Contributions to Macroeconomics

Volume 6, *Issue* 1 2006 *Article* 1

Inflation Inertia in Sticky Information Models

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Abstract

This paper considers whether the sticky information model of Mankiw and Reis (2002) can robustly deliver inflation inertia. I find that four features of the model play a key role in determining inflation inertia: the frequency of information updating, the degree of real rigidities, the nature and persistence of monetary policy, and the presence or not of information stickiness elsewhere in the economy. Real rigidities serve to dampen firms' desired price changes and are a critical element in delivering inflation inertia. The type of monetary policy, money-growth vs. interest rate rules, also matters, with Taylor rules making inflation inertia less likely than under money growth rules. Adding sticky information in consumption to the model yields a more gradual adjustment of output, thereby decreasing the incentive for firms to change prices on impact and increasing the inertia of inflation. I also explore the implications of using random versus fixed durations of information rigidity and argue that with the latter, the choice of the policy rule has a smaller effect on the qualitative response of inflation. These results allow us to sort out some conflicting conclusions on inflation inertia in sticky information models and suggest that inertia is more sensitive to parameter choices than previously thought.

KEYWORDS: Inflation Inertia, Sticky Information

*I am grateful to Bob Barsky, Yuriy Gorodnichenko, Chris House, Peter Ireland, Peter Morrow, Ricardo Reis, and three anonymous referees for helpful comments and to the Robert V. Roosa Dissertation Fellowship for financial support. Contact Information: Olivier Coibion, 123 Lorch Hall, Department of Economics, 611 Tappan St., Ann Arbor, MI 48109. Email: ocoibion@umich.edu.

1 Introduction

Stylized facts serve as useful benchmarks with which to evaluate models. The observed hump-shape response of inflation to monetary shocks has received particular attention in recent years. This is due to the fact that this result is not only empirically robust but also surprisingly difficult to reproduce in simple monetary models. Most famously, the New Keynesian Phillips Curve (NKPC), based on the assumption that firms face costs to changing prices, is incapable of generating such a response without the addition of numerous (and frequently ad-hoc) propagation mechanisms. Mankiw and Reis (2002, henceforth MR) present an alternative "sticky information" model, based on the assumption that firms face costs to updating their information, which can deliver inflation responses to monetary shocks that are strikingly similar to those observed in the empirical literature without resorting to additional external mechanisms. In this paper, I consider the robustness of their results to more general aggregate demand settings and how to reconcile the conflicting findings of previous studies also concerned with applying sticky information to DSGE models.

The failure of the basic NKPC to match the observed response of inflation to monetary shocks has led many authors to propose solutions within the context of sticky price models.[1] However, these typically rely upon the addition of rule-of-thumb firms who use ad-hoc rules for changing prices. While this type of behavior helps sticky price models yield more plausible theoretical responses to shocks and receives strong empirical support, the lack of microfoundations renders the use of such models problematic for policy analysis. The appeal of MR's approach is that it relies upon the single alternative assumption that firms update their information according to a Poisson process.[2] They argue that this one deviation from a flexible-price and information model can generate inflation inertia and reproduce the positive correlation between output and changes in inflation that is observed in the data.[3]

Several papers investigate the robustness of these results by integrating the sticky information Phillips Curve (SIPC) into dynamic general equilibrium models and draw very different conclusions. Keen (2004), Collard and Dellas (2004), and Andres et al (2005) conclude that the SIPC fails to live up to the claims of MR in more sophisticated models. Trabandt (2005) and Korenok and

[1] Gali and Gertler (1999), Woodford (2003) and Christiano, Eichembaum and Evans (2005) are well-known examples.
[2] Reis (2005) shows that when firms face a fixed cost to updating information, aggregation across firms will lead to a Poisson process for the arrival rate of information, thereby providing strikingly strong microfoundations for the sticky information model.
[3] I will use the term "inflation inertia" to mean the hump-shape response of inflation to monetary shocks, rather than just persistent inflation responses (in the sense of high autocorrelation).

Swanson (2004) conclude instead that the findings of MR are robust, but that a "hybrid" sticky price model performs equally well.

In this paper, I seek to determine whether the results of MR are indeed robust and why these different papers draw opposite conclusions. I first investigate the sources of inflation inertia in the stylized setup of MR and place particular emphasis on the role of real rigidity. While real rigidity (or strategic complementarity in price setting) has been identified as an important mechanism in generating persistent real effects from nominal shocks in New Keynesian models, it also plays a role in the sticky information model. I show that without sufficient amounts of real rigidity, the sticky information model cannot deliver inflation inertia.

I then consider how more realistic demand settings affect the likelihood of observing inflation inertia in response to monetary shocks. In particular, I focus on the effect of forward-looking consumers and the choice of a money growth or a Taylor rule to capture the effects of monetary policy. The latter choice implies an endogenous response of policymakers to deviations of inflation and output, which makes inflation inertia more difficult to achieve in an otherwise identical model. I argue that adding sticky information to consumers helps produce an inertial response of output and thus makes inflation inertia easier to achieve, but the results remain sensitive to parameter values. Following Dupor and Tsuruga (2005), I also consider the implications of using a fixed duration of information rigidity rather than a Poisson process for the arrival of information as assumed in MR. In this case, given enough strategic complementarity in price setting, the peak response of inflation occurs at the time when all firms have learned about the shock, regardless of whether a money growth or Taylor rule is used.

The structure of the paper is as follows. In section 2, I describe the sources of inflation inertia in the model of MR. Section 3 presents a more general model that allows us to compare alternative assumptions about policy rules, consumer information delays, and the timing assumptions of information rigidity. In Section 4, I present the main results through impulse responses and sensitivity analysis to parameter values. Section 5 considers how this relates to the findings of previous authors. Section 6 concludes.

2 Sources of inflation inertia in the sticky information model

The sticky information model introduced by MR consists of a quantity equation

$$y_t = m_t - p_t \qquad (1)$$

where y is the log of real output, m is the log of nominal income, and p is the log price level. The exogenous process for nominal income is

$$\Delta m_t = \rho_m \Delta m_{t-1} + \varepsilon_t \qquad (2)$$

where $\rho_m \in [0,1]$. Equations (1) and (2) describe aggregate demand in the model.

