Habit Formation and the Persistence of Monetary Shocks*

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First Draft: November 2001
Revised: March 2003

Abstract

This paper studies the persistent effects of monetary shocks on output. Previous empirical literature documents this persistence, but standard general equilibrium models with sticky prices fail to generate output responses beyond the duration of nominal contracts. This paper constructs and estimates a general equilibrium model with price rigidities, habit formation, and costly capital adjustment. The model is estimated via Maximum Likelihood using U.S. data on output, real money balances, and the nominal interest rate. Econometric results suggest that habit formation and adjustment costs to capital play an important role in explaining the output effects of monetary policy. In particular, impulse response analysis shows that the model generates persistent, hump-shaped output responses to monetary shocks.

JEL Classification: E3, E4, E5
Key Words: Habit formation, endogenous persistence, monetary policy

*We thank Mick Devereux, Peter Ireland, Robert King, and an anonymous referee for helpful comments and suggestions. Financial support from the Social Sciences and Humanities Research Council and the Fonds pour la Formation de Chercheurs et l’Aide à la Recherche is gratefully acknowledged. Correspondence: Francisco J. Ruge-Murcia, Département de sciences économiques, Université de Montréal, C.P. 6128, succursale Centre-ville, Montréal (Québec) H3C 3J7, Canada. E-mail: francisco.ruge-murcia@umontreal.ca

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1 Introduction

In a recent paper, Chari, Kehoe, and McGrattan (2000) find that standard dynamic stochastic general equilibrium (DSGE) models with sticky prices fail to generate persistent output effects to monetary shocks. More precisely, the response of output to a money growth shock does not last beyond the duration of price contracts, even if contracts are staggered. Hence, unless one assumes an implausibly large degree of price rigidity, this type of models cannot replicate the persistent output response obtained using, for example, Vector Autoregressions (VARs). Previous empirical literature based on VARs documents a persistent, hump-shaped response of output to a monetary shock with a peak around 4 to 6 quarters after the shock [see Bernanke and Mihov (1998), Christiano, Eichenbaum and Evans (1999), and our benchmark VAR below]. The failure of DGSE models to replicate this feature of the data, is referred to as “the persistence problem.”

This paper studies the effects of monetary policy on output using a DSGE model with sticky prices, habit formation, and adjustment costs to capital. Price rigidity is modeled as in Calvo (1983), where each firm has a constant exogenous probability of changing its price in every period. Habit formation has been employed previously by (among others) Abel (1990), Constantinides (1990), and Campbell and Cochrane (1999) to study the equity premium puzzle, by Carrol, Overland, and Weil (2000) to explain the growth-to-savings causality, and by Fuhrer (2000) to explain the excess smoothness of consumption and inflation inertia. Because habit-forming agents dislike large changes in consumption, the consumption response to shocks is smoother and more persistent than predicted by the Permanent Income Hypothesis (PIH) with time-separable utility. In a general-equilibrium framework, habit formation affects the resource allocation by agents. In particular, habit-forming agents adjust their labor supply more gradually to attain a smoother and more persistent consumption profile. In turn, this should translate into a more persistent output path. This suggests that habit formation is a plausible candidate to explain the persistent and hump-shaped output response to monetary policy shocks.

The model is estimated by the method of Maximum Likelihood (ML) using U.S. data on output, real money balances, and the nominal interest rate. The ML procedure yields plausible estimates of the structural parameters. Impulse response analysis indicates that monetary shocks lead to a persistent and hump-shaped output response. When the fit of the estimated DSGE model is compared with that of an unrestricted VAR, the Mean Square Error (MSE) of the DSGE model is smaller than the one of the VAR for output and real money balances and only slightly larger for the nominal interest rate. Variance decomposition indicates that money growth explains more than 50 per cent of the (conditional)
output variability at horizons of less than a year. In the long run, money growth explains only 27.1 per cent of the unconditional output variability while 71.4 per cent is explained by technology shocks.

The empirical analysis of two restricted versions of the model indicates that habit formation interacts with costly capital adjustment to increase the propagation of monetary shocks in the model. Adjustment costs to capital spread out investment and output responses to shocks, while habit formation magnifies output persistence through its effect on labor supply. This result parallels those obtained by Jermann (1998) and Boldrin, Christiano, and Fisher (2001). These authors find that a combination of habit formation and some factor rigidity is helpful in explaining the equity premium puzzle and some business cycle facts.

Other papers that study the persistent output effects of monetary shocks include Bergin and Feenstra (2000); Dotsey and King (2001); Dib and Phaneuf (2001); and Ambler, Guay, and Phaneuf (2003). Bergin and Feenstra construct a model where the interaction of materials inputs and translog preferences leads to endogenous output persistence. Translog preferences dissuade firms from charging higher prices by making the elasticity of demand facing a given firm depend on the firm’s relative price. Dotsey and King construct a model that incorporates variable capital utilization, materials input, and labor flexibility. Results indicate that these three features are mutually reinforcing and magnify output persistence. Dib and Phaneuf, and Ambler, Guay, and Phaneuf construct DSGE models with sticky prices and costly adjustment to labor. Their results show that adding adjustment costs to the labor input generates endogenous output persistence to monetary shocks. After our research was completed, we found a closely related and independent paper by Christiano, Eichenbaum, and Evans (2001). These authors examine both output and inflation persistence using a limited participation model that incorporates price and wage rigidities, optimizing and non-optimizing price and wage setting, habit formation, adjustment costs in investment, and variable capital utilization. Their results suggest that wage rigidity and variable capital utilization are also important to explain output persistence in response to monetary shocks. Although apparently distinct, the crucial features of these models work through the same channel to increase output persistence. They prevent the rapid change in the real marginal cost after a monetary shock and lead to stronger nominal rigidity.

The rest of the paper is organized as follows: Section 2 presents the theoretical model, Section 3 describes the estimation procedure and data, Section 4 reports empirical results, and Section 5 concludes.
2 The Model

The economy consists of (i) an infinitely-lived representative household, (ii) a representative final good producer, (iii) a continuum of intermediate good producers indexed by $i \in [0, 1]$, and (iv) a government. Intermediate goods are used in the production of the final good. The final good is perishable and can be used for either consumption or investment. There is no population growth. The population size is normalized to one.

2.1 Households

The representative household maximizes lifetime utility defined by:

$$U_t = E_t \sum_{s=t}^{\infty} \beta^{s-t} u_s(c_s, c_{s-1}, m_s, \ell_s),$$

where $\beta \in (0, 1)$ is the subjective discount factor and $u(\cdot)$ is the instantaneous utility function. Households derive utility from the consumption of the final good ($c_t$), real money balances ($m_t$), and leisure ($\ell_t$). The household’s preferences exhibit internal habit formation. That is, utility depends on current consumption relative to a habit stock determined by the household’s own past consumption. Then, consumption levels in adjacent periods are complements. In particular, the instantaneous utility function is assumed to be:

$$u_t(c_t, c_{t-1}, m_t, \ell_t) = \left(\frac{c_t}{c_{t-1}}\right)^{1-\eta_1} + \frac{b_t(m_t)^{1-\eta_2}}{1-\eta_2} + \frac{\psi(\ell_t)^{1-\eta_3}}{1-\eta_3},$$

(1)

where $m_t = M_t / P_t$, $M_t$ is the nominal money stock, $P_t$ is the aggregate price index, $b_t$ is a preference shock, $\psi > 0$ measures the weight of leisure in the utility function, and $\eta_1, \eta_2, \eta_3$ are positive preference parameters different from one. In the special case where $\eta_j \to 1$ for $j = 1, 2, 3$, the logarithmic utility function is obtained. In the special case where $\gamma = 0$, there is no habit formation and households care only about the absolute level of current consumption. In principle, the habit stock could also include consumption levels prior to time $t - 1$. Fuhrer (2000) estimates a model where the stock of habit is a weighted average of past consumption and finds that the habit-formation reference level is essentially the previous period’s consumption level.

In addition to money, households can hold interest-bearing, one-period nominal bonds. The gross nominal interest rate on bonds due at time $t+1$ is denoted by $R_t$. The household’s resources in period $t$ consist of the principal and the return on bonds purchased at time $t-1$, money holdings set aside in period $t-1$, wages and rents received from selling labor and renting capital to firms, dividends, and lump-sum transfers from the government.
The household’s income in period $t$ is allocated to consumption, investment, money holdings, and the purchase of nominal bonds. Investment increases the household’s stock of capital according to:

$$k_{t+1} = (1 - \delta)k_t + \Gamma(x_t/k_t)k_t,$$

(2)

where $\delta \in (0, 1)$ is the depreciation rate of capital and $\Gamma(\cdot)$ is a positive and concave function. The assumption that $\Gamma(\cdot) > 0$ means that investment unambiguously increases the capital stock. The assumption that $\Gamma(\cdot)$ is concave means that large proportional changes in the capital stock are marginally more costly than smaller ones. This specification of capital adjustment costs has been employed previously by (among others) Baxter and Crucini (1993), King and Watson (1996), and Jermann (1998). In the special case where $\Gamma(\cdot) = x_t/k_t$, there are no adjustment costs and one unit invested becomes one unit of capital.

