to model adjustment costs of capital. Finally they assume Calvo-pricing. It seems that the latter features are responsible for the difference. The analysis of this issue is left for future research.

The model presented here can also be extended to include wage staggering as another nominal rigidity. It would be particularly interesting to investigate the interaction with sticky prices to create inflation and output persistence. In addition the inclusion of variable capacity utilization could further enhance persistency, as suggested by [5, Christiano/Eichenbaum/Evans (2001)].

The analysis of wage staggering is of particular interest since Woodford has recently shown that "allowing for wage stickiness does not matter all that much, if our goal is simply to construct a positive model of the comovement of inflation and output and the way that both can be affected by monetary policy".[12] This gives a justification to neglect wage staggering in positive stochastic DGE models and casts some doubt on the role some authors give to sticky wages.

A Appendix

A.1 Household's Equations

The efficiency condition for consumption results in

$$\begin{aligned} & (1-\sigma)\,\beta b c^{\sigma b-b-\sigma}\widehat{c}_{t+1} \\ = \; & \left[-\sigma-\beta b\,(\sigma b-b-1)\right] c^{\sigma b-b-\sigma}\widehat{c}_{t}+b\,(\sigma-1)\,c^{\sigma b-b-\sigma}\widehat{c}_{t-1} \\ & -(1-\beta b)\,c^{\sigma b-b-\sigma}\widehat{\lambda}_{t} \end{aligned} \tag{53}$$

A hat ($\widehat{\ }$) represents the relative deviation of the respective variable from its steady state ($\widehat{c}_t = (c_t - c)/c$).
The cyclical behavior of labor is determined by

$$\begin{aligned} 0 = \quad & -n\gamma\sigma\,(1-n)^{-\sigma-1}\,\widehat{n}_{t} \\ & +\gamma\,(1-n)^{-\sigma}\,\widehat{\lambda}_{t}+\gamma\,(1-n)^{-\sigma}\,\widehat{w}_{t} \end{aligned} \tag{54}$$

The efficiency condition for money determines the respective demand function. So one gets

$$\begin{aligned} & \beta\,(1-\beta b)\,c^{\sigma b-b-\sigma}\widehat{P}_{t+1}-\beta\,(1-\beta b)\,c^{\sigma b-b-\sigma}\widehat{\lambda}_{t+1} \\ = \; & -\sigma m^{-\sigma}\widehat{M}_{t} \\ & -(1-\beta b)\,c^{\sigma b-b-\sigma}\widehat{\lambda}_{t} \\ & +\left[\beta\,(1-\beta b)\,c^{\sigma b-b-\sigma}+\sigma m^{-\sigma}\right]\widehat{P}_{t} \end{aligned} \tag{55}$$

[12] See [23, Woodford (2002)], p. 104/105.

The nominal interest rate follows, according to (17),

$$-\widehat{P}_{t+1}+\widehat{\lambda}_{t+1}=-\widehat{P}_t-\frac{R}{1+R}\widehat{R}_t+\widehat{\lambda}_t \tag{56}$$

in the approximated form, with R (respective r for the real rate) as the steady state values. The real rate r_t was deduced via the Fisher equation (see (18)) so that the approximated equation is given by

$$\widehat{\lambda}_{t+1}=-\frac{r}{1+r}\widehat{r}_t+\widehat{\lambda}_t \tag{57}$$

Optimal investment is determined from the efficiency condition for i_t:

$$0=-\widehat{\lambda}_t+\widehat{\theta}_t+\frac{\phi''}{\phi'}\frac{i}{k}\widehat{i}_t-\frac{\phi''}{\phi'}\frac{i}{k}\widehat{k}_{t-1} \tag{58}$$