Aggregate supply utilizes two equations. The first describes firm j's instantaneously optimal price conditional on information dated $t\text{-}k$

$$p^{\#}_{t,t-k} \equiv E_{t-k}\left[p_t + \alpha y_t\right] \tag{3}$$

where smaller values of α correspond to greater degrees of real rigidity (or strategic complementarity in price setting). A firm seeking to determine what price to charge will look at the aggregate price level (as a measure of what other firms are doing) and the level of aggregate demand. The coefficient of real rigidity determines the relative importance of aggregate demand in the price setting decision. Low values of α (high real rigidity) indicate that the firm cares relatively more about the pricing decisions of other firms than about aggregate demand.

The second equation is the sticky information price level, which relies upon a Poisson process applied to information updating, where μ is the probability that a firm will not be able to update its expectations each period. The price level can then be written as

$$p_t = (1-\mu)\sum_{j=0}^{\infty}\mu^j p^{\#}_{t,t-j}\ . \tag{4}$$

Combining (3) and (4) yields the Sticky Information Phillips Curve (SIPC)

$$\pi_t = \frac{(1-\mu)}{\mu}\alpha y_t + (1-\mu)\sum_{j=0}^{\infty}\mu^j E_{t-1-j}\left(\pi_t + \alpha\Delta y_t\right) \tag{5}$$

in which inflation depends on current output, as well as past expectations of current inflation and changes in output.

MR show that, for μ=0.75 and α=0.1, the sticky information model can generate a hump-shape response to shocks to nominal income, gradual and costly disinflations, and a positive correlation between output and inflation. Given the inability of the basic sticky price model to reproduce any of these phenomena, this is a striking result. To understand why inflation is inertial in the sticky information model, consider the response of the model to a monetary shock out of the steady state. For simplicity, I normalize all expectations dated before the shock to be zero. Assuming the shock occurs at time zero, the price level equation reduces to

$$p_t = \left(1-\mu^{t+1}\right)p^{\#}_{t,t} \tag{7}$$

so that the price level is simply the fraction of firms which have updated their information times the price they all set.

To have inflation inertia, we first need changes in the price level to be relatively small initially. This will occur if the fraction of firms who update their information in the first few periods is small ($1>\mu>>0$) *and* these firms have optimal prices that are largely unaffected by the shock. Significant real rigidities

($0<\alpha<<1$) are critical here so that firms care relatively more about the price level, which will be largely unchanged if few firms know about the shock, than about the shock to aggregate demand. We subsequently need large movements in the price level in later periods. While the fact that more firms will be aware of the change plays an important role here, it is critical that all firms still have an optimal price sufficiently different from the original price level. For this, we need shocks to be sufficiently long-lived. If the nominal income shock is short-lived, by the time many firms become aware of the shock, they will no longer change their prices because the effect of the shock will have largely dissipated. Thus, three elements play critical roles in generating inflation inertia in this model: the size of nominal and real rigidities, as well as the persistence of the shock.

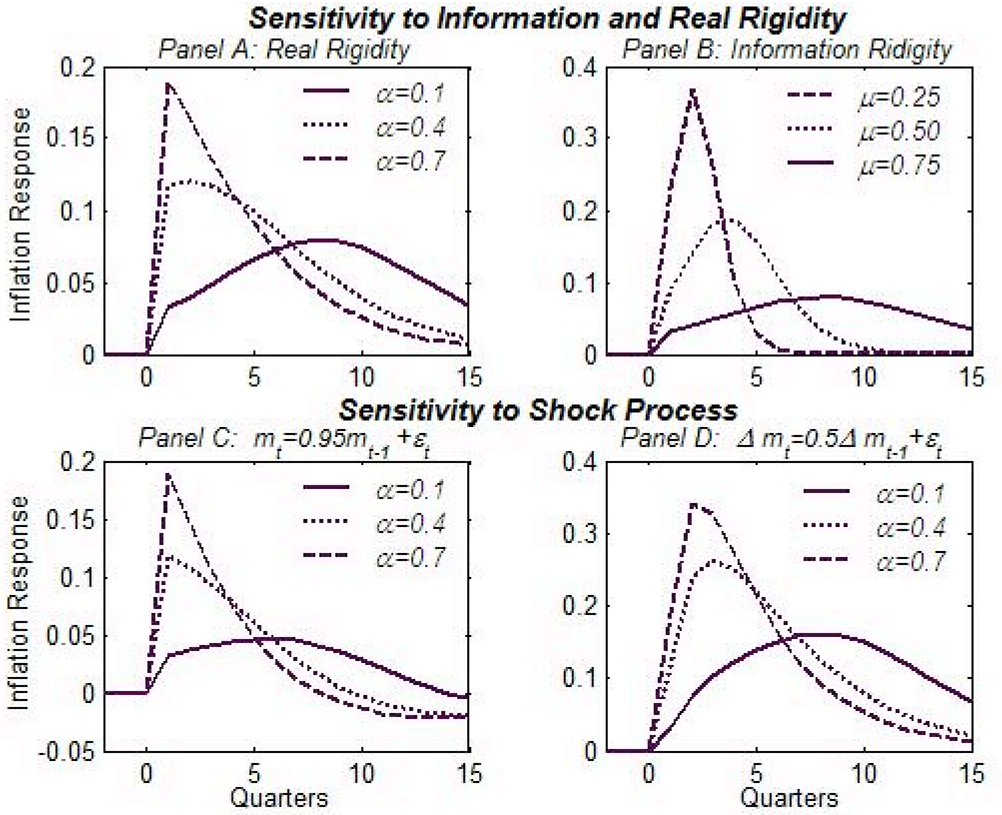
The importance of these elements has long been emphasized in the New Keynesian literature. Ball and Romer (1990) and Kimball (1995), for example, characterize the importance of having both real and nominal rigidities to generate persistent real effects from nominal shocks. Woodford (2003) shows that the persistence of output can be replicated in New Keynesian models if there is enough strategic complementarity in price setting. The same intuition naturally extends to the sticky information model. However, real rigidity now also plays a new role. Specifically, it is necessary to generate inflation inertia.