The representative household’s budget constraint (expressed in real terms) is:

$$c_t + a_t + m_t + x_t \quad (R_{t-1}/\pi_t)a_{t-1} + (m_{t-1}/\pi_t) + w_t n_t + q_t k_t + d_t + \tau_t,$$

(3)

where $a_t = A_t/P_t$ is the real value of nominal bond holdings, $A_t$ is nominal bond holdings, $\pi_t$ is the gross rate of inflation between $t - 1$ and $t$, $w_t$ is the real wage, $n_t$ is the number of hours worked, $q_t$ is the real rental rate of capital, $d_t$ are dividends, and $\tau_t$ are lump-sum transfers or taxes. The household’s time endowment is normalized to one.

The representative household maximizes its lifetime utility subject to the budget constraints (3) and the no-Ponzi-game condition. The first-order necessary conditions associated with the optimal choice of $c_t, M_t, \ell_t, k_{t+1}, x_t$, and $A_t$ for this problem are:

$$\lambda_t = (1/c_{t-1})(c_t/c_{t-1})^{-\eta_1} - \beta \gamma E_t[(c_{t+1}/c_t^{1+\gamma})(c_{t+1}/c_t)^{-\eta_1}],$$

(4)

$$b_t m_t^{-\eta_2} = \lambda_t[(R_t - 1)/R_t],$$

(5)

$$(1 - n_t)^{-\eta_3} = \lambda_t w_t/\psi,$$

(6)

$$\varsigma_t = \beta E_t[\lambda_{t+1} q_{t+1} + \varsigma_{t+1}(1 - \delta + \Gamma(x_{t+1}/k_{t+1}) - (x_{t+1}/k_{t+1})\Gamma'(x_{t+1}/k_{t+1}))],$$

(7)

$$\lambda_t = \varsigma_t \Gamma'(x_t/k_t),$$

(8)

$$\lambda_t = \beta R_t E_t(\lambda_{t+1}/\pi_{t+1}),$$

(9)

where $\lambda_t$ is the Lagrange multiplier associated with the household’s budget constraint at time $t$ and equals the marginal utility of consumption at time $t$, and $\varsigma_t$ is the Lagrange multiplier associated with the law of motion of capital. Condition (5) determines money demand by equating the marginal rate of substitution of money and consumption to $(R_t - 1)/R_t$, where $R_t$ is the gross return of the nominal bond. The interest elasticity of money is equal to $-1/\eta_2$.\(^1\) The preference shock $b_t$ has the interpretation of a money demand shock. Condition

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\(^1\)Strictly speaking, $-1/\eta_2$ is the elasticity with respect to $(R_t - 1)/R_t$ rather than $R_t - 1$. 
determines labor supply by equating the marginal rate of substitution between labor and consumption to the real wage. Condition (7) prices the marginal unit of capital. Condition (8) equates the benefit and cost of installing the marginal unit of capital. Condition (9) prices the nominal bond. Conditions (7) and (9) imply that the \textit{ex-ante} real interest rate should be equal to the \textit{ex-ante} real return on capital.

### 2.2 The Final-Good Producer

Final good producers are perfectly competitive and aggregate the intermediate goods into a single perishable commodity. Their technology is constant elasticity of substitution (CES):

\[ y_t = \int_0^1 y_t(i)^{(\theta-1)/\theta} di^{\theta/(\theta-1)}, \quad (10) \]

where \( y(i) \) is the input of intermediate good \( i \), and \( \theta > 1 \) is the elasticity of substitution between different goods. As \( \theta \to \infty \), goods become perfect substitutes in production. The final good producer solves the static problem:

\[ \text{Max} \quad P_t y_t - \int_0^1 P_t(i) y_t(i) di, \]

subject to (10). \( P_t(i) \) is the price of the intermediate good \( i \) and \( P_t \) is the aggregate price index. The solution of this problem yields the input demand of good \( i \):

\[ y_t(i) = \left( \frac{P_t(i)}{P_t} \right)^{-\theta} y_t, \quad (11) \]

where the elasticity of demand is \( \theta \). The zero-profit condition implies that the aggregate price index is given by:

\[ P_t = \int_0^1 P_t(i)^{(1-\theta)} di^{1/(1-\theta)}. \quad (12) \]

### 2.3 The Intermediate-Good Producer

The representative firm \( i \) produces its differentiated good using the Cobb-Douglas technology:

\[ y_t(i) = z_t k_t(i)^{\alpha} n_t(i)^{1-\alpha}, \quad (13) \]

where \( 0 < \alpha < 1 \) and \( z_t \) is a serially correlated technology shock. The technology shock is common to all intermediate good producers. Unit-cost minimization determines the demands for labor and capital inputs. Formally,

\[ \text{Min} \quad w_t n_t(i) + q_t k_t(i), \]

\[ \{ n_t(i), k_t(i) \} \]
subject to $z_t k_t(i)^\alpha n_t(i)^{1-\alpha} = y_t(i) \geq 1$. First-order conditions are:

\begin{align*}
    w_t &= (1 - \alpha) \phi_t[y_t(i)/n_t(i)], \\
    q_t &= \alpha \phi_t[y_t(i)/k_t(i)],
\end{align*}

where the real marginal cost ($\phi_t$) is the Lagrange multiplier associated with the constraint. Since technology is common, and labor and capital are perfectly mobile across industries, conditions (14) and (15) imply that all firms must have the same capital/labor ratio.

Intermediate-good producers are monopolistically competitive. Each firm faces the downward sloping demand curve (11) for its differentiated good. Firm $i$ chooses its nominal price $P(i)$ taking as given aggregate demand and the price level. Nominal prices are assumed to be sticky. Price stickiness is modeled as in Calvo (1983). That is, a firm changes its price with constant and exogenous probability $1 - \varphi$ in every period. Alternatively, one could assume explicit costs of changing prices or Taylor’s staggered price setting. Quadratic costs of price adjustments can be shown to yield an aggregate pricing equation similar to the one obtained using Calvo’s model. Aggregation is somewhat easier using Calvo-type than Taylor-type price rigidity because it is not necessary to keep track of heterogeneous price cohorts. From the point of view of estimating the average length of price contracts, Calvo’s model is also easier to implement because the log likelihood function is continuous on $\varphi$. This follows from the fact that the probability of prices changes is continuous in the interval $[0, 1]$. On the other hand, the contract length in Taylor’s model is an integer number and, consequently, the log likelihood function is discontinuous on this parameter.

Let us denote by $P^*_t$ the optimal price set by a typical firm at period $t$. It is not necessary to index $P^*_t$ by firm because all the firms that change their prices at a given time, choose the same price [see Woodford (1996)]. The total demand facing this firm at time $s$ for $s \geq t$ is $y^*_s = (P^*_t/P_s)^{-\theta} y_s$. The probability that $P^*_t$ “survives” at least until period $s$, for $s \geq t$, is $\varphi^{s-t}$. Then, the intermediate good producer chooses $P^*_t$ to maximize:

\[
    E_t \sum_{s=t}^{\infty} (\beta \varphi)^{s-t} \Lambda_{t,s} (P^*_t - \Phi_s) y^*_s,
\]

where $\Lambda_{t,s} = (\lambda_s/P_s)/(\lambda_t/P_t)$ and $\Phi_s$ is the nominal marginal cost at time $s$. Differentiating with respect to $P^*_t$ yields:

\[
    P^*_t = \left( \frac{\theta}{\theta - 1} \right) \left( \frac{E_t \sum_{s=t}^{\infty} (\beta \varphi)^{s-t} \Lambda_{t,s} y^*_s \Phi_s}{E_t \sum_{s=t}^{\infty} (\beta \varphi)^{s-t} \Lambda_{t,s} y^*_s} \right).
\]

Equation (16) shows that the optimal price depends on current and expected future demands and nominal marginal costs. Due to price stickiness, the equilibrium markup is not constant, as it would be if prices were flexible.
Assuming that price changes are independent across firms, the law of large numbers implies that $1 - \varphi$ is also the proportion of firms that set a new price each period. The proportion of firms that set a new price at time $s$ and have not changed it as of time $t$ (for $s < t$), is given by the probability that a time-$s$ price is still in effect in period $t$. It is easy to show that this probability is $\varphi^{t-s} (1 - \varphi)$. It follows that the aggregate price level can be written as:

$$
P_t = \left( (1 - \varphi) \sum_{s=-\infty}^{t} \varphi^{t-s} (P^*_t)^{1-\theta} \right)^{1/\theta}.
$$

This expression can be written in recursive form as $P_t^{1-\theta} = \varphi P_{t-1}^{1-\theta} + (1 - \varphi) (P^*_t)^{1-\theta}$.