The first order condition for capital implies:

$$\beta z\widehat{\lambda}_{t+1}+\beta z\widehat{z}_{t+1}+\beta\left(1-\delta\right)\widehat{\theta}_{t+1}-\beta\frac{\phi''}{\phi'}\frac{i}{k}\frac{i}{k}\widehat{i}_{t+1}=-\beta\frac{\phi''}{\phi'}\frac{i}{k}\frac{i}{k}\widehat{k}_t+\widehat{\theta}_t \tag{59}$$

Capital evolves over time according to

$$\widehat{k}_t=\left(1-\delta\right)\widehat{k}_{t-1}+\delta\widehat{i}_t \tag{60}$$

A.2 Finished Goods Firm's Equations

Since the focus is on a symmetric equilibrium the only equation that remains for the finished goods firm is the price index.

$$0=\frac{1}{2}\widehat{P}_{0,t}+\frac{1}{2}\widehat{P}_{0,t-1}-\widehat{P}_t \tag{61}$$

In order to avoid too many variables $\widehat{P}_{1,t}$ is dropped and replaced by $\widehat{P}_{0,t-1}$.

A.3 Intermediate Goods Firm's Equations

The optimum conditions of the cost minimization problem determine the real wage and the rental rate of capital (see (28) and(29)), with the $j's$ dropped of course.

$$0 = \left(\alpha-1\right)\widehat{n}_t+\left(1-\alpha\right)\widehat{k}_{t-1}+\widehat{\psi}_t+\widehat{a}_t-\widehat{w}_t \tag{62}$$

$$0 = \alpha\widehat{n}_t-\alpha\widehat{k}_{t-1}+\widehat{\psi}_t+\widehat{a}_t-\widehat{z}_t \tag{63}$$

The production function is given by the Cobb-Douglas-functions of the intermediate goods firms and valid in aggregate variables.

$$0 = -\widehat{y}_t + \alpha \widehat{n}_t + (1-\alpha)\,\widehat{k}_{t-1} + \widehat{a}_t \tag{64}$$

The condition for optimal two period pricing is given in (38). Its Taylor approximation can be written as

$$\begin{aligned}
&\beta\left[\epsilon\psi - (\epsilon-1)\right]\widehat{\lambda}_{t+1} + \beta\left[\epsilon^2\psi - (\epsilon-1)^2\right]\widehat{P}_{t+1} + \beta\left[\epsilon\psi - (\epsilon-1)\right]\widehat{y}_{t+1} \\
&+\beta\epsilon\psi\widehat{\psi}_{t+1} = (\epsilon-1)(1+\beta)\,\widehat{P}_{0,t} + \left[(\epsilon-1) - \epsilon\psi\right]\widehat{\lambda}_t \\
&+\left[(\epsilon-1)^2 - \epsilon^2\psi\right]\widehat{P}_t + \left[(\epsilon-1) - \epsilon\psi\right]\widehat{y}_t - \epsilon\psi\widehat{\psi}_t
\end{aligned} \tag{65}$$

A.4 Market Clearing Conditions and Other Equations

The Taylor expansion of the aggregate market clearing condition is given by

$$0 = -\widehat{y}_t + \frac{c}{y}\widehat{c}_t + \frac{i}{y}\widehat{i}_t \tag{66}$$

The markup μ_t is determined by the ratio of price over nominal marginal cost ($\mu = P/(P\psi)$ and as there is no steady state inflation it follows that $\mu_t = 1/\psi_t$. So the Taylor approximation can be written as

$$0 = \widehat{\mu}_t + \widehat{\psi}_t \tag{67}$$

A.5 The Monetary Authority and further Equations

To close the model one needs to assume some exogenous process for money supply. Here it will be assumed that money $\widehat{M_t}$ follows an AR(2)-process (see the discussion in the main text). This implies that the growth rate of $\widehat{M_t}$ follows an AR(1)-process. In order to model this properly one has to add the equation

$$0 = \widehat{\widehat{M_t}} - \widehat{g}_{M_t} \tag{68}$$

where $\widehat{g}_{M_t}$ is the exogenous stochastic process that will have the same characteristics as $\widehat{M_t}$.