The particular role played by strategic complementarity in price setting can best be seen in the response of the sticky information model to a permanent shock to the level of money. If there is neither strategic complementarity nor substitutability in price setting, then the response of the sticky information model is *identical* to that of the basic sticky price model.[4] In this case, there is no inflation inertia. As strategic complementarity in price setting rises (α falls), the qualitative response of inflation changes and becomes hump-shaped for a low enough α.[5] This is illustrated in panel A of Figure 1, in which μ=0.75 as in MR. For α=0.7, inflation peaks in the period of the shock, as would be true in the sticky price model. When α=0.4, inflation peaks one quarter after the shock. Finally, with α=0.1 as assumed in MR, inflation peaks nearly two years after the shock.

Panel B illustrates the response of inflation to a permanent shock to the level of nominal GDP for different levels of information rigidity (assuming α=0.1). As firms update their information more frequently, inflation inertia becomes increasingly hard to generate. Similarly, panels C and D show the response of inflation to temporary shocks to the level and the growth rate of

[4] This is formally demonstrated in the appendix.
[5] In a continuous time version of the model, one can show that $\alpha<1/2$ is a necessary and sufficient condition for inflation inertia in the sticky information model in response to a permanent shock to the level of nominal income if there is a positive level of information rigidity ($\mu>0$).

Figure 1: Inflation inertia in the sticky information model of Mankiw-Reis.



Note: The baseline parameter values are μ=0.75, α=0.1, and a permanent shock to the level of nominal income (ρ_m=0). Panels A and B consider variations in α and μ separately where other parameters are at baseline values. Panels C and D consider alternative shock processes for different values of α.

nominal income respectively for different levels of α (assuming μ=0.75). Again, whether inflation inertia is present is sensitive to parameter values. If there is not enough strategic complementarity given a shock process, inflation will jump on impact just as it would in the sticky price model.

The evidence above indicates that for the SIPC to be able to generate a hump-shaped response of inflation to monetary policy shocks, high enough levels of information and real rigidities are necessary, as well as that the shock be sufficiently persistent. The qualitative response of inflation is thus sensitive to parameter values. Most empirical estimates of the degree of information rigidity yield μ approximately equal to 0.75, as assumed by MR and subsequent papers.[6] In addition, Woodford (2003) argues that a value of α of between 0.1 and 0.15 is both empirically and theoretically plausible. Finally, typical estimates of the time series process of nominal income are consistent with nominal income growth following an AR(1) process with persistence parameter of about 0.5.[7] Thus, since the parameters used by MR are not particularly controversial, one could view the sensitivity of the SIPC to less realistic parameter values as a moot point.

However, given the stylized demand side assumptions of MR, it is nonetheless worthwhile pondering how other demand side assumptions would affect their results. MR correctly argue that their simpler approach best draws out the implications of different supply-side assumptions. But if one is interested in matching the response of inflation to that observed in the data, which embodies the endogenous response of consumers and policymakers, more sophisticated demand side approaches are warranted. I now turn to how such approaches affect the results of MR.

3 Model

In this section, I apply the notion of sticky information to a model with firms, consumers and monetary policy-makers. Because sticky-information is at least as likely to apply to consumers as firms, I allow for sticky-information in consumption in a way that nests the standard consumer maximization problem.[8]

The model consists of three sectors: firms, consumers, and the central bank. Production is composed of an intermediate goods sector of monopolistic competitors, whose products are combined into a final good by a perfectly competitive industry. The consumer's problem is a standard representative agent problem, except for the fact that utility depends upon an index of consumption levels chosen by subagents. These agents act to maximize the expected utility of the representative agent, but only control their individual consumption of the final

[6] See Mankiw and Reis (2003), Carroll (2003), Khan and Zhu (2002), Andres et al (2005), and Kiley (2005) for such estimates, though Coibion (2005) presents a contrarian view. In addition, Reis (2005 and 2004) shows that for reasonable costs of information, inattentiveness for firms and consumers could plausibly exceed one year.

[7] See MR and Woodford (2001) among others.

[8] Reis (2004) provides rigorous microfoundations for consumers facing costs of information updating. It must be emphasized that Reis' approach yields different implications for the time series properties of consumption than that assumed here. I follow a simpler approach designed to be highly tractable, directly comparable to the sticky information Phillips Curve, and easily applicable in a DSGE model. In addition, this approach could easily be extended to sticky information in wage-setting and investment. While inconsistent with Reis (2004), this setup is consistent with the information diffusion mechanism described in Carroll (2003). Mankiw and Reis (2005) also consider an alternative approach to integrating sticky information in consumption.

good. Finally, the central bank sets interest rates or the money supply according to a pre-specified rule.

3.1 Consumers

The consumer's problem is written in a standard representative agent setup

$$\max_{\{N_{t+z}(j)\},\{B_{t+z}\},\{M_{t+z}\},\{C_{t+z}(i)\}} E_{t-k}\sum_{z=0}^{\infty}\beta^{z}\left[\frac{Z_{t+z}^{1-\sigma}-1}{1-\sigma}-\frac{\Gamma}{1+\eta^{-1}}\int_0^1 N_{t+z}(j)^{1+\eta^{-1}}\partial j+\frac{\Omega}{1-v}\left[\left(\frac{M_{t+z}}{P_{t+z}}\right)^{1-v}-1\right]\right]$$

subject to

$$C_{t+z}+\frac{M_{t+z}}{P_{t+z}}+\frac{B_{t+z}}{P_{t+z}}\leq\int_0^1 N_{t+z}(j)\frac{W_{t+z}(j)}{P_{t+z}}\partial j+\frac{B_{t+z-1}}{P_{t+z}}R_{t+z-1}+\frac{M_{t+z-1}}{P_{t+z}}+\Pi_{t+z}+T_{t+z}$$

$$Z_t=\left[\int_0^1 C_t(i)^{\frac{\phi-1}{\phi}}\partial i\right]^{\frac{\phi}{\phi-1}}$$

$$C_t=\int_0^1 C_t(i)\partial i$$

where M_t represents money holdings, $N_t(j)$ and $W_t(j)$ are labor supplied to and wage earned in intermediate goods sector j respectively, B_t are riskless bonds held which earn the nominal gross interest rate R_t, P_t is the price of final goods at time t, $C_t(i)$ is consumption of the final good by subagent i, C_t is the sum of subagent consumption levels, Z_t is the consumption aggregator that matters for utility, Π_t are profits, and T_t are exogenous transfers.