### 2.4 The Government

The government comprises both fiscal and monetary authorities. There is no government spending or investment. The government makes lump-sum transfers to households each period. Transfers are financed by printing additional money in each period. Thus, the government budget constraint is:

$$
\tau_t = m_t - m_{t-1}/\pi_t,
$$

where the term on the right-hand side is seigniorage revenue at time $t$. Money is supplied exogenously by the government according to $M_t = \mu_t M_{t-1}$, where $\mu_t$ is the (stochastic) gross rate of money growth.\(^2\) In real terms, this process implies

$$
m_t \pi_t = \mu_t m_{t-1}.
$$

### 2.5 Stochastic Shocks

The economy is subject to shocks to technology ($z_t$), money supply growth ($\mu_t$), and money demand ($b_t$). These shocks follow the exogenous stochastic processes:

$$
\ln z_{t+1} = (1 - \rho_z) \ln z + \rho_z \ln z_t + \epsilon_{z,t},
$$

$$
\ln \mu_{t+1} = (1 - \rho_\mu) \ln \mu + \rho_\mu \ln \mu_t + \epsilon_{\mu,t},
$$

$$
\ln b_{t+1} = (1 - \rho_b) \ln b + \rho_b \ln b_t + \epsilon_{b,t},
$$

where $\rho_z, \rho_\mu,$ and $\rho_b$ are strictly bounded between $-1$ and $1$ and the innovations $\epsilon_t = (\epsilon_{z,t}, \epsilon_{\mu,t}, \epsilon_{b,t})'$ are assumed to be normally distributed with a zero mean and variance-covariance.

\(^2\)It is easy to extend the model to allow an endogenous process for money supply whereby money growth (or the nominal interest rate) follows, for example, a Taylor-type rule. Yun (1996) finds that making the money supply endogenous does not make a significant difference regarding the real effects of monetary shocks.
Asymmetric equilibrium for this economy is a collection of 13 sequences \((c_t, m_t, n_t, x_t, k_{t+1}, y_t, \lambda_t, \phi_t, P_t, P^*_t, q_t, w_t, \text{ and } R_t)_{t=0}^\infty\) such that households maximize utility, firms maximize profits, and all markets clear, given the initial stocks of habit, real balances, and capital, and the exogenous stochastic processes \((z_t, \mu_t, b_t)\).

Since the model cannot be solved analytically, the equilibrium conditions are log-linearized around the deterministic steady state to obtain a system of linear difference equations. After some manipulations, the log-linearized version of the model can be written as:

\[
\begin{bmatrix}
X_{t+1} \\
E_t Y_{t+1}
\end{bmatrix} =
\begin{bmatrix}
A_{11} & A_{12} \\
A_{21} & A_{22}
\end{bmatrix}
\begin{bmatrix}
X_t \\
Y_t
\end{bmatrix} +
\begin{bmatrix}
B_1 \\
B_2
\end{bmatrix} Z_{t+1},
\]

(23)

\[
Z_{t+1} = \rho Z_t + \epsilon_{t+1},
\]

(24)

where \(X_t = (\hat{k}_t, \hat{m}_{t-1}, \hat{c}_{t-1})'\) is a 3 \times 1 vector that contains the predetermined variables of the system (the circumflex denotes percentage deviations from the deterministic steady state); \(Y_t = (\hat{c}_t, \hat{\mu}_t, \hat{\lambda}_t, \hat{q}_t)'\) is a 4 \times 1 vector that contains the forward looking variables; \(Z_t = (\hat{z}_t, \hat{\mu}_t, \hat{b}_t)'\) is a 3 \times 1 vector that contains the exogenous shocks; \(\epsilon_t = (\epsilon_{z,t}, \epsilon_{\mu,t}, \epsilon_{b,t})'\) is a 3 \times 1 vector with the innovations to \(z_t, \mu_t\), and \(b_t\), respectively; \(\rho\) is a 3 \times 3 diagonal matrix with elements \(\rho_z, \rho_\mu, \text{ and } \rho_b\); and \(A_{11}, A_{12}, A_{21}, A_{22}, B_1, \text{ and } B_2\) are submatrices of appropriate size that contain combinations of structural parameters. The Blanchard-Kahn forward-backward solution method can be applied to (23) to obtain:

\[
\begin{align*}
X_{t+1} &= A_{11} X_t + A_{12} Y_t + B_1 Z_t, \\
Y_t &= F_1 X_t + F_2 Z_t,
\end{align*}
\]

(25)

where \(F_1\) and \(F_2\) are both 4 \times 3 matrices that include nonlinear combinations of the structural parameters contained in \(A_{11}, A_{12}, A_{21}, A_{22}, B_1, \text{ and } B_2\). For the precise form of these matrices and the conditions for a unique solution, see Blanchard and Kahn (1980). Finally, the remaining (static) variables of the model can be collected in the 6 \times 1 vector \(S_t = (\hat{x}_t, \hat{n}_t, \hat{w}_t, \hat{\phi}_t, \hat{R}_t, \hat{y}_t)'\) that follows

\[
S_t = CX_t + DZ_t,
\]

(26)

where \(C\) and \(D\) are matrices of size 6 \times 3 whose elements are also nonlinear combinations of structural parameters.
3 Estimation Method and Data

The model is estimated by the method of Maximum Likelihood (ML) using the Kalman filter. Previous papers that use ML procedures to estimate DGSE models include Christiano (1988), Altug (1989), Bencivenga (1992), McGrattan (1994), Hall (1996), McGrattan, Rogerson, and Wright (1997), Kim (2000), and Ireland (2001). The Kalman filter allows us to deal with unobserved or poorly measured predetermined variables (like the stock of capital) and yields the optimal solution to the problem of predicting and updating state-space models. Hansen and Sargent (1998) show that the ML estimator obtained by applying the Kalman filter to the state-space representation of DGSE models is consistent and asymptotically efficient.

For the Kalman-filter estimation procedure, the transition (or state) equation is constructed using equations (24) and (25) to collect the predetermined and exogenous variables of the system into the $6 \times 1$ vector $H_t = (X_t, Z_t)' = (k_t, m_{t-1}, z_t, \mu_t, b_t)'$ that follows the process:

$$H_{t+1} = QH_t + e_{t+1},$$

(27)

where

$$Q = \begin{bmatrix} A_{11} + A_{12}F_1 & A_{12}F_2 + B_1 \\ 0 & \rho \end{bmatrix}$$

is a $6 \times 6$ matrix and $e_t = (0, 0, 0, \epsilon_t)' = (0, 0, \epsilon_{zt}, \epsilon_{\mu t}, \epsilon_{bt})'$ is a $6 \times 1$ vector.

The measurement equation consists of the processes for output, real money balances, and the nominal interest rate. After some fairly straightforward transformations, these variables are written as functions of $H_t$:

$$\xi_t = WH_t,$$

(28)

where $\xi_t = (m_t, y_t, R_t)'$ is a $3 \times 1$ vector and $W$ is a $3 \times 6$ matrix. The elements of $Q$ and $W$ are nonlinear functions of the structural parameters of the model. These elements are computed from the Blanchard-Kahn solution of the DSGE model in each iteration of the optimization procedure. Note that the estimation procedure imposes all restrictions implied by the theoretical model. Standard errors were computed as the square root of the diagonal elements of the inverted Hessian of the log likelihood function evaluated at the maximum. At the estimated ML parameters, the condition for existence of a unique model

As is well known, the Maximum Likelihood estimation of DSGE models using more observable variables than structural shocks leads to a singular variance-covariance matrix of the residuals. One strategy to address this issue is to add measurement errors to the observable variables. A possible drawback to this approach is that measurement errors lack a structural interpretation and essentially capture specification error. Still, in preliminary work, we considered this approach. When we added measurement errors to all observable variables, we found that not all variances were identified or that some of them converged to zero. When we added only as many errors as needed to make the system nonsingular, we found that results were very sensitive to the variable that was assumed to be measured with noise.
solution is satisfied. That is, the number of explosive characteristic roots of the system of linear difference equations equals to the number of non-predetermined variables.