As it is interesting to study the implications for the inflation rate Π this equation is further added to the system:

$$0 = -\widehat{\Pi}_t + \widehat{P}_t - \widehat{P}_{t-1} \tag{69}$$

There are now 21 variables
$\widehat{c}_t, \widehat{c}_{t-1}, \widehat{i}_t, \widehat{y}_t, \widehat{\lambda}_t, \widehat{\theta}_t, \widehat{k}_t, \widehat{k}_{t-1}, \widehat{n}_t, \widehat{w}_t, \widehat{z}_t, \widehat{\mu}_t, \widehat{\psi}_t, \widehat{r}_t, \widehat{R}_t, \widehat{P}_t, \widehat{P}_{t-1}, \widehat{P}_{0,t}, \widehat{P}_{0,t-1}, \widehat{\Pi}_t, \widehat{M_t}$
but only 17 equations so four tautologies must be added to the model. These are

$$\widehat{P}_{0,t} = \widehat{P}_{0,t} \tag{70}$$
$$\widehat{P}_t = \widehat{P}_t \tag{71}$$
$$\widehat{k}_t = \widehat{k}_t \tag{72}$$
$$\widehat{c}_t = \widehat{c}_t \tag{73}$$

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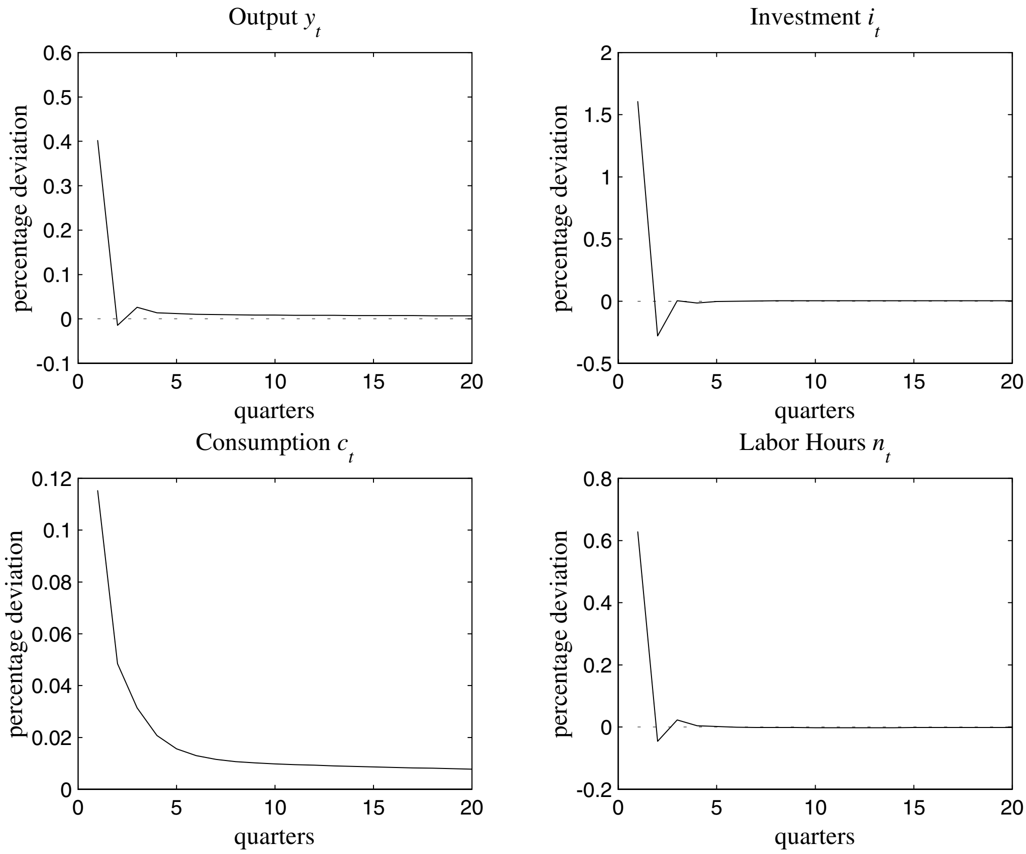