The maximization problem is separated into two parts. First, a continuum of sub-agents indexed from 0 to 1 each choose $C_t(i)$ to maximize expected aggregate utility conditional on their (possibly outdated) information set taking all other choices as exogenously determined.[9] The first order condition for a subagent with information dated $t-k$ is

$$E_{t-k}\left[Z_t^{-\sigma+\phi^{-1}}C_t\left(i\right)^{-\phi^{-1}}\right]=E_{t-k}\mathrm{X}_t \tag{8}$$

where X_t is the Lagrangian multiplier on the budget constraint. If all subagents had the same information (dated t), then equation (8) would reduce to the standard FOC with respect to consumption. It will thus be convenient to define the gap between the marginal utilities of consumption and wealth, log-linearized around the steady-state as

$$x_t^c\equiv-\sigma c_t-\chi_t \tag{9}$$

[9] The sub-agents are all purchasing the same final good.

which will be referred to as the consumption gap.[10] One can then write the log-linearized perceived optimal level of individual consumption by a subagent with information dated *t-k* as

$$c^{\#}_{t,t-k} = E_{t-k}\left[c_t + \phi x^c_t\right] \tag{10}$$

An interesting feature of this setup is the presence of strategic complementarity or substitutability in consumption, determined by whether ϕ is greater or less than one. Suppose the marginal utility of consumption is greater than the shadow value of wealth, or equivalently the consumption gap is positive. If ϕ is greater than one, then individuals will wish to raise their relative consumption; this is the case of strategic substitutability. When ϕ is less than one, individuals will not raise their consumption much because they care more about others' consumptions than about the marginal utility incentive of consumption. This feature can help generate persistence in consumption, just as it does with price setting in sticky price models.

The representative agent controls the remaining decisions over individual labor supplies, saving, and money holdings. I assume that the representative agent always has complete and up-to-date information. His log-linearized first-order conditions are then

$$\frac{1}{\eta}n_t(i) + \sigma c_t + x^c_t = w_t(i) - p_t \qquad \forall i \tag{11}$$

$$E_t \Delta c_{t+1} = \frac{1}{\sigma}E_t\left[i_t - \pi_{t+1} - \Delta x^c_{t+1}\right] \tag{12}$$

$$m_t - p_t = \frac{\sigma}{v}c_t - \frac{1}{v(\bar{R}-1)}i_t - \frac{1}{v}x^c_t \tag{13}$$

The first is the standard labor supply condition, augmented by the consumption gap. The second condition, drawn from optimal choice of bond holdings, is the traditional consumption Euler equation, which now includes the expected change in the consumption gap.[11] Finally, equation (13) is the money demand equation.

I follow MR and assume that the adjustment of subagents' expectations follows a Poisson process, as in Calvo (1983). Specifically, each period there is a constant probability that an individual will be able to update his information set. When one is allowed to do so, complete information is acquired and rational expectations apply to all future time periods. The consumer bases all subsequent decisions on these expectations until he is allowed to update their information once again. The probability of updating is independent of the amount of time

[10] I use lower-case letters to denote log-deviations from the non-stochastic steady-state and the fact that, once linearized, c_t=z_t. .
[11] Note that i_t is the log-deviation of the gross nominal interest rate from its steady-state value.

since the last updating occurred. Letting 1-λ denote the probability of updating information each period, log-linearized aggregate consumption is

$$c_t = (1-\lambda)\sum_{j=0}^{\infty}\lambda^j c^{\#}_{t,t-j} . \tag{14}$$

The appendix shows that, given the optimal consumption levels determined by (10) and the bond condition (12), the Euler equation for aggregate consumption can be rewritten as

$$c_t = \omega E_t c_{t+1} + (1-\omega)c_{t-1} - \frac{\varpi}{\sigma}E_t\left(i_t - \pi_{t+1}\right) + \varpi\Omega_{t-1} . \tag{15}$$

where $\omega \equiv \frac{\sigma\phi(1-\lambda)(1+\lambda)+\lambda^2}{\left[\sigma\phi(1-\lambda)+\lambda\right](1+\lambda)} \in \left[\frac{1}{2},1\right], \varpi \equiv \frac{\sigma\phi(1-\lambda)}{\sigma\phi(1-\lambda)+\lambda} \in [0,1]$,

$\Psi_t = (1-\sigma\phi)\Delta c_t + \phi(i_{t-1} - \pi_t)$,

and $\Omega_{t-1} = \left(\frac{\lambda}{\sigma\phi(1-\lambda)}\right)\left[E_{t-1}\Psi_t - \lambda\sum_{j=0}^{\infty}\lambda^j\left(E_{t-1-j}\Delta\Psi_{t+1} + \Delta E_{t-1-j}\Psi_t\right)\right]$.

There are several aspects of this relationship worth noting. First, when λ=0, i.e. when there are no old information sets, the expression reduces to the standard consumption Euler equation. Second, the assumption of sticky information naturally generates a backward-looking component to the consumption function, but the weight on the forward-looking part of consumption is bounded below by one-half, while the backward-looking component is bounded above by one-half. Thus, even if one allowed for significant delays in information updating, aggregate consumption would still maintain a strong forward-looking component. The reason is that even with information delays, consumers are choosing their consumption in a forward-looking manner. Third, the coefficient on the real interest rate will be less than the intertemporal elasticity of substitution. Estimates of the IS curve frequently find near-zero estimates of the IES and have difficulty explaining such a phenomenon[12]. In this model, as the degree of sticky information approaches one, the coefficient on the expected real interest rate goes to zero regardless of the IES.

Finally, old expectations, as represented by Ω_{t-1}, play a role in determining current consumption. This occurs in three ways. First, the previous period's expectation of the current change in consumption as well as the previous period's real interest rate tend to raise current consumption. The second term is a weighted average of old expectations of the future change in the growth rate of consumption as well as the future change in the real interest rate. The third and

[12] See Fuhrer and Rudebusch (2004) for recent IS curve estimates.

final term captures the revision of past expectations of the current real interest rate and change in consumption.