The model was estimated using quarterly U.S. data on output, real money balances, and the rate of nominal interest. The series were taken from the database of Federal Reserve Bank of St.-Louis. The sample is 1960:Q1 to 2001:Q2. Output is measured by real GDP per capita. The stock of nominal money is measured by M2 per capita. By measuring these two series in per capita terms, we aim to make the data compatible with our model, where there is no population growth. Population is measured by the civilian, noninstitutional population, 16 years old and over. The gross nominal interest rate is measured by the 3-month U.S. Treasury bill rate. Since the variables in the model are expressed in percentage deviations from the steady state, the output and real money series were logged and detrended linearly. The nominal interest rate series was logged and demeaned. We also estimated the model using Hodrick-Prescott (HP) filtered data and obtained very similar results to the ones reported below.

4 Empirical Results

This section reports the econometric results of this project. Sections 4.1 to 4.5 report, respectively, Maximum Likelihood estimates, fitness and specification tests, impulse-response analysis, second moments, and variance decomposition for the model in Section 2. Section 4.6 discusses the results for the restricted versions of the model.

4.1 Maximum Likelihood Estimates

The estimated structural parameters are the preference parameters \( \eta_2 \) and \( \eta_3 \), the habit persistence parameter \( \gamma \), the probability that an intermediate-good producer keeps its price fixed in a given quarter \( \varphi \), the parameters of the shock processes \( \rho^z, \rho^\mu, \rho^b, \sigma^z, \sigma^\mu, \) and \( \sigma^b \) and the elasticity of investment with respect to the price of installed capital at the steady state. Denoting with subscript \( ss \) the level of a variable in steady state, this elasticity is defined as \( \chi = -[(x_{ss}/k_{ss})\Gamma''(x_{ss}/k_{ss})/\Gamma'(x_{ss}/k_{ss})]^{-1} \in (0, \infty) \). Note that \( \chi \) depends on the curvature of the investment cost function \( \Gamma(x_t/k_t) \). In the linear case where \( \Gamma(x_t/k_t) = x_t/k_t \), \( \chi \to \infty \) because it is costless to adjust the capital stock.

Remaining parameters were either poorly identified or additional evidence about their magnitude is available. Data on national income accounts suggest that a plausible value for the share of capital in production is 0.36. The subjective discount factor is fixed to 0.99,
meaning that the steady-state gross real interest rate is approximately 1.01.\(^4\) The rate of depreciation is fixed to 0.025. The gross rate of money growth (and inflation) at the steady state is fixed to 1.017. This value corresponds to the average gross rate of money growth during the sample period. Two important structural parameters that are poorly identified are the elasticity of demand (\(\theta\)) and the curvature parameter of the consumption component in the utility function (\(\eta_1\)). Markup estimates reported by Basu and Fernald (1994) for U.S. data indicate that \(\theta\) is approximately 10. Estimates of the curvature of the utility function with respect to consumption range from 0.5 to 5. We assume \(\eta_1 = 2\), but sensitivity analysis indicates that the results do not depend crucially on the magnitudes of \(\theta\) and \(\eta_1\).\(^5\) Finally, fixing the proportion of time worked in steady date (\(n_{ss}\)) amounts to fixing either the mean of the technology shock (\(z\)) or the weight of leisure in the utility function (\(\psi\)). We do not assign particular values to these parameters during the estimation procedure. Instead, we adjust them so that along with the ML estimate of \(\eta_3, n_{ss} = 0.31\). This means that the proportion of time worked in steady state is approximately one third.

Maximum Likelihood (ML) estimates of the parameters and their standard errors are reported in Column 1 of Table 1. The ML estimate of the habit-formation parameter (\(\gamma\)) is 0.98 (0.016). The term in parenthesis is the standard error. This estimate is significantly different from zero, but is not significantly different from one, at standard levels. Its magnitude is larger than, but still consistent with, the values of 0.80 (0.19) and 0.90 (1.83), reported by Fuhrer (2000); 0.63 (0.14), reported by Christiano, Eichenbaum, and Evans (2001); 0.73, reported by Boldrin, Christiano, and Fisher (2001); and 0.938 (1.775), reported by Heaton (1995).

The estimated elasticity of investment with respect to the price of installed capital is 0.47 (0.11). This value is higher than the point estimates of 0.34 and 0.28 reported by Kim (2000) and Christiano, Eichenbaum, and Evans (2001), respectively, but it is considerably lower than the typical value used to calibrate standard Real Business Cycle (RBC) models [see, for example, Baxter and Crucini (1993)].

The estimated probability that an intermediate good producer keeps its price unchanged (or, equivalently, the proportion of firms that do not change prices) is 0.847 (0.034) per quarter. This implies that the average length of price contracts is \(1/(1 - 0.847) = 6.56\)

\(^4\)Given the large degree of habit persistence reported here (see below), the approximation of the real interest rate by the inverse of the subjective discount factor might not be very accurate. However, sensitivity analysis suggests that empirical results are robust to the precise value of \(\beta\). We thank a referee for bringing this point to our attention.

\(^5\)We also performed single and joint Lagrange Multiplier tests of the null hypothesis that the true values of \(\beta, \delta, \eta_1, \alpha,\) and \(\theta\) are the ones assumed during estimation. In all cases, one cannot reject the null hypothesis. However, these results should be interpreted with caution because they might also reflect low test power.
Previous estimates on the average time between price adjustments vary substantially. Galí and Gertler (1999) find that $\phi$ is approximately 0.83. Their estimate implies that prices are fixed between five and six quarters. Cecchetti (1986) reports that the average number of years since the last price adjustment for U.S. magazines ranges from 1.8 to 14. Kashyap (1995) finds that the average time between price changes in 12 mail-order catalog goods is approximately 4.9 quarters. Taylor (1999) surveys empirical studies on price setting and finds that the average duration of price contracts is about 4 quarters in the United States. Bils and Klenow (2001) document substantial heterogeneity in the frequency of price adjustments among the goods surveyed by the U.S. Bureau of Labor Statistics and report a median price duration of only 1.66 quarters. Christiano, Eichenbaum, and Evans (2001) find that the average length of price contracts is about 2 quarters and that of wage contracts is roughly 3.3 quarters.

The parameter estimates for the curvature parameters of leisure and real balances in the utility function are 1.59 (2.88) and 3.9 (0.83), respectively. These results imply an elasticity of labor supply with respect to the real wage (for a given marginal utility of consumption) of $(1 - n)/(\eta_3 n) = (1 - 0.31)/(1.59 \cdot 0.31) = 1.4 \ (2.99)$, and an interest elasticity of money demand of $-1/\eta_2 = -1/3.09 = -0.32 \ (0.09)$. The latter estimate is very close to the one of 0.39 reported by Chari, Kehoe, and McGrattan (2000), but larger than the estimates of 0.10 and 0.11 found by Christiano, Eichenbaum, and Evans (2001) and Dib and Phaneuf (2001), respectively.

Finally, estimates of the autoregressive coefficients of the shock processes indicate that all shocks are very persistent. Very persistent technology and money demand shocks are also reported by Kim (2000), Ireland (2001), and Dib and Phaneuf (2001). The estimate of $\rho^\mu$ is higher than values found when money growth is estimated using a univariate process [for example, as in Chari, Kehoe, and McGrattan (2000)].

## 4.2 Fit and Specification Tests

This section evaluates the goodness of fit of the model and performs specification tests on the model residuals. The goodness of fit is assessed both graphically and quantitatively. First, consider Figure 1 that plots the observed and fitted series of U.S. output, real money balances, and the nominal interest rate. The Figure suggests that the model tracks well the dynamics of the three variables. This impression is confirmed quantitatively by two measures of the goodness of fit, namely the $R^2$ and the Mean Square Error (MSE). The $R^2$ measures the proportion of the total variation in the dependent variable that is explained.
by the model. The MSE is computed as:

\[ \text{MSE} = \left( \frac{\sum_{t=2}^{T} (X_t - X_t^p)^2}{T - 1} \right), \]

where \( T = 166 \) is the number of observations, \( X_t \) is either output, real money balances, or the rate of nominal interest, and \( X_t^p \) is the value predicted by the model. These measures of fit are also compared with those of an unrestricted Vector Autoregression (VAR) of order one. In order to make the comparison meaningful, this VAR contains the same variables used to estimate the model.\(^6\)

Results are reported in the Panels A and B of Table 2. The \( R^2 \)s for output, real money balances, and the nominal interest rate are 0.948, 0.945, and 0.893, respectively. Thus, roughly 95 per cent of the total variation of real money balances and output can be explained by a sticky-price DSGE model with habit formation and costly capital adjustment. The model does not explain as well the behavior of the nominal interest rate, but still can account for more than 89 per cent of the total variation of this series. For all variables, the \( R^2 \)s of the model are lower than the ones of the VAR. However, the model yields smaller MSEs for output and real money balances than the VAR.