Figure 1: Impulse Response Functions for $\widehat{y}_t, \widehat{i}_t, \widehat{c}_t, \widehat{n}_t$

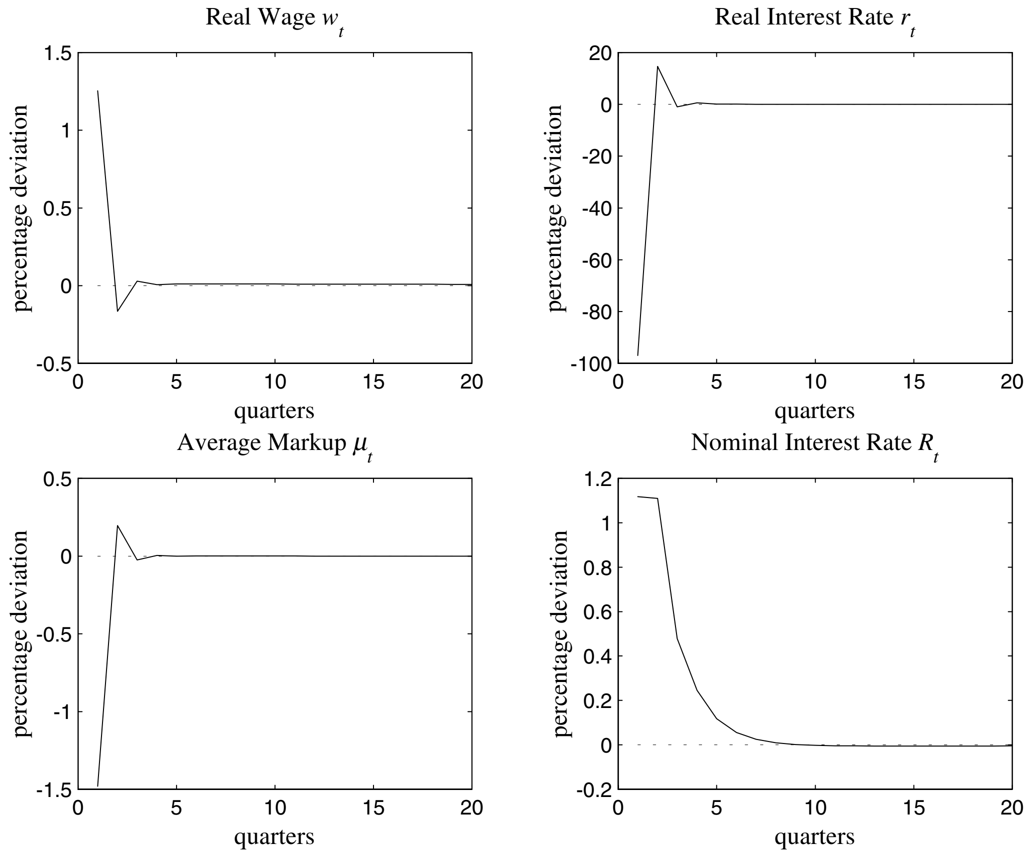

Figure 2: Impulse Response Functions for $\widehat{w}_t, \widehat{r}_t, \widehat{\mu}_t, \widehat{R}_t$

