Macroeconomic Dynamics, **3**, 1999, 368–383. Printed in the United States of America.

REAL PROPAGATION OF MONETARY SHOCKS: DYNAMIC COMPLEMENTARITIES AND CAPITAL UTILIZATION

David Cook
Hong Kong University of Science & Technology

This paper studies the dynamic propagation of a liquidity shock through two real propagation channels: dynamic complementarities and time-varying capital utilization. The findings for an economy with intertemporal externalities are: (1) An otherwise transient liquidity shock will have real effects on output for several years; (2) time-varying capital utilization strongly augments this propagation; (3) the real effects of monetary shocks last longer when external productivity depreciates faster; and (4) nominal prices respond more sluggishly to a change in the money supply when there is a strong real propagation channel.

Keywords: Liquidity Effect, Intertemporal Externalities, Propagation, Capital Utilization

1. INTRODUCTION

This paper studies two business-cycle propagation mechanisms, intertemporal externalities and time-varying capital utilization, which transmit the real effects of monetary shocks across time. Rational-expectations monetary models offer a particularly interesting context for the study of persistent business cycles. The real effects that occur as a consequence of unexpected monetary shocks are typically due to a short-run rigidity-like demand misperception [Lucas (1972)], sticky prices [King (1991)], nominal wage contracts [Cho and Cooley (1995)] or limited participation in financial markets [Lucas (1990); Fuerst (1992)]. The rigidity prevents rational agents from reacting fully to innovations in money supply. When the rigidity ceases to constrain, the real effects disappear. By contrast, considerable empirical evidence exists that demonstrates the persistence of business cycles in general [Cogley and Nason (1995)] and the persistence of the real effects of money shocks in particular [Christiano et al. (1996); Strongin (1995)]. One means of introducing persistence into monetary models is to assume that nominal rigidities disappear only slowly [Christiano and Eichenbaum (1992) or Rotemberg (1996)].

I wish to thank Woon Gyu Choi, Steven Durlauf, Rodolfo Manuelli, Lee Ohanian, John Shea, Yi Wen, two anonymous referees, and the associate editor of this journal for valuable discussions and comments. All errors are mine. Address correspondence to: Department of Economics, Hong Kong University of Science & Technology, Clear Water Bay, Kowloon, Hong Kong; e-mail: davcook@usthk.ust.hk.

 1365-1005/99 $9.50

Another approach is to assume the existence of a real propagation channel. An empirical literature outlines the effects of monetary shocks on the U.S. economy using vector autoregressions [see Bernanke and Gertler (1995), among others]. A characteristic response to an expansionary monetary shock is a sharp liquidity effect (a drop in short-term interest rates) and a persistent output expansion. Though the liquidity effect is not entirely transient, the output effects of monetary shocks outlast the interest-rate effects. The peak output effects often are found to occur many periods after the peak interest-rate effects. This timing indicates the importance of the propagation that occurs after the liquidity effect has diminished. Qualitatively, capital accumulation could offer a real propagation channel; a liquidity effect might enhance current investment in physical capital and, thus, production possibilities in subsequent periods. In practice, the quantitative effects of this transmission mechanism are insubstantial. The capital stock does not vary much over the cycle simply because the stock of capital is much larger than any changes in investment due to short-term shocks.

Intertemporal learning spillovers are another channel through which current activity can qualitatively affect future productivity. Researchers long have suggested that current production activity creates, as a byproduct, experience that is useful in future production [see Arrow (1985) or Rapping (1965)]. Much of this experience could be nonrival, increasing the productivity even of firms not directly involved in its creation. The quantitative properties of intertemporal externalities have been studied by Cooper and Haltiwanger (1996), Cooper and Johri (1997), and Durlauf (1993). The purpose of this paper is to examine the quantitative effects of this type of propagation in a monetary model.

The model presented here studies the persistence of monetary shocks in a limited participation model [see Fuerst (1992) or Christiano (1991)]. In the limited participation framework, a financial intermediary accepts household bank deposits and makes short-term credit available to firms. A rigidity prevents savers from quickly adjusting bank deposits after a change in the money stock. An unexpected shock to the money supply can have strong effects on interest rates and, through credit markets, on real output. The financial rigidities are temporary, though. In lieu of an additional propagation mechanism, the real effects of unexpected monetary shocks are short-lived. I supplement this framework with two propagation mechanism. First, I assume that firms can vary capital utilization rates through time. Time-varying capital utilization augments the effects of movements in interest rates and productivity on equilibrium output. Extensive evidence supports the notion that capital services vary over the business cycle [see Burnside et al. (1995) or Shapiro (1996)]. Second, dynamic productivity complementarities act as an intertemporal propagation channel. A firm that produces output in one period generates productivity available to other firms in subsequent periods. An increase in aggregate output in one period leads to higher aggregate productivity in subsequent periods. The combined propagation channels cause an otherwise transitory monetary shock to have persistent effects on output and employment. The real shocks far outlive the initial liquidity effect.

2. MODEL

The model economy is inhabited by four agents: a representative household, a representative firm, a bank, and the monetary authority. The monetary authority sets the money growth rate exogenously by injecting reserves into the banking system. The remaining agents act as price takers in competitive markets.