Specification tests for serial correlation of the residuals and neglected Autoregressive Conditional Heteroskedasticity (ARCH) are reported in Table 3. Consider first the Durbin-Watson test for first-order autocorrelation (see Panel A). Comparing the test statistic with the 5 per cent critical value of its tabulated distribution indicates that (i) one cannot reject the hypothesis of no autocorrelation for the real money balances and output residuals, but (ii) one can reject it for the nominal interest rate residuals. Similarly, Portmanteau tests for up to two-order autocorrelation (see Panel B) yield statistics that are below (above) their 5 per cent critical value for real money balances and output (nominal interest rate).\(^7\)

The Lagrange Multiplier (LM) tests for neglected ARCH were computed as the product of the number of observations and the uncentered \( R^2 \) of the OLS regression of the squared residual on a constant and two of its lags. Under the null hypothesis of no conditional heteroskedasticity, the statistic is distributed chi-square with as many degrees of freedom as the number of lagged squared residuals included in the regression. Results in Panel C indicate that the hypothesis of no conditional heteroskedasticity cannot be rejected at the 5 per cent level for output and real money balances, but that it can be rejected for the nominal interest rate.

\(^6\)Note that the state-space and VAR models are non-nested, and, consequently, standard Likelihood Ratio, Lagrange Multiplier, and Wald tests would not be appropriate.

\(^7\)Under the null hypothesis of no autocorrelation, the Portmanteau test statistic is distributed chi-square with as many degrees of freedom as autocorrelations are tested for.
The model also generates predictions regarding series whose actual data were not used in the estimation procedure; for example, consumption, investment, the rate of inflation, and the real marginal cost. The real marginal cost is not directly observable, but under certain conditions, it can be proxied by the labor share in national income [see Galí and Gertler (1999) for a detailed discussion]. Figure 2 plots the actual and predicted series of U.S. consumption, investment, inflation, and the real marginal cost. From this Figure, it is clear that the model generates consumption and investment dynamics that are similar to the ones of their detrended U.S. counterparts. However, predicted investment is much smoother than the data.

The model does poorly in explaining the behavior of the real marginal cost and inflation. This result reflects a drawback of inflation models based on forward-looking pricing rules. It is easy to show that, under Calvo-type pricing, the inflation deviation from steady state equals the present discounted value of current and future expected real marginal cost deviations from steady state. This means that inflation inherits the dynamic properties of the real marginal cost and that current inflation is not helpful in predicting future inflation. Because lagged inflation is absent from the inflation equation, forward-looking pricing rules imply that inflation is less persistent than usually found in the data. To address this shortcoming of the model, some authors [for example, Galí and Gertler (1999)] assume the existence of rule-of-thumb firms that fix their prices as a function of past inflation. Another problem with our model is that the real marginal cost is more volatile than the labor share in national income would suggest. One possibility is that the labor share in national income is a poor empirical proxy for the real marginal cost. More likely, the real marginal cost in our model is excessively volatile because it abstracts from supply-side features like variable capital utilization and adjustment costs to labor input.

4.3 Impulse-Response Analysis

This section examines the response of the economy to a shock to the growth rate of the money supply. Hereafter, we refer to this shock as a money supply shock. Figure 4 reports the responses of output, consumption, investment, hours worked, inflation, and the nominal interest rate to a 1 per cent money supply shock predicted by the model. These responses are compared with those generated by a VAR of order 2, which are depicted in Figure 3. In order to be consistent with the model, the VAR contains U.S. observations of the same variables and the shock to the money growth rate is interpreted as the money supply shock.

Following the shock, there is an increase in aggregate demand that causes output and consumption to increase. The consumption response is hump-shaped because under habit
formation, agents smooth both the level and the change of consumption. Comparing Figures 3 and 4, we see that both the VAR and the model predict a hump-shaped responses by output and consumption, though the model humps are much more restrained than those of the VAR. The peak of the output (consumption) response in the model takes place after two (four) quarters, rather than the five (six) quarters in the VAR.

Figure 4 shows that investment and hours worked increase following a (positive) monetary shock. This result is due to the fact that aggregate demand is expected to increase in subsequent periods because prices adjust slowly. Note, however, that the investment (hours worked) response in the model is smaller (larger) than predicted by the VAR. The predicted large effect of the monetary shock on hours worked is most likely due to the fact that employment changes are costless in the model. Following the shock, the increase in output is accommodated initially with an increase in hours worked because the capital stock is predetermined. Without frictions, this initial effect can be large. Moreover, since capital is costly to adjust, this initial effect is persistent.

The model predicts an increase in the rates of nominal interest and inflation after a monetary shock. In contrast, the VAR shows that the initial response by both variables is negative. That is, the model does not generate a liquidity effect, nor can explain the price puzzle. The reason is that the estimated money growth process is highly autocorrelated. Thus, after a positive money supply shock, expected inflation increases by a magnitude that is larger in absolute value than the decrease in the real interest rate. As a result, the net effect of the money supply shock on the nominal interest rate is positive.

The estimated model generates predictions regarding the effects of technology and money demand shocks. It is important to examine these effects in order to understand the overall dynamic response of aggregate variables to the different shocks. Figure 5 reports the response of the variables to a 1 per cent technology shock. Because prices are rigid, the aggregate supply curve is upward sloping. A positive technology shock shifts the aggregate supply curve to the right. Consequently, output increases and prices decrease. The responses of output and consumption are persistent and hump-shaped. Hours worked decrease following a technology shock. The intuition of this result is as follows. After a positive technology shock, the firm is able to satisfy current demand with lower input levels. Consequently, the labor input decreases on impact. Eventually, as demand increases and capital is adjusted, labor demand increases.

In standard Real Business Cycle (RBC) models, an increase in productivity is followed by an increase in hours worked. However, recently, various authors [see Galí (1999) and the references therein] have remarked that, in some settings, hours worked can decrease after a productivity increase. In particular, Galí shows that when the standard RBC model is
extended to include monopolistic competition and sticky prices, positive technological shocks lead to a short-term decline in hours worked. This is because the productivity increase, coupled with price rigidity, incite firms to produce the same output with less labor. Using a structural VAR and data from G-7 countries, Galí finds that the data are consistent with the predictions of the model in that employment declines in response to a positive technology shock. Similar results are also found by Dib and Phaneuf (2001) and Vigfusson (2002) using DSGE models.

Finally, the impulse response functions generated by a 1 percent money demand shock are plotted in Figure 6. Since money supply is unchanged and prices are rigid, this shock produces a downward shift of aggregate demand in current and subsequent periods. Consequently, output, consumption, hours worked, and investment decrease. As a result of habit formation, the response of consumption has an inverted hump shape with a trough around three periods after the shock.

4.4 Second Moments

This section compares statistically the second moments predicted by the model with those computed using U.S. data. We examine the standard deviations, autocorrelations, and cross-correlations of output, real money balances, the rates of inflation and nominal interest, consumption, hours worked, and investment.

In principle, it is possible to derive analytical expressions for the moments predicted by the model. However, this is algebraically cumbersome and it does not deliver the standard deviations of the second moments. As an alternative, we employ stochastic simulation to construct estimates of the predicted moments and their standard deviations. Estimates of the predicted moments are constructed using a simulated series of 10000 observations of the variables with parameter values fixed to the ML estimates of the model. This is conceptually similar to the approach followed by researchers who compute the moments of calibrated DSGE models via simulation.

Estimates of the standard errors of the moments are computed as follows. We take a draw from the (asymptotically) jointly normal distribution of the ML estimates, generate a simulated series of 10000 observations of the variables, and compute the moments of interest. We repeat this procedure 200 times and then compute the standard deviations of the moments across the 200 replications. This approach is akin to a parametric bootstrap, but avoids the need to reestimate the model each time (which is very costly computationally in the case of DSGE models). These standard errors will incorporate the parameter uncertainty that arises from the fact that the moments predicted by the model depend on
structural parameters that are unknown. The goal of computing standard errors for the predicted moments is to construct a well-defined statistical metric to judge the distance between the predicted moments and those observed in the data.