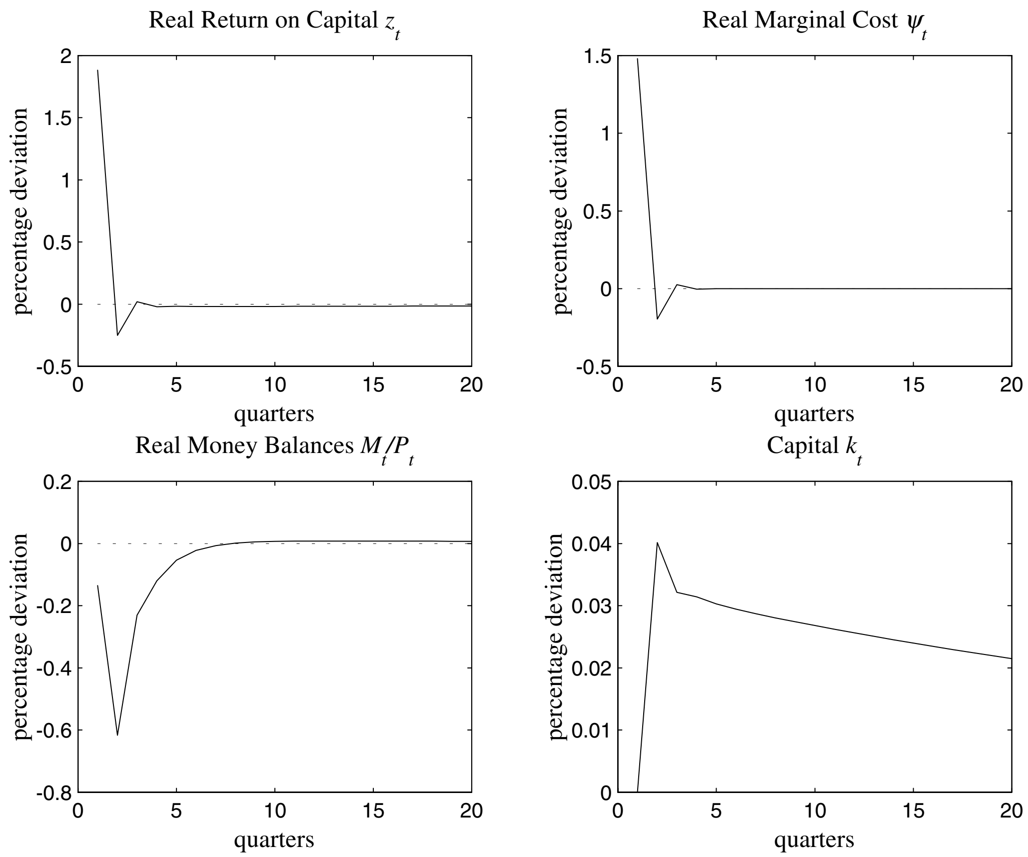

Figure 3: Impulse Response Functions for $\widehat{z}_t, \widehat{\psi}_t, \widehat{M_t} - \widehat{P}_t, \widehat{k}_t$