3.2 Firms

Final goods are produced in a competitive industry that combines a continuum of intermediate goods using a CES aggregator

$$Y_t = \left(\int_0^1 Y_t(j)^{\frac{\theta-1}{\theta}} \partial j \right)^{\frac{\theta}{\theta-1}}$$

where θ is the elasticity of substitution between intermediate goods. Since there is no capital or government in the model, the goods market clearing condition is simply $Y_t=C_t$. The price level must be

$$P_t = \left(\int_0^1 P_j(j)^{1-\theta} \partial j \right)^{\frac{1}{1-\theta}} \quad .$$

Each intermediate variety is produced monopolistically using a production function linear in labor supplied $Y_t(j)=A_tN_t(j)$ where A_t denotes the aggregate level of technology and follows $a_t=\rho_a a_{t-1}+e_t$ such that e_t is *iid* $(0, \sigma_a^2)$. Each monopolist must hire a specific type of labor supply, assumed without loss of generality to be indexed by the same number as that firm's index, but does so as a price-taker. The demand faced by firm *j* depends upon its relative price as well as aggregate demand

$$Y_t(j) = \left(\frac{P_t(j)}{P_t} \right)^{-\theta} Y_t .$$

A firm's desired price at any moment in time is a constant markup over marginal cost. Log-linearizing around a zero-inflation steady state, the desired price can then be written as

$$p_t^{\#} = p_t + \frac{1+\eta\sigma}{\theta+\eta} y_t - \frac{1+\eta}{\theta+\eta} a_t + \frac{\eta}{\theta+\eta} x_t^c . \tag{16}$$

If all firms are free to set prices and have the same information, then $p_t^{\#} = p_t$. Let such an outcome determine the firm flexible-information natural level of output y_t^f. We can write it as

$$y_t^f = \frac{(1+\eta) a_t - \eta x_t^C}{1+\eta\sigma} .$$

The flexible information equilibrium for firms thus depends on technology as well as on the consumption gap that arises when some consumers have outdated expectations. Define the firm output gap $x_t^f \equiv y_t - y_t^f$ as the difference between actual output and output when all firms have flexible information. We can then rewrite a firm's perceived instantaneously optimal price, conditional on information dated *t-k*, as

$$p^{\#}_{t,t-k} = E_{t-k}\left[p_t + \alpha x^f_t \right] \tag{17}$$

where $\alpha=(1+\eta\sigma)/(\theta+\eta)$ is the degree of strategic complementarity in price setting.

Imposing another Poisson process on information updating of firms (with $1-\mu$ being the probability of updating information in any period), the log-linearized price level is

$$p_t = (1-\mu)\sum_{s=0}^{\infty} \mu^s p^{\#}_{t,t-s} \tag{18}$$

which can be rearranged to yield the sticky information Phillips Curve

$$\pi_t = \frac{(1-\mu)}{\mu}\alpha x^f_t + (1-\mu)\sum_{j=0}^{\infty}\mu^j E_{t-1-j}\left(\pi_t + \alpha\Delta x^f_t\right) . \tag{19}$$

Current inflation thus depends on the current output gap as well as on past expectations of the current inflation rate and changes in the output gap.[13]

3.3 Monetary policy

I allow for two types of monetary policy. First, the central bank may follow an exogenous money growth process given by

$$\Delta m_t = \rho_m \Delta m_{t-1} + \varepsilon_t . \tag{20}$$

where ε_t is $iid(0,\sigma_m^2)$. Alternatively, the central bank is assumed to set interest rates using a Taylor rule with interest smoothing as follows

$$i_t = (1-\rho_i)\left[\Phi_\pi \pi_t + \Phi_y x^N_t\right] + \rho_i i_{t-1} + \xi_t \tag{21}$$

where ξ_t is $iid(0,\sigma_i^2)$, $x^N_t \equiv y_t - y^N_t$, and $y^N_t \equiv \left(\frac{1+\eta}{1+\eta\sigma}\right)a_t$ is the level of output when neither firms nor consumers have sticky information.

3.4 Parameter Values

I let η, the Frisch labor supply elasticity, be 1/3. σ, the inverse of the intertemporal elasticity of substitution, is set to 2. I assume θ =10, which is consistent with a steady state markup of about ten percent. This implies that the degree of strategic complementarity in price setting is approximately 0.16. For the interest rate rule, I follow Taylor (1993) and let $\Phi_\pi=1.5$ and $\Phi_y=0.5$ and consider different levels of interest smoothing (ρ_i). The discount factor β is set to

[13] Note here that the correct measure of the output gap in the Phillips Curve is the difference between actual output and output with flexible information for firms, but not necessarily for consumers.

0.99. To get a unit income elasticity of money demand, I set $\nu=\sigma$. Finally, the degree of information rigidity for firms is set to μ=0.75, while that for consumers (λ) is initially assumed to be zero.[14]

4 Results

I turn now to the impulse responses of inflation and output to monetary shocks. I first consider the implications of using money growth versus Taylor rules for the central bank. In this case, I limit the analysis to the case with purely forward-looking consumers. I then examine the role played by sticky information in consumption, in particular its implications for inflation inertia. Finally, I briefly consider a similar analysis when one replaces the Poisson process for the arrival of information with a fixed duration of information rigidity.

4.1 Money growth vs. Taylor rules

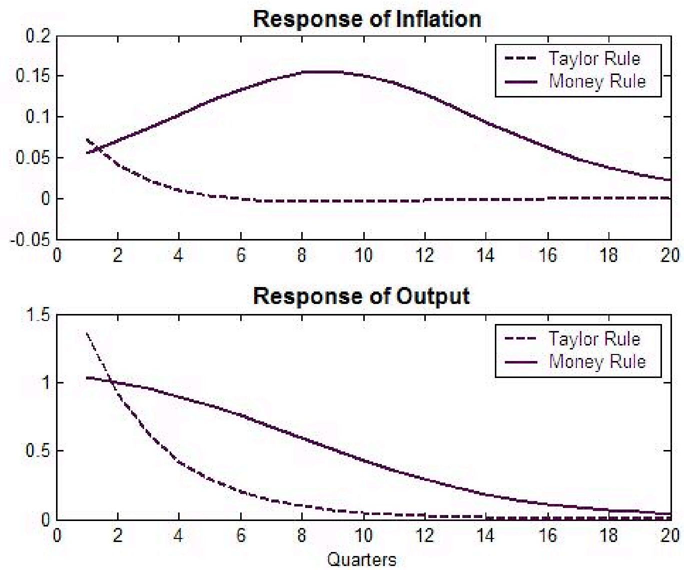
In this section, I focus on the implications of two alternative formulations for the central bank's actions. The first is to assume that the money supply follows an autoregressive process in the growth rate, for which I assume an AR(1) coefficient of 0.5. The second approach follows Taylor (1993) and assumes that the central bank sets interest rates in response to the current state of the economy, as described by equation (21), with a baseline degree of interest rate smoothing of 0.8.