Panel A and B in Table 3 report, respectively, the moments computed using U.S. data and those predicted by the model. First, consider the standard deviations of the variables. In most cases the moments predicted by the model are numerically close to those observed in U.S. data. However, the hypothesis that the true moment is the one computed using the data is rejected in four cases. In particular, the model predicts that the nominal interest rate and investment (inflation and hours worked) are less (more) volatile than observed in the data. Some of these results were partly anticipated on the basis of findings reported above. LM tests for neglected ARCH indicate that the model fails to capture the time-varying volatility of the nominal interest rate. Figure 2 shows that the model predicts smoother investment and more volatile inflation than found in the U.S. series. A possible explanation for the result that hours worked are predicted to be more volatile than in the data is that there are no frictional labor costs in the model. While households/firms face costs in adjusting their capital stock, they are able to change the number of hours worked without any penalty.

Second, consider the first-order autocorrelations. The hypothesis that the true autocorrelation is the one computed using U.S. data is rejected in five cases. In part, these rejections reflect the high precision with which the model autocorrelations are estimated. However, because the model autocorrelations are numerically very close to the ones in U.S. data, the persistence implications of the model are broadly consistent with the data.

Finally, consider the contemporaneous cross-correlations between the variables. In many cases, the cross-correlations involving inflation and hours worked, and remaining variables are statistically different from the ones computed using U.S. data. In particular, inflation is procyclical in the model and acyclical in the data. However, the distance between these cross-correlations is not as remarkable as for the hours-worked series. Hours worked are mildly countercyclical in the model and highly procyclical in the data. The estimated cross correlations are $-0.147$ and $0.897$, respectively.

In general, Real Business Cycle models generate highly procyclical employment series. However, as seen in the previous section, models with sticky prices can predict that employment is countercyclical because employment responds negatively to technology shocks. In our model, as in Galí (1999), hours worked respond positively to monetary shocks. Whether the cross-correlation between hours worked and output is positive or negative depends on the relative magnitude of technology and money supply shocks. In our model, the Maximum Likelihood estimate of the standard deviation of technology shocks is fairly high. Hence, the
negative effect of technology shocks on hours worked dominates the positive effect of money supply shocks. The fact that technology shocks dominate the employment response will be clearer in the next section when we examine the unconditional variance decomposition of hours worked.

### 4.5 Variance Decomposition

In this section, we study the relative importance of monetary shocks for the fluctuations of output, investment, consumption, hours worked, inflation, and the nominal interest rate. To that effect, we compute the fraction of the conditional variance of the forecasts at different horizons that is attributed to each of the model’s shocks. This variance decomposition is plotted in Figure 7. As the horizon increases, the conditional variance of the forecast error of a given variable converges the unconditional variance of that variable. The decompositions of the unconditional variances are reported in Table 5. Recall that a money supply shock is a shock to the growth rate of the money supply while the money demand shock is a shock to the preference parameter of money in the utility function. Several results are apparent from Figure 7 and Table 5. *First*, money supply shocks account for the largest part of the conditional variance in forecasting output in the short run (i.e., less than a year). At higher horizons, most of the conditional variance is due to technology shocks. In the long-run, 27 per cent of the unconditional variance of output is attributed to money supply shocks, 2 per cent to money demand shocks, and 71 per cent to technology shocks. *Second*, money supply shocks and technology shocks are equally important in explaining the conditional variance of consumption in the very short run. However, as the horizon increases the contribution of technology shocks increases and that of money supply shocks decreases. In the long-run, 77.3 per cent of the variance of consumption is explained by technology shocks and only 21.6 per cent by money supply shocks. *Third*, money supply shocks account for the largest part of the conditional variance in forecasting investment in the short-run. As the horizon increases, the contribution of technology shocks increases and the one of money supply shocks decreases but even in the long-run, money supply shocks explain half of the variance of investment. *Fourth*, money supply shocks explain most of the fluctuations of the rate of inflation at all horizons. *Fifth*, consistent with what we found in the previous section, technology shocks explain most of the variation in hours worked at all horizons. *Finally*, money demand shocks play an important role in explaining the fluctuations of the nominal interest rate. At horizons of less than six quarters, money demand shocks explain more

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When the model was calibrated using a standard error for the technology shock that is closer to the one used in RBC models, we obtained a fairly high, positive correlation between employment and output.
than 50 per cent of the conditional variance of the nominal interest rate. In the long-run, money demand shocks explain roughly 45 per cent of the conditional variance of the nominal interest rate.

4.6 The Role of Habit Formation and Capital Adjustment Costs

This section examines the empirical contribution of habit formation and capital adjustment costs to the propagation mechanism of the model. To that end, we solve and estimate via Maximum Likelihood two restricted versions of the model. One version is a sticky-price model with neither habit formation, nor frictional costs in capital adjustment. This model is similar to the one calibrated by Yun (1996) and King and Watson (1996) and is obtained by restricting $\gamma = 0$ and $\Gamma(\cdot) = x_t/k_t$ in the model in Section 2. The other version allows capital adjustment costs but keeps the restriction that $\gamma = 0$.

First, consider the version of the DSGE model with sticky prices and capital adjustment costs but without habit formation. Comparing this model and the one in Section 2, will allow us to assess the role of habit formation in the propagation of money supply shocks. Maximum Likelihood estimates of the structural parameters of this restricted model are reported in Column 2 of Table 1. Note that estimates are not substantially different from the ones reported in Column 1 for the model with both habit formation and capital adjustment costs. The exception is the elasticity of investment with respect to the price of installed capital evaluated at the steady state ($\chi$). Regardless of the starting values in the optimization routine, $\chi$ would converge to zero. Zero is the minimum value of $\chi$ in the parameter space, and implies that the capital stock is infinitely costly to adjust. Thus, investment is zero. Since the estimate of $\chi$ is on the boundary of the parameter space, regularity conditions fail and standard errors cannot be computed as usual. To address this issue, we imposed the restriction $\chi = 0$ at the maximum (or, more precisely, $\chi = 1 \times 10^{-5}$) and then computed standard errors as the square root of the diagonal elements of the inverted Hessian.

Although this model’s implication for investment is counterfactual, the $R^2$s and Mean Square Errors reported in Table 2 indicate that its fit for output, real money balances, and the nominal interest rate are similar to the model that also includes habit formation. However, specification tests reported in Table 3 show that output residuals are serially correlated. Thus, it would appear that this restricted model does not capture the output dynamics as well as the model in Section 2.

Panel C in Table 4 reports the standard deviations, autocorrelations, and cross-correlations of the variables with their standard errors in parenthesis. Results are similar to the ones

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9This approach was suggested to us by Robert King.
reported in Panel B for the model with habit formation but with three caveats.  *First,* the standard errors of the moments predicted by this model are larger than the ones of the model with habit formation. This is due to the fact that parameter estimates have larger standard errors. Hence, *t*-tests of the hypothesis that the true moment is the one computed using U.S. data tend to rejected less often than in Panel B. *Second,* since investment is zero, the standard deviation of investment and all cross correlations that involve this variable are zero as well. *Finally,* because investment is zero, consumption and output are perfectly correlated.

Figure 8 reports the responses predicted by the model to a shock to the growth rate of the money supply. Output, consumption, and hours worked jump immediately after the shock and return fairly quickly to their steady-state levels. Without habit formation, the dynamics are monotone and lack the hump-shaped pattern predicted by the VAR and the model in Section 2. The nominal interest and inflation rates respond to money supply shock in a qualitatively similar manner as in the model with habit formation. Comparing these results with the ones in the previous sections, indicates that habit formation magnifies output persistence in response to a monetary shock. The reason is that habit-forming agents allocate resources to obtain a smoother and more persistent consumption profile than agents with time-separable preferences. This implies a more persistent path of labor supply and output following a shock.

Our results are broadly consistent with Fuhrer (2002). Fuhrer examines the effect of habit formation in a monetary policy model. His model is a structural Vector Autoregression with restrictions that arise from the consumption’s Euler equation, a Taylor-type monetary policy rule, and a price contracting model similar to that in Fuhrer and Moore (1995). Fuhrer shows that habit formation improves the output dynamics without worsening the other dynamic interactions of the model. However, our results regarding the inflation dynamics are different from his. Comparing the inflation responses in Figures 4 and 8, and the predicted moments in Panels B and C of Table 4, indicate that habit formation has little effect on the inflation dynamics of our DSGE model. The reason for this discrepancy is the assumed pricing behavior of firms. Calvo-type pricing is forward looking and implies a lower inflation persistence than in the data. On the other hand, Fuhrer and Moore’s formulation is equivalent to a two-sided inflation specification where inflation depends on both its leads and lags. This formulation appears to capture better the observed inflation persistence.

Now consider a DSGE model with sticky prices alone. This model is obtained by imposing the restrictions $\gamma = 0$ and $\Gamma(\cdot) = x_t/k_t$ on the model in Section 2. These restrictions mean that there is neither habit formation, nor adjustment costs to the capital stock. Because it is costless to adjust the capital stock, the elasticity of investment with respect to
the price of installed capital is infinity.