2.1. The Household's Problem

The infinitely lived representative household maximizes expected utility from consumption, C_t, and leisure, L_t, as in Hansen (1985) and Rogerson (1988):

$$E_0 \sum_{t=0}^{\infty} \beta^t (\ln C_t + B \cdot L_t). \qquad \textbf{(1)}$$

The household's time endowment, T, can be used for leisure or labor, H_t:

$$T = L_t + H_t. \qquad \textbf{(2)}$$

The household begins every period with a quantity of currency held as bank deposits, N_t, and a quantity of remaining cash on hand, $M_t - N_t$. The household faces a cash-in-advance constraint on consumption purchases,

$$M_t - N_t \geq P_t C_t, \qquad \textbf{(3)}$$

where P_t is the nominal price of goods. At the end of period t, the household receives interest payments on bank deposits, R_t; wage payments for its labor effort, $W_t H_t$; and lump-sum dividend payments from the representative firms and financial intermediaries, D_t. The household selects next-period money demand M_{t+1} and deposits N_{t+1}:

$$M_{t+1} = R_t N_t + W_t H_t + (M_t - N_t - P_t C_t) + D_t. \qquad \textbf{(4)}$$

2.2. The Bank and the Monetary Authority

The representative financial intermediary or bank holds deposits. The monetary authority creates new currency by injecting reserves into the banking system. The available credit for lending, LOAN_t is

$$\text{LOAN}_t = N_t + \mu_t M_t, \qquad \textbf{(5)}$$

where μ_t is the money growth rate at time t. The monetary authority sets the money growth rate exogenously. I assume that the growth rate follows an AR(1) process:

$$\mu_t = (1 - \rho)\mu + \rho\mu_{t-1} + \varepsilon_t \qquad \textbf{(6)}$$

It is unlikely that any monetary authority acts purely exogenously. The point of this paper is to examine the dynamics of the response to an exogenous shock and it is customary to assume an AR(1) process for exogenous monetary policy [see Cooley and Hansen (1995)]. Christiano et al. (1997) argue that an AR(1) process plausibly describes the dynamics of exogenous policy shocks in the United States.

2.3. The Firm's Problem

The representative firm maximizes the discounted sum of real profits, D_t^Y:

$$E_0 \sum_{t=0}^{\infty} \beta^t \omega_t \frac{D_t^Y}{P_t}. \tag{7}$$

The stochastic discount factor ω_t is the household's current shadow value of a real dividend payment. The firm's objective is to maximize the present discounted value of the dividend payments or, equivalently, its own equity price. The firm earns revenues by selling goods and must purchase investment goods and hire labor. The firm faces a cash-in-advance constraint on its wage bill and must borrow currency from the bank to pay wages. The profits at time t are

$$D_t^Y = P_t Y_t - R_t W_t H_t - P_t I_t, \tag{8}$$

where Y_t is output at time t and I_t is investment. The production function is

$$Y_t = Z_t^{\gamma} (U_t K_t)^{\theta} (X_t H_t)^{1-\theta}, \tag{9}$$

where Z_t is a publicly available technology, U_t is the rate of capital utilization, and K_t is the capital stock. The term X_t is deterministic technology growing at net rate η. The capital stock is accumulated through investment:

$$K_{t+1} = (1 - \delta_t) K_t + I_t. \tag{10}$$

The depreciation term is time varying. Depreciation occurs through utilization [see Greenwood et al. (1988)] and through capital adjustment [see Baxter and Crucini (1993)]:

$$\delta_t = \delta_1 U_t^{\phi} + \delta_2 \left(\frac{I_t}{K_t} - \Lambda \right)^2. \tag{11}$$

The externality is a stationary period-by-period external spillover:

$$Z_t = Y_{t-1} \cdot e^{-\eta t}. \tag{12}$$

2.4. Equilibrium

Define Ψ_t as the history of all shocks up to time t. Define the allocation functions $C_t(\Psi_t)$, $I_t(\Psi_t)$, $Y_t(\Psi_t)$, $H_t(\Psi_t)$, $U_t(\Psi_t)$, $K_{t+1}(\Psi_t)$, $M_{t+1}(\Psi_t)$, $N_{t+1}(\Psi_t)$, $Z_{t+1}(\Psi_t)$, and the price function $P_t(\Psi_t)$, $W_t(\Psi_t)$, $R_t(\Psi_t)$. A competitive equilibrium is a collection of allocation and price functions that solve the problem of the representative household, bank, and firm, at which all markets clear, and satisfies (12). These market-clearing conditions are that the goods market clears,

$$C_t + I_t = Y_t; \tag{13}$$

the loan market clears,

$$\mathrm{LOAN}_t = W_t H_t; \tag{14}$$

the money market clears,

$$M_{t+1} = (1 + \mu_t) M_t; \tag{15}$$

and labor supply equals labor demand.

There is no guarantee that the equilibrium is stable and unique at all parameter values. Given a number of conditions (sufficiently low elasticity of depreciation with respect to capital utilization, sufficiently low capital adjustment costs, sufficiently high labor elasticity of output, sufficiently high elasticity of output with respect to the externality), an indeterminacy can arise. In all of the parameterizations studied in this paper, the equilibrium is locally unique. See Wen (1997a, b) for discussion of the role of capital utilization and capital adjustment costs in multiple equilibrium models.

3. CALIBRATION

3.1. Parameter Values

I examine a numerical approximation of the model. The approximation is derived by log linearizing the first-order conditions as in King et al. (1987). The linear equations are solved using algorithms in King and Watson (1995) and Sims (1997). Many of the parameters of the equation are common to business-cycle models. Burnside and Eichenbaum (1996) study a real model with variable capital utilization. From that paper, I draw the parameters $\beta = 1.03^{-0.25}$, $\theta = 0.326$, $\eta = 0.0034$. In that paper, the utilization elasticity of depreciation, $\phi = 1.56$, is selected to be consistent with a steady-state depreciation rate, $\bar{\delta} = 0.0195$. The capital adjustment parameter, δ_2, is selected so that elasticity of the investment/capital ratio with respect to Tobin's q is 15 as in Baxter and Crucini (1993). As in Baxter and Crucini (1993), the capital adjustment function is parameterized so that capital adjustment contributes nothing to depreciation along the balanced growth path; the parameter Λ is set at $\eta + \bar{\delta} = 0.0229$. I parameterize the exogenous money growth process by estimating an AR(1) process of the growth rate of nonborrowed reserves from 1960 : 1 to 1995 : 4: $\rho = 0.21$ and $\mu = 0.012$.