The results are presented in Figure 2. The top panel shows the response of inflation under each policy setting. The difference is stark: whereas inflation is inertial with a money growth rule, it peaks on impact when using the Taylor rule. The critical difference between the two models is the endogenous response of the central bank to higher inflation and output with a Taylor rule. Because the central bank seeks to reduce inflation and output, positive inflation and output lead to higher real interest rates than is the case with a money growth rate rule. This causes output to fall rapidly, despite the fact that the interest smoothing parameter is relatively high at 0.8. As discussed in section 2, to have inflation inertia, it is critical that the output gap not go to zero too rapidly, else firms have little incentive to change prices when they learn about the shock.

Figure 3 considers the time of the peak response of inflation with a Taylor rule for different levels of interest smoothing and other parameter values. With the benchmark set of parameters, inflation inertia can occur if the degree of interest smoothing is sufficiently high. Increasing the persistence of the shock yields a more gradual adjustment of output, making inflation inertia a more likely outcome. Similarly, higher values of σ (or lower values of the intertemporal

[14] When λ is subsequently allowed to be positive, I will consider different values of ϕ.

Figure 2: Taylor rules vs. money growth rules

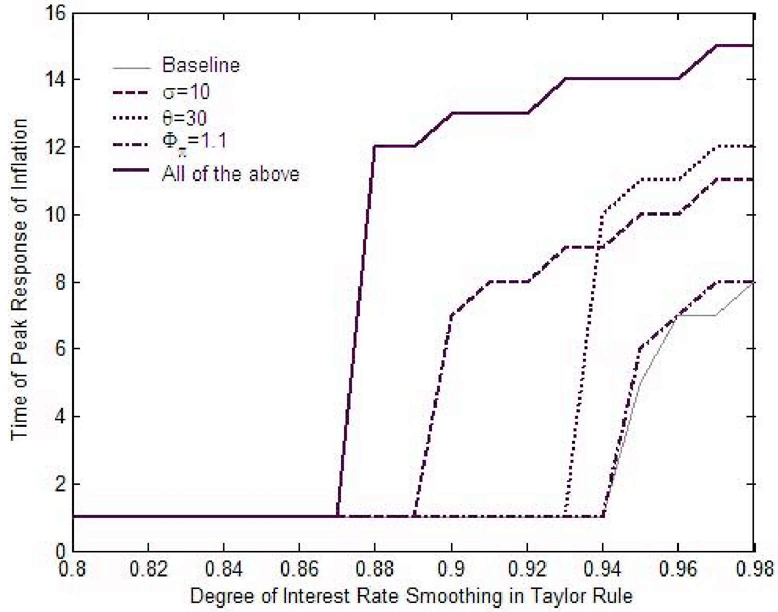


Note: The figure plots impulse responses of output and inflation to a one-unit shock to the money growth rate and the Taylor rule in the model described in section 3. All parameter values are at the baseline levels.

elasticity of substitution) lead to slower responses of output, thereby allowing inflation inertia for sufficiently persistent shocks to the interest rate. Lower levels of Φ_π also help generate inflation inertia, since the central bank reacts less to inflation. Finally, higher levels of θ, by raising the strategic complementarity in price setting, allow for inflation inertia to appear at lower levels of interest smoothing. Nonetheless, even when all of these elements are added (σ=10, θ=30, $\Phi_\pi = 1.1$), inflation inertia is not present unless the degree of interest smoothing is about 0.9.

At the root of the problem is the central bank's endogenous response combined with forward-looking consumers. The latter, by "frontloading" the response of output to a monetary shock, make it difficult for inflation to respond slowly to a shock since aggregate demand is highest on impact. But this is also counterfactual. Empirically, the response of output to monetary shocks is delayed, though less so than that of inflation. The lack of inflation inertia for typical parameter values in this setting may thus simply reflect the failure of the model to generate sufficient inertia in output.

Figure 3: Time of peak inflation with a Taylor rule for alternative parameter values



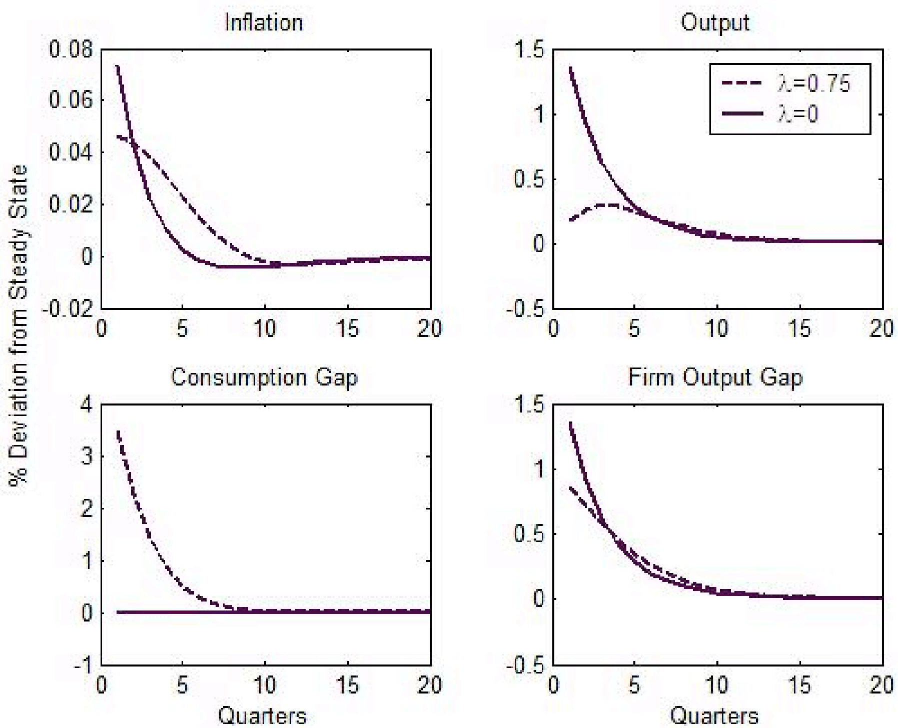
Note: Figure 3 displays the time at which inflation achieves its maximum value for alternative rates of interest smoothing (ρ_i) in the Taylor rule. The shock is assumed to occur at $t=1$. The first (Baseline) line represents the baseline parameter values. The following three lines represent a single deviation from baseline values. The final line includes the three previous deviations from baseline parameter values.