Maximum Likelihood estimates of the parameters are reported in the Column 3 of Table 1. The estimate of the probability that an intermediate good producer keeps its price unchanged in a given quarter is $\hat{\varphi} = 0.346 (0.457)$. This estimate is very imprecise and one cannot reject the hypothesis that the true value is either zero or one. Estimates of the preference parameters $\eta_2$ and $\eta_3$ are quantitatively very large, imprecisely estimated, and in the latter case not statistically different from zero. Finally, estimates of $\rho_z$, $\rho_\mu$, and $\rho_b$ indicate that structural shocks are persistent. Because the parameters are imprecisely estimated, the results below regarding predicted second moments and impulse responses should be interpreted with caution.

Tests for serial correlation and neglected ARCH (see Column 3 in Table 3) suggest that this version of the model is misspecified. Durbin-Watson and Portmanteau tests for autocorrelation of the residuals yield statistics above the 5 per cent critical value for all variables. Consequently, the hypothesis of no serial correlation of the residuals is rejected for all variables. Lagrange Multiplier tests for neglected ARCH indicate that the hypothesis of no conditional heteroskedasticity can be rejected for the nominal interest rate and real money balances at the 5 and 10 per cent levels, respectively. In summary, these test results indicate that the joint dynamics of output, real balances, and interest rates are very poorly captured by an estimated DSGE model with sticky prices alone.

Panel D of Table 4 reports second moments predicted by the model and their standard errors. Because the parameter estimates are very imprecise, the standard errors of the moments predicted by this model are also large. Thus, in many cases, the null hypothesis that the true moment is the one computed using U.S. data cannot be rejected despite large quantitative differences. In general, this model predicts more volatile output, real balances, inflation, and investment, and much less volatile hours worked than in the data. As in the previous models, inflation is less persistent than observed in U.S. data. Real balances are essentially uncorrelated the real variables because the estimated price rigidity is small.

Figure 9 plots the impulse responses predicted by this model. Monetary shocks have a small effect on output, consumption, investment, and hours worked. These variables (and inflation) adjust rapidly in response to monetary shocks and return close to their steady state values after only one period. The reason is that, without capital adjustment costs, firms can pull forward in time their response to a monetary shock.\footnote{In some unreported counterfactual experiments, we set the parameter that determines price rigidity ($\varphi$) to different values from its Maximum Likelihood estimate and obtained similar impulse responses to the ones reported in Figure 9. Only the magnitude of the effects varies depending on the degree of price stickiness.}

In summary, the estimation of a DSGE model with sticky prices alone using U.S. data on
output, real balances, and the nominal interest rate, yields imprecise parameter estimates, captures poorly the dynamics of the dependent variables, and is misspecified in the sense that residuals are serially correlated.

Our results are also consistent with Jermann’s (1998) finding that habit formation alone is insufficient to explain the equity premium puzzle and salient business cycles facts in a general equilibrium framework. The reason is that, in general equilibrium, households can modify the intertemporal allocation of resources. Hence, the only difference between RBC models with and without habit formation is that consumption is smoother in the former than in the latter. With no adjustment costs, consumers can reallocate resources freely to decrease the volatility of the marginal rate of substitution and obtain a smoother consumption profile than that predicted by the Permanent Income Hypothesis. Thus, capital adjustment costs in Jermann (1998) and factor allocation frictions across sectors in Boldrin, Christiano, and Fisher (2001) limit the scope of resource allocation and, along with habit formation, help to explain the equity premium puzzle in a general equilibrium setup. In this paper, price rigidities are necessary for money to be non-neutral, and the interaction of some factor-market inflexibility (capital adjustment costs) and habit formation is necessary to explain the persistent output response to monetary shocks.

5 Conclusion

This paper constructs a DSGE model with sticky prices, habit formation, and costly capital adjustment that accounts for the persistent and hump-shaped response of output to monetary shocks. The model is estimated by the method of Maximum Likelihood using U.S. data on output, real money balances, and the nominal interest rate. Econometric results indicate that U.S. prices are fixed on average for six and a half quarters. The peak of the output response takes place after two quarters, that is less than the five quarters found in a benchmark VAR model. Also, the size of the hump is smaller in the DSGE model than in the VAR. Variance decomposition indicates that money growth explains more than 50 per cent of the (conditional) output variability at horizons of less than a year. In the long run, money growth explains only 27.1 per cent of the unconditional output variability while 71.4 per cent is explained by technology shocks. The empirical analysis of two restricted versions of the model suggests that habit formation interacts with costly capital adjustment to increase the internal propagation mechanism of the model.

The DSGE fits U.S. output and real money balances better than an unrestricted VAR and does slightly worse for the nominal interest rate. The model also tracks well the behavior of consumption and investment. For hours worked, the estimated model produces impulse
responses to monetary and technological shocks that are consistent with recent theoretical developments in business cycle models that incorporate price rigidities and monopolistic competition. It is also consistent with impulse responses from structural VARs that find that employment decreases after a positive technology shock but increases after a positive monetary shock. However, when we consider the overall effects of both shocks on hours worked, we find that the technological shocks outweigh the effect of monetary shocks and employment is countercyclical. We conclude that the estimated model may either overestimate the role of technological shocks relatively to monetary shocks and/or employment decisions (either from the demand or from the supply side) are not well specified. The model also does poorly in explaining the U.S. inflation rate. This is partly the result of assuming a forward-looking pricing rule. Including additional features would allow DSGE models to capture other features of the data like inflation persistence and, perhaps, the liquidity effect. In future work, we intent to extend this model to allow for a backward looking component in the price rule.
Table 1. Maximum Likelihood Estimates

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameter</th>
<th>Habit/Adjustment Costs</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<tr>
<td>Habit parameter</td>
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<td></td>
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<td></td>
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<td>Probability of no price change</td>
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<td></td>
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<tr>
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<td></td>
<td></td>
<td>(0.826)</td>
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<tr>
<td>Preference parameter</td>
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<td>Coefficient technology shock</td>
<td>$\rho_z$</td>
<td>0.867*</td>
</tr>
<tr>
<td></td>
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<td>(0.051)</td>
</tr>
<tr>
<td>Coefficient money supply shock</td>
<td>$\rho_\mu$</td>
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<td>(0.033)</td>
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<td>Coefficient money demand shock</td>
<td>$\rho_b$</td>
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</tr>
<tr>
<td></td>
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<td>(0.019)</td>
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<tr>
<td>S.D. of technology innovation</td>
<td>$\sigma_{\epsilon_z}$</td>
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<td>(0.023)</td>
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<td>$\sigma_{\epsilon_\mu}$</td>
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<tr>
<td>S.D. of money demand innovation</td>
<td>$\sigma_{\epsilon_b}$</td>
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<tr>
<td>Value of log-likelihood function</td>
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<td>2408.30</td>
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Notes: S.D. is standard deviation. The figures in parenthesis are standard errors. The superscript * denotes the rejection of the null hypothesis that the parameter is zero at the 5 per cent significance level. The restrictions imposed on the parameters were $\gamma, \varphi \in (0, 1)$, $\rho_z, \rho_\mu, \rho_b \in (-1, 1)$, and $\eta_2, \eta_3, \chi, \sigma_{\epsilon_z}, \sigma_{\epsilon_\mu}, \sigma_{\epsilon_b} \in (0, \infty)$. For the purpose of computing standard errors for the second model, we fixed $\chi$ to $1 \times 10^{-5}$. 
Table 2. Measures of Fit

<table>
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<tr>
<th>Variable</th>
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<th>Unrestricted</th>
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<td>0.945</td>
<td>0.945</td>
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<tr>
<td>$R$</td>
<td>0.893</td>
<td>0.892</td>
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Panel A. $R$ Squared

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<th>$m$</th>
<th>$R$</th>
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<td>7.544</td>
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<td>$m$</td>
<td>4.599</td>
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<td>$R$</td>
<td>0.416</td>
<td>0.421</td>
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B. Mean Square Error ($\times 10^{-5}$)
Table 3. Specification Tests