The remaining parameter to be selected, the elasticity of output with respect to the externality, is likely to be most controversial. Cooper and Johri (1997) offer evidence that the intertemporal externality is quite large ($\gamma = 0.37$). Cooper and Johri (1997) derive that figure by estimating a manufacturing production function using instrumental variables. Here, I confirm these results using a longer data set with more disaggregated data. I examine the Cobb-Douglas gross output production function:

$$Y_{j,t} = (U_{j,t}K_{j,t})^{\varphi_1}(H_{j,t})^{\varphi_2}(M_{j,t})^{\varphi_3}Y_{t-1}^{\varphi_4}X_{j,t}, \qquad \textbf{(16)}$$

where $Y_{j,t}$ is gross output in industry j at period t; $U_{j,t}K_{j,t}$ is industry capital services; $H_{j,t}$ is total employment hours; $M_{j,t}$ is non-energy materials used; Y_{t-1} is the U.S. GDP in the previous year; and $X_{j,t}$ is a stochastic technology term. The NBER Productivity Database [see Bartelsman and Gray (1994)] has annual data on input usage and output for 447 four-digit SIC code manufacturing industries spanning 1958 to 1991. I assume as in Burnside et al. (1995) that energy use, $E_{j,t}$, is proportional to capital services. I examine the four-digit industry j, in log first-differenced form. The gross output production function with Δ representing the lag first-difference operator and small letters representing logarithms:

$$\Delta y_{j,t} = \varphi_j + \varphi_1\Delta e_{j,t} + \varphi_2\Delta h_{j,t} + \varphi_3\Delta m_{j,t} + \varphi_4\Delta y_{t-1} + \omega_{j,t}, \qquad \textbf{(17)}$$

where $\varphi_j + \omega_{j,t}$ represents the growth rate of the stochastic technology shock $\Delta x_{j,t}$. The right-hand-side variables are likely endogenous to the error term which represents a stochastic productivity shock. I estimate (17) using instrumental variables.

Following Burnside et al. (1995), I create a list of monetary policy instruments using identified vector autoregressions. I estimate an ordered VAR with four lags of the vector ($y_{t:q}$, $p_{t:q}$, $pcom_{t:q}$, $FF_{t:q}$, $nbr_{t:q}$, $tr_{t:q}$); the subscript $t:q$ denotes year t, quarter q. These variables are $y_{t:q}$, gross domestic product; $p_{t:q}$, the GDP deflator; $pcom_{t:q}$, a commodities price index; $FF_{t:q}$, the Federal Funds rate; $nbr_{t:q}$, nonborrowed reserve holdings; and $tr_{t:q}$, total reserve holdings. The policy shocks to the Federal Funds rate, $\upsilon_{t:q}^{FF}$, are then identified as having no contemporaneous effect on ($y_{t:q}$, $p_{t:q}$, $pcom_{t:q}$). I repeat the process for the ordered vector ($y_{t:q}$, $p_{t:q}$, $pcom_{t:q}$, $nbr_{t:q}$, $FF_{t:q}$, $tr_{t:q}$) identifying nonborrowed reserve policy shocks, $\upsilon_{t:q}^{\text{NBR}}$, as having no contemporaneous effect on ($y_{t:q}$, $p_{t:q}$, $pcom_{t:q}$). Because the VAR's are estimated quarterly, each specification produces four monetary shocks per year. The instrument vector, $money_t = (\upsilon_{t:q}^{FF}, \upsilon_{t:q}^{\text{NBR}})$, has eight elements. The lagged money shocks, $money_{t-1}$, are used as instruments for each industry's inputs at time t; the elements of $money_{t-2}$, are used as instruments for lagged GDP growth, Δy_{t-1}. These instruments are used to estimate the industry production functions under the restriction that all industries have the same parameters with the exception of the constant term which can vary across industries.

The parameter estimates are in Table 1. The coefficient on the dynamic complementarity is consistent with Cooper and Johri (1997). The parameter on lagged GDP growth is 0.41. The coefficients on labor and capital services are consistent with standard notions of the relative labor and capital intensities in value added. In (16), I assumed a unit elasticity of substitution between materials and value added; Burnside et al. (1995) or Cooper and Johri (1997) assume a zero elasticity of substitution. I estimate a representative production function imposing their value:

$$\Delta y_{j,t} = \varphi_j + \varphi_1 \Delta e_{j,t} + \varphi_2 \Delta h_{j,t} + \varphi_4 \Delta y_{t-1} + \omega_{j,t}. \tag{18}$$

The parameter values in (18) are in Table 1, column B. The change in specification of materials elasticity does not have any substantive effect on the size or significance of the external term. Finally, I estimate this production function using the growth rate of the capital stock rather than the growth rate of energy as a proxy for capital services. The coefficient on capital is essentially 0 (see Table 1, column C). This illustrates the importance of modeling variable capital utilization for understanding the dynamics of a technology shock. The estimates of the parameter γ in this paper are slightly different than that of Cooper and Johri (1997), but for the sake of comparison, I adopt their number.