4.2 Forward-looking vs. sticky information consumers

I now turn to the implications of including sticky information in consumption when monetary policy is characterized by a Taylor rule. To do so, one must now calibrate the degree of information rigidity for consumers as well as the degree of strategic complementarity in consumption ϕ. For information rigidity, I follow Carroll (2003) who uses survey data and finds that the diffusion of information from professional forecasters to consumers approximately follows a Poisson process with λ=0.75. I then assume as a baseline value that ϕ=0.15, so that strategic complementarity in consumption is approximately the same as that in price setting. While admittedly ad-hoc, a low value of ϕ is qualitatively similar to the high estimated values of external habits. I will later consider alternative values in sensitivity analysis.

The top two panels of figure 4 present the response of inflation and output to a shock to the Taylor rule (ρ_i=0.8) when there is either no sticky information in

Figure 4: Response of the sticky information model to a shock to the Taylor rule with sticky information for consumers



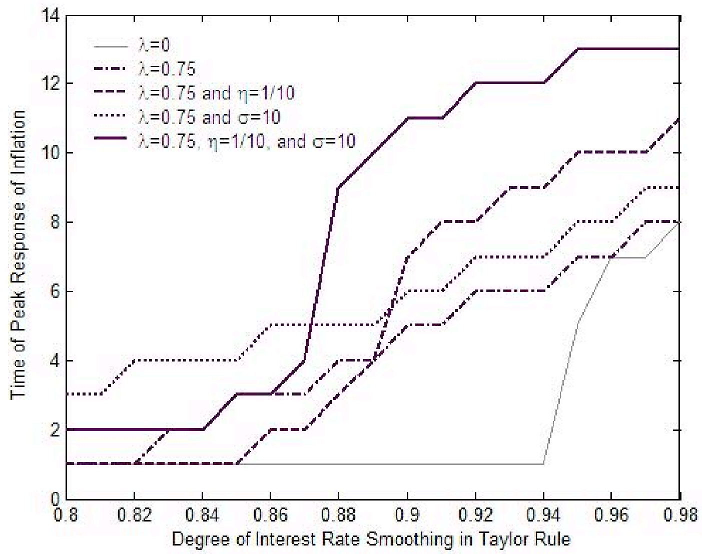
Note: This figure shows impulse responses of economic variables to a unit shock to the interest rate for baseline parameter values, with the addition of sticky information consumers (*λ=0.75*) and strategic complementarity in consumption assumed to be *ϕ=0.15*. The Consumption Gap and Firm Output Gap are described in the text.

consumption (λ=0) or equal amounts of information rigidity for firms and consumers (μ=λ=0.75). Note first that adding sticky information to consumption has the desired effect of generating inertia in output. The impact effect on output of an interest rate shock is small, and output follows a hump-shaped response that peaks 2 quarters after the shock. However, there is still no inflation inertia, though inflation does respond more slowly than when there is no information rigidity for consumers.

To see why this is the case, one must consider the effect of sticky information for consumers on the firm's price setting decision. Specifically, we can rewrite equation (17) as

$$p_{t,t-k}^{\#} = E_{t-k}\left[p_t + \alpha\left(x_t^N + \left(\frac{\eta}{1+\eta\sigma} \right) x_t^c \right) \right] \tag{22}$$

Figure 5: Sensitivity of inflation inertia with Taylor rule and sticky information for consumers

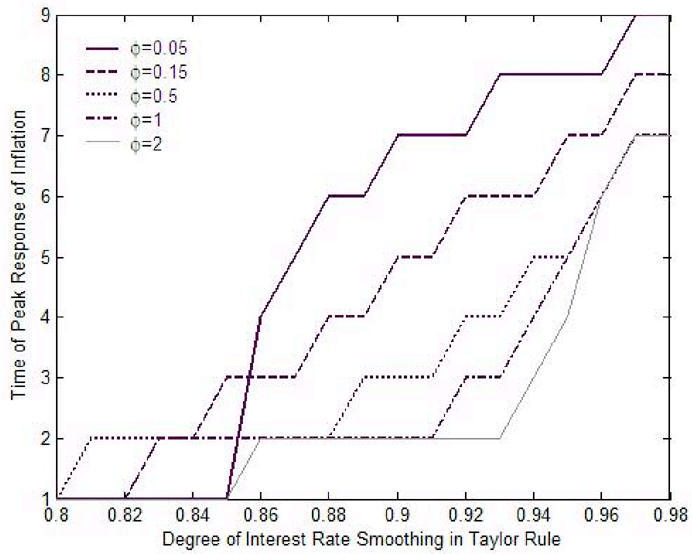


Note: The figures displays the time at which inflation peaks after a shock to the interest rate for different levels of interest smoothing and varying parameter values with sticky information in consumption. The shock occurs at *t=1*.

In response to a monetary shock, the natural output gap simply follows output. However, the firm output gap, which is what matters for price setting decisions, is also a function of the consumption gap. This is because the consumption gap affects the optimal labor supply decision. The consumption gap depends on the marginal utility of wealth χ_t relative to that of consumption. Since the MU of wealth is a purely forward-looking process (because the representative agent has full information) whereas consumption is sticky (because of the information rigidity of subagents), the consumption gap jumps on impact and follows an AR(1) type time path, as illustrated in the bottom left panel of Figure 4. The firm output gap x_t^f, being the weighted sum of the natural output gap and the consumption gap, is dominated by the movements in the consumption gap and so also follows an AR(1) type time path. Because it converges more slowly to the steady state than when there is no information rigidity for consumers, inflation also adjusts more slowly. However, inflation inertia requires a slower adjustment still.