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<tbody>
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<td></td>
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<td>No/Yes</td>
<td>No/No</td>
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</tr>
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<tr>
<td>$y$</td>
<td>2.15</td>
<td>1.47*</td>
<td>1.42*</td>
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<td>$m$</td>
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<td>2.02</td>
<td>0.62*</td>
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<tr>
<td>$R$</td>
<td>1.50*</td>
<td>1.44*</td>
<td>1.57*</td>
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<tr>
<td>B. Portmanteau Test</td>
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<td></td>
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<tr>
<td>$y$</td>
<td>1.12</td>
<td>19.16*</td>
<td>20.80*</td>
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<tr>
<td>$m$</td>
<td>1.86</td>
<td>2.69</td>
<td>108.93*</td>
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<tr>
<td>$R$</td>
<td>14.27*</td>
<td>14.39*</td>
<td>14.04*</td>
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<tr>
<td>C. LM Test for Neglected ARCH</td>
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<td></td>
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<td>$y$</td>
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<td>$m$</td>
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<td>5.01</td>
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<tr>
<td>$R$</td>
<td>26.77*</td>
<td>25.69*</td>
<td>25.54*</td>
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</tbody>
</table>

Notes: The superscript * denotes the rejection of the null hypothesis of no autocorrelation (conditional homoskedasticity in the case of the test for neglected ARCH) at the 5 per cent significance level.
Table 4. Standard Deviations, Autocorrelations, and Cross Correlations

<table>
<thead>
<tr>
<th>Moment</th>
<th>(y)</th>
<th>(m)</th>
<th>(R)</th>
<th>(\pi)</th>
<th>(c)</th>
<th>(n)</th>
<th>(x)</th>
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</tr>
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<td>3.693</td>
<td>5.659</td>
<td>0.635</td>
<td>0.620</td>
<td>3.336</td>
<td>1.364</td>
<td>11.535</td>
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<tr>
<td>Autocorr.</td>
<td>0.962</td>
<td>0.964</td>
<td>0.948</td>
<td>0.890</td>
<td>0.965</td>
<td>0.970</td>
<td>0.914</td>
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<tr>
<td>Cross Corr.</td>
<td>1</td>
<td>0.615</td>
<td>−0.097</td>
<td>0.0720</td>
<td>0.932</td>
<td>0.897</td>
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<tr>
<td></td>
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<td>1</td>
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<td>−0.063</td>
<td>0.036</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>B. Habit Formation/Adjustment Costs (Yes/Yes)</strong></td>
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<td>S.D.</td>
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<td>5.413</td>
<td>0.481*</td>
<td>1.928*</td>
<td>4.494</td>
<td>9.394*</td>
<td>5.464*</td>
</tr>
<tr>
<td>(1.024)</td>
<td>(0.997)</td>
<td>(0.058)</td>
<td>(0.212)</td>
<td>(1.138)</td>
<td>(3.654)</td>
<td>(1.188)</td>
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<tr>
<td>Autocorr.</td>
<td>0.981</td>
<td>0.982*</td>
<td>0.911*</td>
<td>0.821*</td>
<td>0.990*</td>
<td>0.785*</td>
<td>0.911</td>
</tr>
<tr>
<td>(0.013)</td>
<td>(0.004)</td>
<td>(0.018)</td>
<td>(0.028)</td>
<td>(0.005)</td>
<td>(0.036)</td>
<td>(0.036)</td>
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</tr>
<tr>
<td>Cross Corr.</td>
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<td>−0.030</td>
<td>0.457*</td>
<td>0.990*</td>
<td>−0.147*</td>
<td>0.921*</td>
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<tr>
<td>(0.273)</td>
<td>(0.163)</td>
<td>(0.129)</td>
<td>(0.009)</td>
<td>(0.258)</td>
<td>(0.015)</td>
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<tr>
<td></td>
<td>1</td>
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<td>−0.614*</td>
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<td>(0.279)</td>
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<td>(0.094)</td>
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<td>(0.269)</td>
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Table 4. Standard Deviations, Autocorrelations, and Cross Correlations (Cont.)

<table>
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<tr>
<th>Moment</th>
<th>$y$</th>
<th>$m$</th>
<th>$R$</th>
<th>$\pi$</th>
<th>$c$</th>
<th>$n$</th>
<th>$x$</th>
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<tbody>
<tr>
<td>S.D.</td>
<td>3.297</td>
<td>6.733</td>
<td>0.476</td>
<td>1.472*</td>
<td>4.285</td>
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<td>0.000</td>
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<tr>
<td>(3.668)</td>
<td>(4.589)</td>
<td>(0.165)</td>
<td>(0.281)</td>
<td>(4.768)</td>
<td>(5.867)</td>
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<td>Autocorr.</td>
<td>0.947</td>
<td>0.988*</td>
<td>0.927</td>
<td>0.761</td>
<td>0.947</td>
<td>0.836*</td>
<td>n.a.</td>
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<td>(0.005)</td>
<td>(0.028)</td>
<td>(0.076)</td>
<td>(0.040)</td>
<td>(0.057)</td>
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<tr>
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<td>0.592</td>
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<td>0.199</td>
<td>1.000</td>
<td>–0.578*</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>(0.396)</td>
<td>(0.211)</td>
<td>(0.274)</td>
<td>–</td>
<td>(0.566)</td>
<td>–</td>
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<tr>
<td></td>
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<tr>
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<td>(0.359)</td>
<td>(0.396)</td>
<td>(0.372)</td>
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<td>(0.211)</td>
<td>(0.102)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.199</td>
<td>0.662</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td></td>
<td>(0.274)</td>
<td>(0.151)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>–0.577*</td>
<td>0.000</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>(0.566)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| S.D.   | 6.105| 7.782| 0.622| 1.182| 5.090| 0.382| 10.177|
| (7.438)| (5.098)| (0.376)| (0.327)| (6.513)| (7.067)| (19.625)|
| Autocorr.| 0.989| 0.992*| 0.954| 0.312*| 0.995*| 0.965| 0.976|
| (0.116)| (0.005)| (0.020)| (0.134)| (0.003)| (0.381)| (0.173)|
| Cross Corr.| 1   | 0.053*| 0.018| 0.025| 0.985| –0.900*| 0.957*|
|            | (0.161)| (0.088)| (0.164)| (0.093)| (0.431)| (0.029)|
|            | 1   | –0.081| –0.131*| 0.054*| –0.072*| 0.047*|
|            | (0.149)| (0.085)| (0.169)| (0.142)| (0.146)| –   |
|            | 1   | 0.575| –0.018| 0.083*| 0.076|
|            | (0.094)| (0.071)| (0.071)| (0.101)| –   | –   |
|            | 1   | 0.019*| 0.143| 0.033|
|            | (0.042)| (0.313)| (0.221)| –   | –   | –   |
|            | 1   | –0.953*| 0.892|
|            | (0.324)| (0.158)| –   | –   | –   | –   |
|            | 1   | –0.739*|
|            | (0.472)| –   | –   | –   | –   | –   |
|            | 1   | –   | –   | –   | –   | –   |

Notes: The superscript * denotes the rejection of the null hypothesis that the true moment equals the one observed in U.S. data.
Table 5. Unconditional Variance Decomposition
Model with Habit Formation and Capital Adjustment Costs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Technology Shocks</th>
<th>Money Supply Shocks</th>
<th>Money Demand Shocks</th>
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</thead>
<tbody>
<tr>
<td>Output</td>
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<td>0.271</td>
<td>0.015</td>
</tr>
<tr>
<td>Investment</td>
<td>0.469</td>
<td>0.493</td>
<td>0.038</td>
</tr>
<tr>
<td>Consumption</td>
<td>0.773</td>
<td>0.216</td>
<td>0.011</td>
</tr>
<tr>
<td>Hours worked</td>
<td>0.872</td>
<td>0.120</td>
<td>0.008</td>
</tr>
<tr>
<td>Inflation rate</td>
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<td>0.756</td>
<td>0.023</td>
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<tr>
<td>Nominal interest rate</td>
<td>0.163</td>
<td>0.389</td>
<td>0.448</td>
</tr>
</tbody>
</table>

Notes: The money supply shock is a shock to the growth rate of the money supply. The money demand shock is a shock to the preference parameter of money in the utility function.
References


Figure 1: Actual (continuous lines) and predicted (dotted lines) values of variables in measurement equation
Figure 2: Actual (continuous lines) and predicted (dotted lines) values of other model variables
Figure 3: Responses to a 1 per cent money supply shock. Model: VAR using U.S. data
Figure 4: Responses to a 1 per cent money supply shock. Model: Habit formation and adjustment costs
Figure 5: Responses to a 1 per cent technology shock. Model: Habit formation and adjustment costs
Figure 6: Responses to a 1 per cent money demand shock. Model: Habit formation and adjustment costs
Figure 7: Variance Decomposition.
Figure 8: Responses to a 1 per cent money supply shock. Model: No habit formation but adjustment costs

[41]
Figure 9: Responses to a 1 per cent money supply shock. Model: No habit formation, no adjustment costs