3.2. Impulse Responses

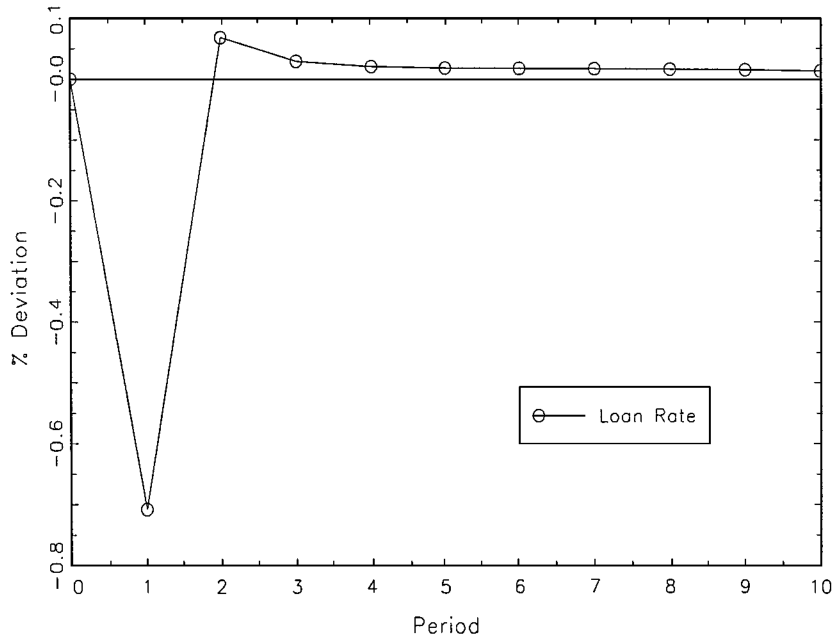
In Figure 1, I demonstrate the dynamic response of the economy (termed the benchmark model) evaluated near the steady state (at the parameter values discussed in the preceding paragraphs) to a 1% shock to the money growth rate. In Figure 1A, I show the response of the nominal interest rate, R_t, to the period-1 money shock. Households are unable to change the nominal quantity of deposits held after the monetary shock. An unexpected money injection into the banking system creates a high concentration of liquidity available for lending to firms. For the loan market to clear, the equilibrium interest rate must fall. A low interest rate reduces the firm's finance costs. After one period, the households are able to adjust their currency portfolio to the shock and the liquidity effect is eliminated.

Table 1. Coefficients of industry production functions

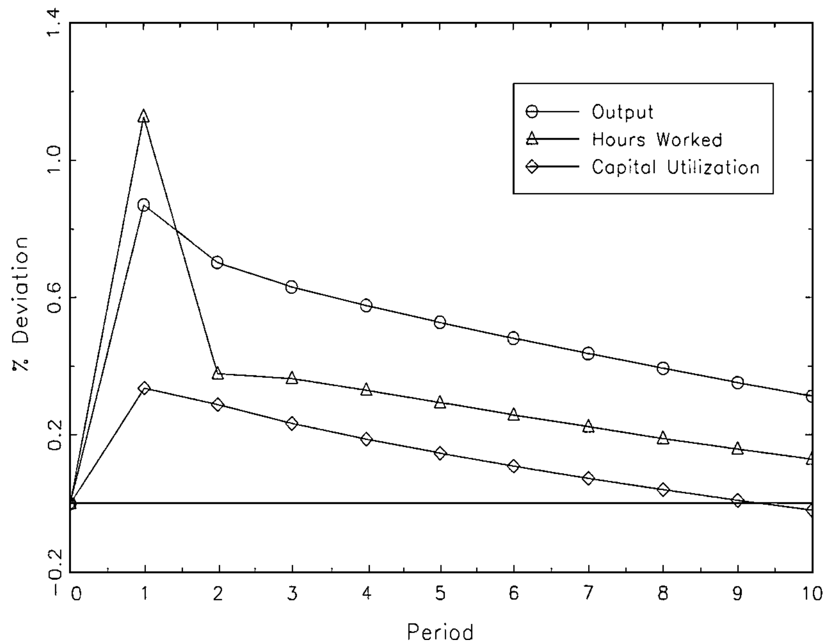
	$\Delta y_{j,t}$[a]		
	A IV[b]	B IV	C IV
$\Delta e_{j,t}$	0.07 (0.01)	0.12 (0.01)	....
$\Delta h_{j,t}$	0.31 (0.01)	0.83 (0.01)	0.34 (0.01)
$\Delta m_{j,t}$	0.594 (0.01)	....	0.60 (0.01)
$\Delta k_{j,t}$	....	....	0.02 (0.03)
Δy_{t-1}	0.44 (0.03)	0.42 (0.05)	0.41 (0.03)

[a] Standard errors in parentheses.
[b] IV, instrumental variables.

https://doi.org/10.1017/S1365100599012043 Published online by Cambridge University Press



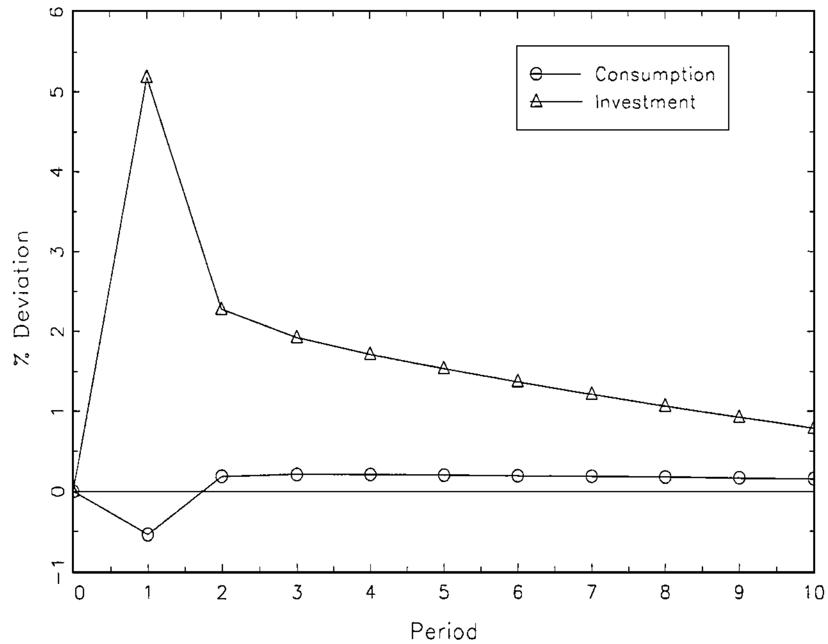
A)