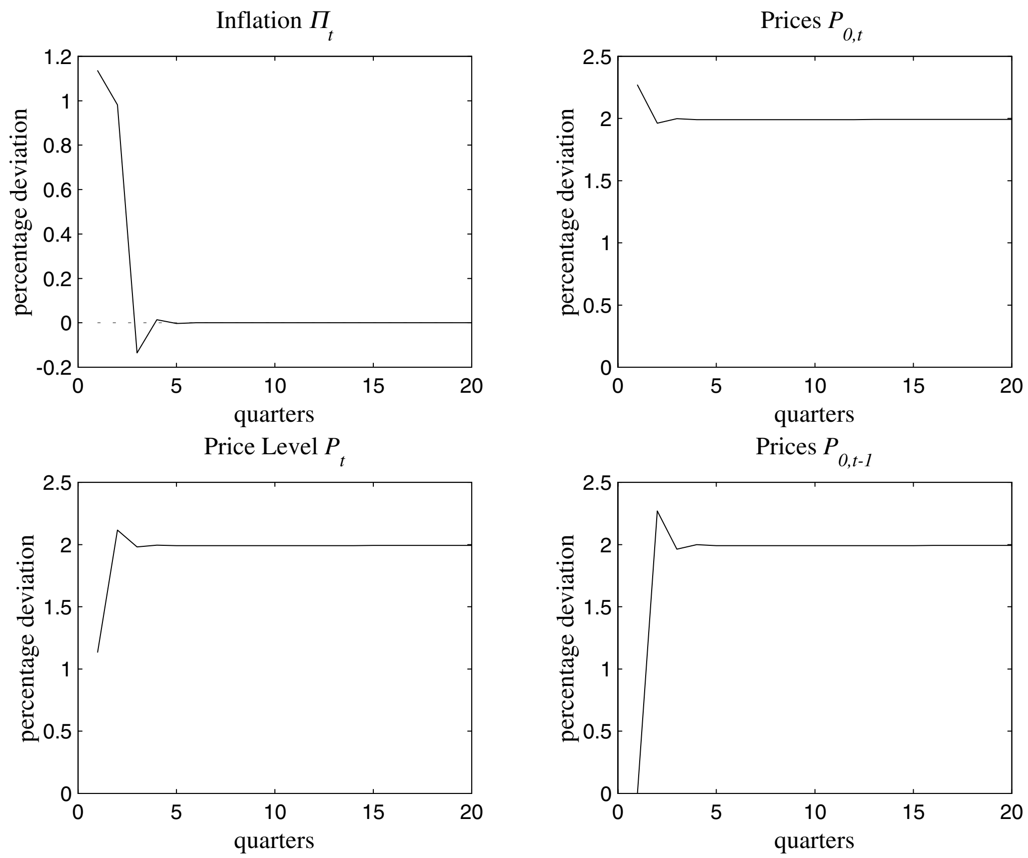

Figure 4: Impulse Response Functions for $\widehat{\Pi}_t$, $\widehat{P}_{0,t}$, $\widehat{P}_t$, $\widehat{P}_{0,t-1}$