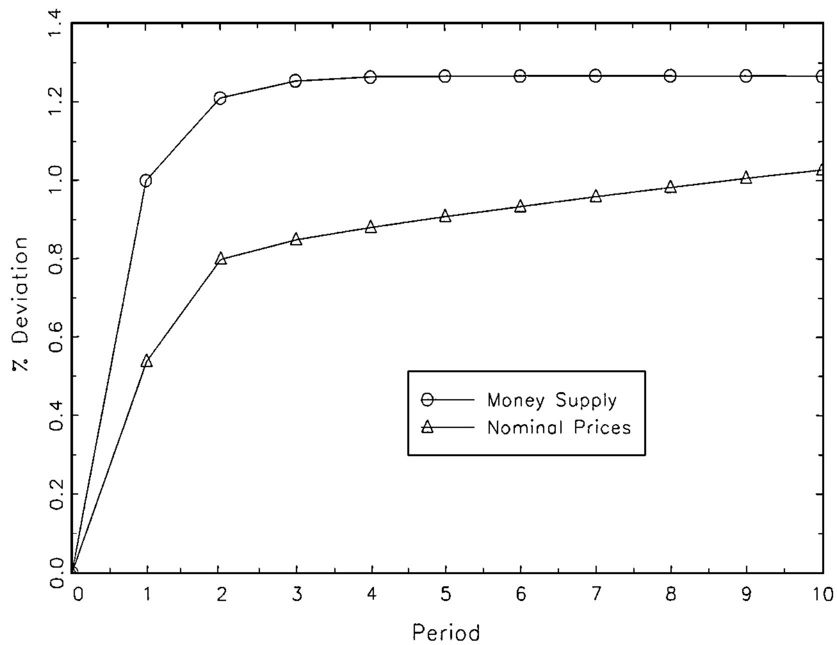
B)

Figure 1. Dynamic response of benchmark model.

https://doi.org/10.1017/S1365100599012043 Published online by Cambridge University Press



C)



D)

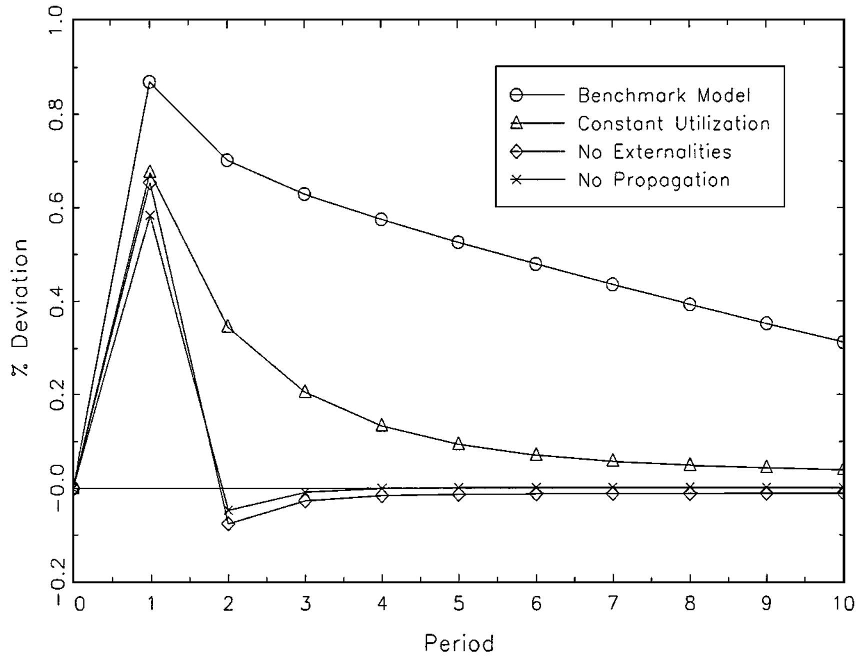
Figure 1. (Continued.)

https://doi.org/10.1017/S1365100599012043 Published online by Cambridge University Press

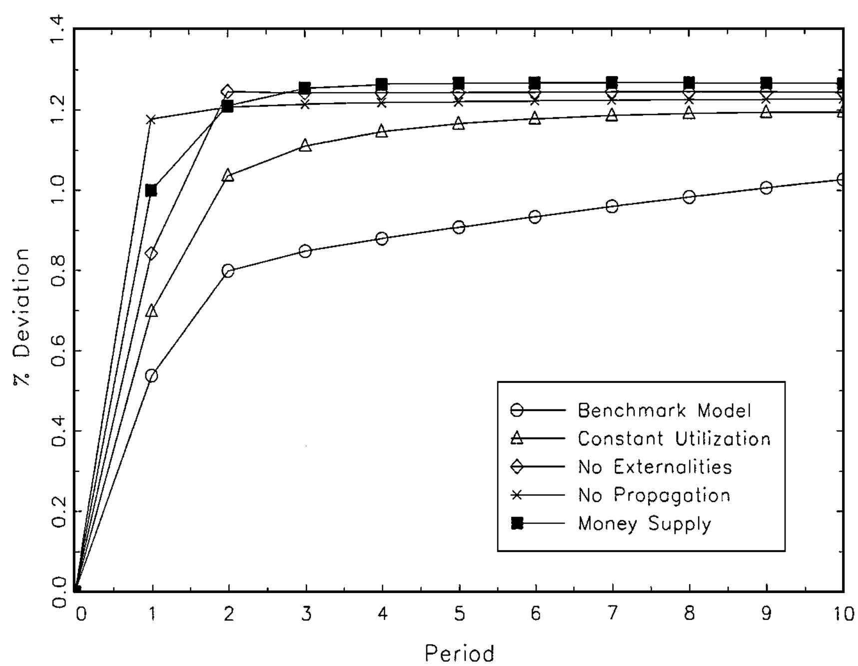
The liquidity effect is strictly transitory; however, the real effects of the temporary money shock are persistent as shown in Figure 1B. In the period of the shock, the low interest rates reduce the cost of hiring workers, increasing labor demand and equilibrium employment. The high employment increases the marginal product of capital services, inducing firms to increase capital utilization. Output jumps sharply as a result. The production externality forms a channel that leads to high productivity in subsequent periods. This keeps input use and production high for many periods after the shock.

The sectoral effects of the shock are shown in Figure 1C. In the initial period of the shock, investment increases sharply while consumption is crowded out. The monetary shock increases demand for credit investment goods as a store of value. Spending on investment goods increases and the equilibrium nominal goods price increases. Consumer cash holdings are fixed in the short run; a higher nominal goods price implies that fewer consumption goods can be bought. After the initial drop in consumption, however, both consumption and investment are above the steady state for many periods. In Figure 1D, I show the increase in money and prices that occurs due to the exogenous policy shock. The money supply level follows a unit root process. The increase in the monetary price level caused by the growth shock is permanent. The money supply grows 1% above its previous level, and then continues to grow. The increase in the price level caused by the monetary shock is itself permanent. However, in the initial period of the shock, the price level rises far less than the money supply. After period 1, the price level rises even more slowly, lagging the growing money supply for many periods. In each period, the household must decide how much cash it is willing to hold rather than spend on goods. Because of propagation, households expect a high level of output in the periods following the monetary expansion. Households will want to have cash for future transactions. They thus are willing to hold the expanding money supply at a slowly increasing nominal price level.

In Figure 2, I compare the benchmark model to model economies without some of the propagation channels. In Figure 2A, I show the effect of a 1% monetary shock on output in each of four models; in Figure 2B, I show the effect of the shock on the price level. The benchmark model is included for comparison; the results are the same as in Figure 1. The second model (constant utilization) is a model with intertemporal externalities (i.e., $\gamma = 0.37$) but constant capital utilization. Here, the level of output increases sharply in the period of the shock but falls much faster in the following periods. Without augmentation by high capital utilization, the monetary shock dissipates much more quickly. The third model (no externalities) is a model with variable capital utilization (i.e., $\phi = 1.56$) but no externalities (i.e., $\gamma = 0$). Here, output increases sharply in the period of the shock but then falls below steady state in the subsequent period because no intertemporal propagation occurs. Capital utilization only serves to augment the propagation of the external term. In the final model (no propagation), I show a standard model with constant capital utilization, no externalities, and no capital adjustment costs ($\delta_2 = 0$). In this model without propagation, output expands in the period of the shock. The real effects of the money shock are reversed as soon as the liquidity effect dissipates.



A) Output



B) Price level

FIGURE 2. Output and price paths for alternative parameterizations.

https://doi.org/10.1017/S1365100599012043 Published online by Cambridge University Press

It is interesting to compare the speed of the price expansion in the four models. It is evident that real propagation contributes to the slow expansion in prices. The slow response of prices to the monetary expansion in the benchmark model can be compared to the model without any of the propagation mechanisms. In period 1, prices increase more quickly than the money supply in the No Propagation model. The over-response of prices to persistent monetary growth is a standard element of rational-expectations monetary models. Households rationally expect future money growth to reduce the value of the current money stock and thus reduce their real money holdings. By contrast, in a model with real propagation, the transactions demand for money increases and households are willing to increase their real money holdings for many periods.

4. LEARNING SPILLOVERS

Though evidence exists in the data that lagged aggregate output is positively associated with subsequent productivity, the exact microeconomic nature of this relationship is unclear. One intuitively plausible channel through which lagged output can affect production as a public good is through learning spillovers. Production of goods or investment creates knowledge as a byproduct. The acquired knowledge is a freely available public good. External learning by doing often has been a feature of endogenous growth models [see Arrow (1985)]. In this literature, knowledge is a stock variable. Learning supplements an accumulable factor that depreciates either not at all [as in much of the empirical literature, see Bahk and Gohrt (1993) or Irwin and Klenow (1994)] or at the same rate as the physical capital stock (as in the theoretical literature). In the business-cycle literature, the intertemporal externality is a flow variable that depreciates every period. It is easy to model the externality as a stock variable by introducing a depreciation term:

$$Z_t = (1-d)Z_{t-1} + \left(Y_{t-1}e^{-\eta t}\right). \tag{19}$$

Selecting the appropriate depreciation rate is more difficult. The externality, Z_t, itself is unobservable. Estimating knowledge depreciation at business-cycle frequencies is made more challenging by the annual nature of the industry data. In lieu of a good parameter estimate, I examine the model at several values of the depreciation rate. In Figure 3, I show the dynamic response of output to a 1% money growth shock at several knowledge depreciation rates. It is clear from Figure 3 that the faster the externality depreciates, the more persistent is the temporary shock. In the benchmark case, when Z_t fully depreciates in one quarter, output increases in period 1 and then slowly declines period by period. The shock diminishes so slowly that, even after eight periods, output is still more than 0.4% over the long-term growth path. When the shock depreciates slightly more slowly, as when $d = 0.75$, there is a sharper dropoff after the initial shock, but following that dropoff, output then diminishes only gradually. The real effects of the monetary shock are almost as long-lived as in the full-depreciation case. Output is 0.3% above steady state eight periods after the shock. This pattern is repeated more dramatically when the knowledge depreciation rate, d, is 0.5 or 0.25. Output rises sharply in the period of