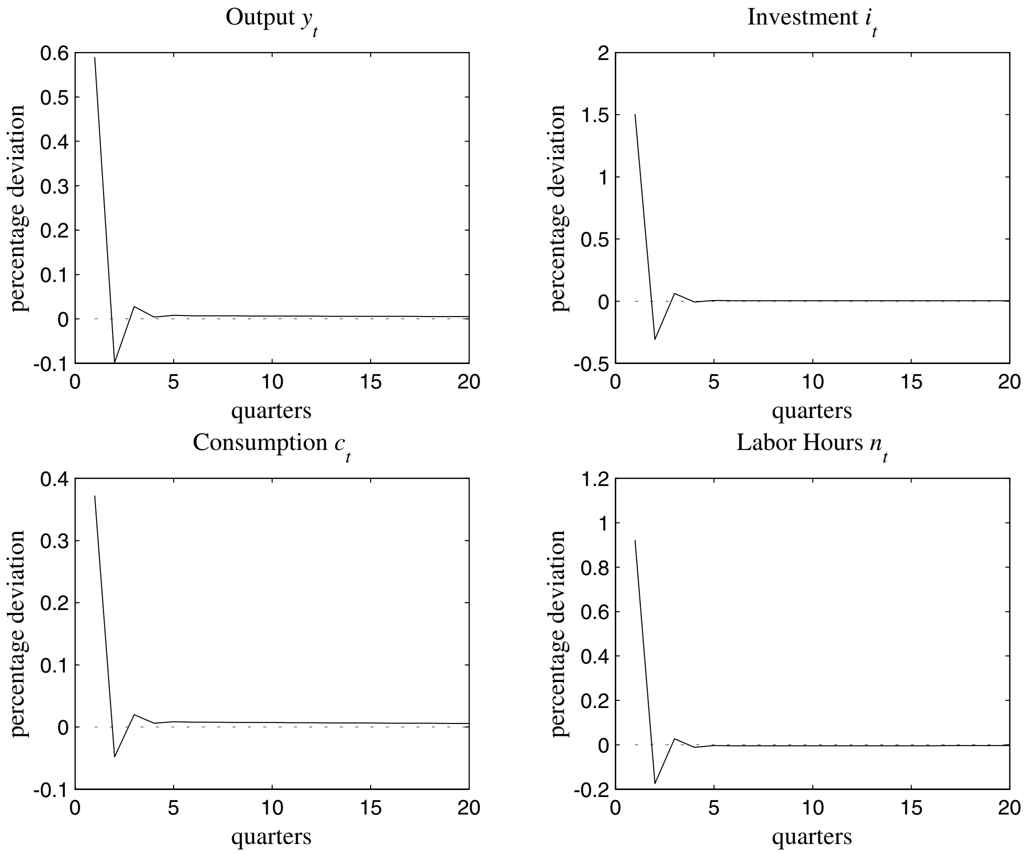

Figure 5: Impulse Response Functions for $\widehat{y}_t, \widehat{i}_t, \widehat{c}_t, \widehat{n}_t$, $b = 0.1$

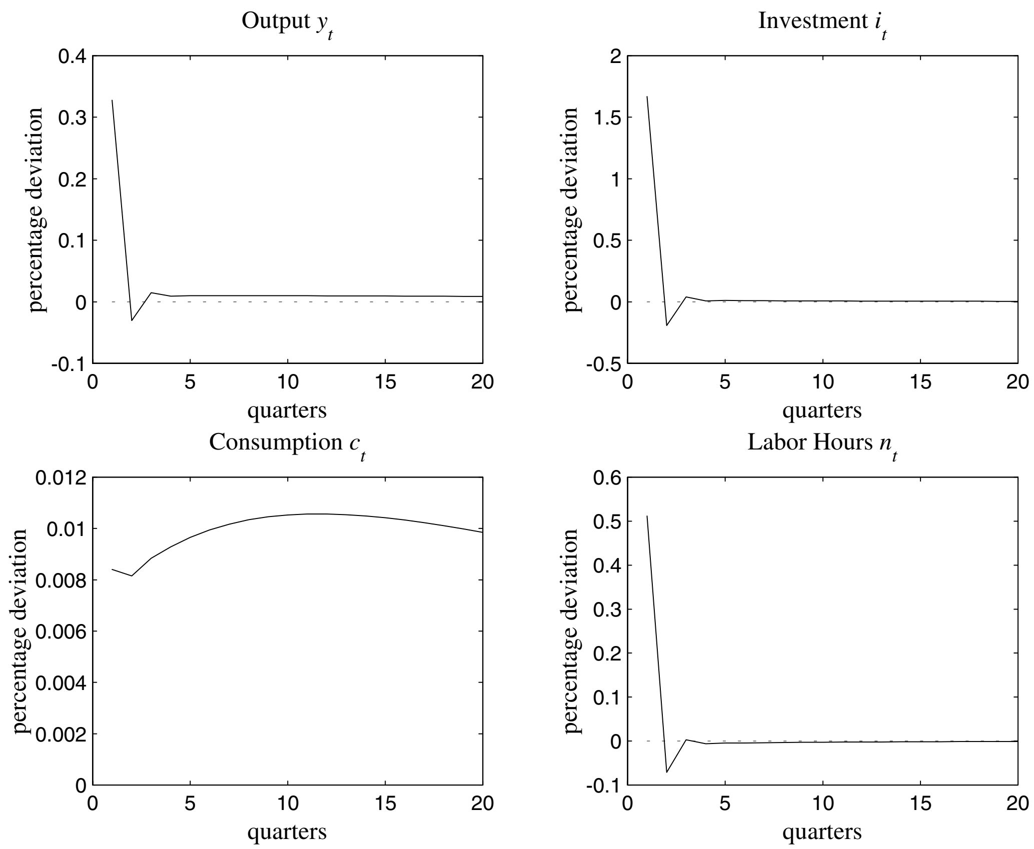

Figure 6: Impulse Response Functions for $\widehat{y}_t, \widehat{i}_t, \widehat{c}_t, \widehat{n}_t$, $b = 1$

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