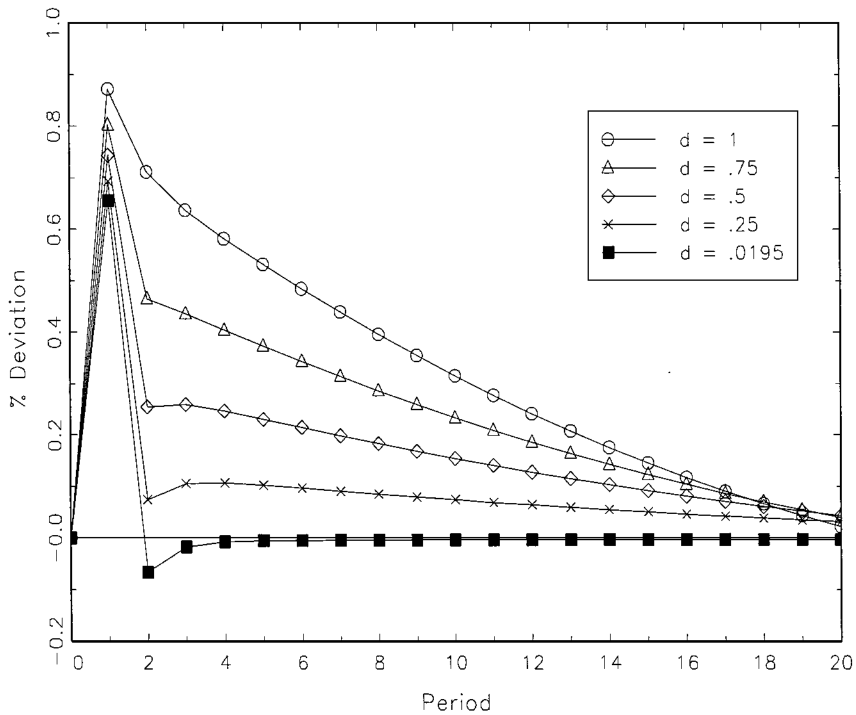


FIGURE 3. Output path at different productivity depreciation rates.

the initial shock. Then, in period 2, output drops sharply and declines slowly afterward. However, even when the depreciation rate is as low as 0.25, output remains substantially above steady state for many periods. However, when the depreciation rate is as slow as that of physical capital (i.e., $d = 0.0195$), there is essentially no propagation of the temporary shock.

Any stock variable with a low depreciation rate will be large relative to one period's flow. Thus, the quantity of this variable will not vary much when affected by a temporary shock. Physical capital, for example, is a poor propagation mechanism because the depreciation is so low. As noted, the depreciation rate of learning is not as easily measured as the depreciation of physical capital. A notion of learning spillovers as accumulated knowledge about production techniques would intuitively indicate a choice of a low depreciation rate. It is difficult to imagine that knowledge about production techniques gained through experience would depreciate in one or two quarters. However, the arguments for business-cycle externalities typically are centered around the advantages of thick markets. These arguments suggest that it is cheaper to produce and sell goods when it is easy to find customers that are good matches for a product. The benefits of thick markets (i.e., the ease of finding good matches) are likely dynamic; contact with customers

https://doi.org/10.1017/S1365100599012043 Published online by Cambridge University Press

can be maintained for future benefit. These contacts could depreciate more quickly than physical plant or knowledge of production techniques.

5. DISCUSSION

This paper quantitatively studies the real propagation of short-term monetary shocks using a monetary model with standard parameters. If intertemporal externalities strongly affect future production possibilities *and* the externalities depreciate quickly, short-term monetary shocks can have long-term real effects. Industry data provide evidence that externalities are important for production dynamics. It is more difficult to obtain hard evidence on the depreciation rate of the externality. It is reasonable to suppose that the depreciation rate would be fast enough to make learning spillovers an important propagation channel. I explicitly study the contribution of variable capital utilization which is shown to be an important supplementary propagation mechanism. The dynamics of nominal goods prices are noteworthy. In the liquidity model without a real propagation mechanism, nominal goods prices increase sharply in response to a money growth shock, even outpacing the growth in the money supply. By contrast, in the model with propagation, the nominal price level increases much more slowly, lagging the increase in the money supply for many periods. This is much closer to the effect of identified monetary shocks in the U.S. economy. Christiano et al. (1997), for example, argue that a sluggish price response to exogenous monetary shocks is a key criterion for assessing a monetary model.

Several elements of this model seem at odds with the basic dynamic response of the U.S. economy to exogenous monetary shocks [as identified using VAR models as in Christiano et al. (1996)]. In the model presented here, the liquidity effect is strictly transitory though evidence from U.S. data suggests a longer-lasting effect. Further, it is also true that the sharpest liquidity effect of a monetary shock proceeds the strongest output effect in the U.S. economy. In all parameterizations of this model, the strongest liquidity effect of the monetary shock is contemporaneous with the effect on production. This suggests that, though intertemporal externalities may be an important part of the monetary transmission mechanism, they are not the only part. Combining this propagation channel with a mechanism that works to prolong the liquidity effect [examples are in Christiano and Eichenbaum (1992) or Cook (1997)] could produce more realistic dynamics.

REFERENCES

Arrow, K.J. (1985) The economic implications of learning by doing. In *Collected Papers of Kenneth J. Arrow*, vol. 5, Production and Capital, pp. 157–180. Cambridge, MA: Harvard University Press.

Bahk, B.H. & M. Gort (1993) Decomposing learning by doing in new plants. *Journal of Political Economy* 101, 561–583.

Bartelsman, E.J. & W.B. Gray (1994) NBER Productivity Database. Mimeo, National Bureau for Economic Research.

Baxter, M. & M.J. Crucini (1993) Explaining saving-investment correlations. *American Economic Review* 83, 416–436.

Bernanke, B.S. & M. Gertler (1995) Inside the black box: The credit channel of monetary policy transmission. *Journal of Economic Perspectives* 9, 27–48.

Burnside, C. & M. Eichenbaum (1996) Factor hoarding and the propagation of business style shocks. *American Economic Review* 86, 1154–1174.

Burnside, C., M. Eichenbaum & S. Rebelo (1995) Capital utilization and returns to scale. In B.S. Bernanke & J.J. Rotemberg (eds.), NBER Macroeconomics Annual 1995, pp. 67–110. Cambridge, MA: MIT Press.

Cho, J.O. & T.F. Cooley (1995) The business cycle with nominal contracts. *Economic Theory* 6, 13–33.

Christiano, L.J. (1991) Modeling the liquidity effect of a monetary shock. *Federal Reserve Bank of Minneapolis Review* 15, 3–34.

Christiano, L.J. & M. Eichenbaum (1992) Liquidity effects and the monetary transmission mechanism. *American Economic Review* 82, 344–353.

Christiano, L.J., M. Eichenbaum & C. Evans (1996) The effect of monetary shocks: Evidence from the flow of funds. *Review of Economics and Statistics* 78, 78–93.

Christiano, L.J., M. Eichenbaum & C. Evans (1997) Sticky price and limited participation models of money: A comparison. *European Economic Review* 41, 1201–1248.

Cogley, T. & J.M. Nason (1995) Output dynamics in real-business-cycle models. *American Economic Review* 85, 492–511.

Cook, D. (1997) The Liquidity Effect and the Loan-Deposit Spread. Mimeo, Hong Kong University of Science and Technology.

Cooley, T.F. & G.D. Hansen (1995) Money and the business cycle. In T.F. Cooley (ed.), *Frontiers of Business Cycle Research*, pp. 175–216. Princeton, NJ: Princeton University Press.

Cooper, R.W. & J. Haltiwanger (1996) Evidence on macroeconomic complementarities. *Review of Economics and Statistics* 78, 78–93.

Cooper, R.W. and A. Johri (1997) Dynamic complementarities: A quantitative analysis. *Journal of Monetary Economics* 40, 97–120.

Durlauf, S.N. (1993) Non-ergodic economic growth. *Review of Economic Studies* 60, 349–366.

Fuerst, T. (1992) Liquidity, loanable funds, and real activity. *Journal of Monetary Economics* 29, 3–24.

Greenwood, J., Z. Hercowitz & G. Huffman (1988) Investment, capacity utilization, and the real business cycle. *American Economic Review* 78, 402–417.

Hansen, G.D. (1985) Indivisible labor and the business cycle. *Journal of Monetary Economics* 16, 309–327.

Irwin, D.A. & P.J. Klenow (1994) Learning by doing spillovers in the semiconductor industry. *Journal of Political Economy* 102, 1200–1227.

King, R.G. (1991) Money and business cycles. Mimeo, University of Rochester.

King, R.G., C. Plosser & S. Rebelo (1987) Technical Appendix to "Production, Growth, and Business Cycles." RCER working paper, University of Rochester.

King, R.G. & M.W. Watson (1995) System reduction and solution algorithms for singular linear difference systems under rational expectations. Mimeo, University of Virginia.

Lucas, R.E., Jr. (1972) Expectations and the neutrality of money. *Journal of Economic Theory* 4, 103–123.

Lucas, R.E., Jr. (1990) Liquidity and interest rates. *Journal of Economic Theory* 50, 237–264.

Rapping, L. (1965) Learning and World War II production functions. *Review of Economics and Statistics* 47, 81–86.

Rogerson, R. (1988) Indivisible labor, lotteries and equilibrium. *Journal of Monetary Economics* 21, 3–16.

Rotemberg, J.J. (1996) Prices, output, and hours: An empirical analysis based on a sticky price model. *Journal of Monetary Economics* 37, 505–523.

Shapiro, M.D. (1996) Macroeconomic implications of variation in the workweek of capital. *Brookings Papers on Economic Activity* 1996, 181–225.

Sims, C.A. (1997) Solving linear rational expectations models. Mimeo, Yale University.
Strongin, S. (1995) The identification of monetary policy disturbances: Explaining the liquidity puzzle. *Journal of Monetary Economics* 35, 463–497.
Wen, Y. (1997a) Indeterminacy, dynamic adjustment costs, and cycles. Mimeo, Hong Kong University of Science and Technology.
Wen, Y. (1997b) Capacity utilization under increasing returns to scale. Mimeo, Hong Kong University of Science and Technology.

APPENDIX: DATA SOURCES

The sectoral data are drawn from the NBER Productivity Database compiled by Bartelsman and Gray (1994). In that database, value added (mnemonic VADD) is defined as shipments plus changes in inventories minus costs of materials used (MATCOST). I measure real gross output as the sum of value added and materials costs deflated by the shipments deflator (PISHIP). Real Materials is materials costs (MATCOST) deflated by the materials deflator (PIMAT). Hours per worker are calculated as total hours of production workers (PRODH) divided by number of production workers (PRODE). This quantity is multiplied by a total number of employees (EMP) to get the proxy for employee hours. The real capital stock is available in the database (CAP). Energy usage is energy expenditures (ENERGY) deflated by the energy deflator (PIEN). The annual measure of U.S. GDP is from Citibase (GADP).

The quarterly data used to estimate the VAR's are from the St. Louis Federal Reserve FRED database and Citibase. The quarterly output figure is real GDP (FRED mnemonic GDPC92); the price level is the GDP deflator (FRED mnemonic GDPCTPI) The federal funds rate, nonborrowed reserves, and total reserves are quarterly means of monthly data (respective FRED mnemonics FEDFUNDS, BOGNONBR, and TRARR). For commodities prices, I use the quarterly mean of the Commodity Research Bureau index (Citibase Mnemonic PSCCOM). The VAR's are estimated using data from 1960:1 to 1995:4.