Figure 5 presents some sensitivity analysis for the degree of inflation inertia as measured by the time of the peak response of inflation. Note first that simply including sticky information for consumers does make inflation inertia a

Figure 6: Sensitivity of inflation inertia to strategic complementarity in consumption



Note: The figure displays the time at which inflation peaks after a shock to the interest rate for different levels of interest smoothing and varying degrees of strategic complementarity in consumption (ϕ) assuming λ=0.75.

more common response to interest rate shocks, but is not enough to delay the response of inflation for ρ_i=0.8. Figure 5 also shows that lower values of the IES or the Frisch labor supply elasticity make inflation inertia a more likely outcome. The reason is found in equation (22). Lower values of η or higher values of σ will slow down the adjustment of the firm output gap by lowering the weight placed on the consumption gap. Figure 6 illustrates the effect of different values of ϕ. Overall, lower levels of ϕ, by yielding slower responses of consumption, help raise the probability of observing inflation inertia. When $\phi \geq 1$, sticky information for consumers has little effect on the likelihood of inflation inertia occurring relative to the case with information rigidity for firms only.

4.3 Staggered information updating vs. Poisson arrival rates

Dupor and Tsuruga (2005) argue that the results of MR are sensitive to the assumption about the timing of information updates. Replacing the Poisson arrival rate with a fixed duration scheme (*a la* Fischer (1977)), they find that the persistence of output is lower and the response of inflation less realistic than those found in MR. To see this, consider the price level when firms update their expectations every N periods

$$p_t = \frac{1}{N}\sum_{j=0}^{N-1} p^{\#}_{t,t-j} \,. \tag{23}$$

Assuming that the shock occurs at time t=1, then all firms have the same information at time N. Thus the price level is $p_N = p^{\#}_{N,N}$ which implies $y_N = 0$ when aggregate demand is represented by a quantity equation. Thus nominal income shocks have no real effects beyond the duration of the information rigidity. We must also have $p_N = m_N$. If the price level adjusts slowly in the first *N-1* periods, then the price level must jump up to m_N at time N, leading to a spike in inflation rather than the gradual hump-shape response in MR.

Because of this difference in results, I also examine the implications of using fixed durations of information rigidity in the model presented in section 3. Thus equation (23) replaces equation (18) for the price level. In addition, I also allow for fixed durations of information rigidity in consumption, so that equation (14) is replaced by

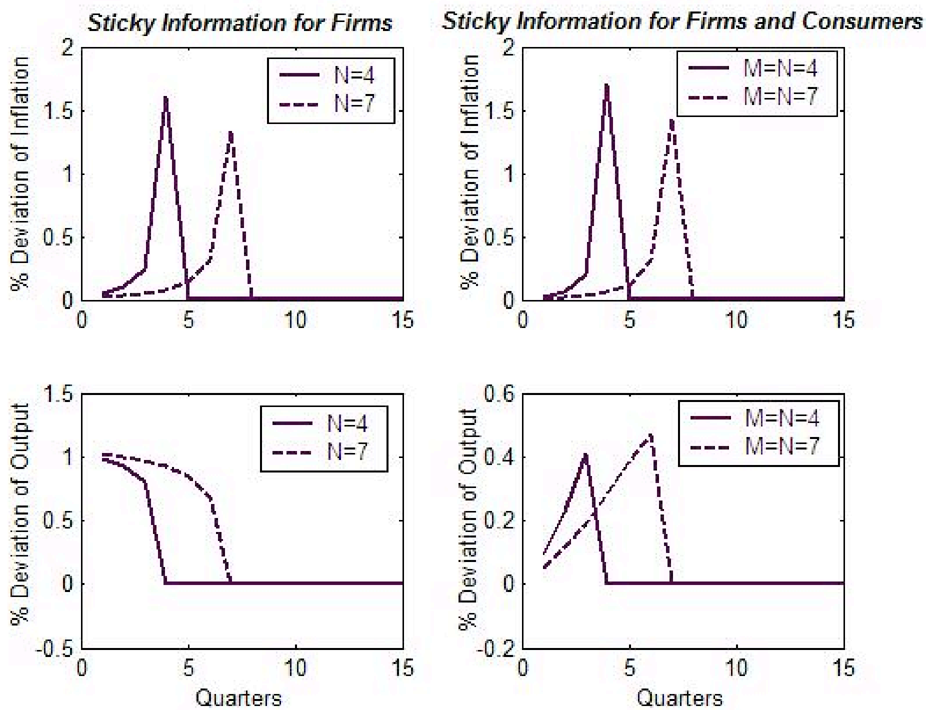
$$c_t = \left(\frac{1}{M}\right)\sum_{j=0}^{M-1} c^{\#}_{t,t-j} \tag{24}$$

where M is the duration of information rigidity in consumption. The choice of values for M and N is open to interpretation. If we seek to match the average duration of information rigidity to that of the Poisson process, then N=4 is equivalent to μ=0.75. On the other hand, if one wishes to match the cross-sectional average age of information, then this would imply N=7. I consider both values for comparison.

Figure 7 presents the responses of inflation and output for the case in which the central bank follows a money growth rule. All parameters are at their baseline levels. The two panels on the left have information rigidity for firms only, whereas those on the right have information rigidity for consumers as well. In all cases, inflation peaks at t=N and output goes to zero at that time. When only firms have sticky information, the peak response of output is instantaneous because of the forward-looking behavior of consumers. Adding sticky information to consumers provides a more gradual response of output to monetary shocks, but does not alter the qualitative response of inflation.

Figure 8 presents the same responses in the case of Taylor rule for interest rates. Again, inflation peaks at t=N and output goes to zero at that time. Sticky information for consumers is again effective at yielding a more hump-shape response of output than with forward-looking consumers. Thus, whereas the choice of a money growth or Taylor rule could alter the qualitative response of inflation with Poisson arrival rates of information, in the case of fixed durations of information rigidity the sticky information model appears to generate inflation inertia, the peak response of which is determined by the value of N.

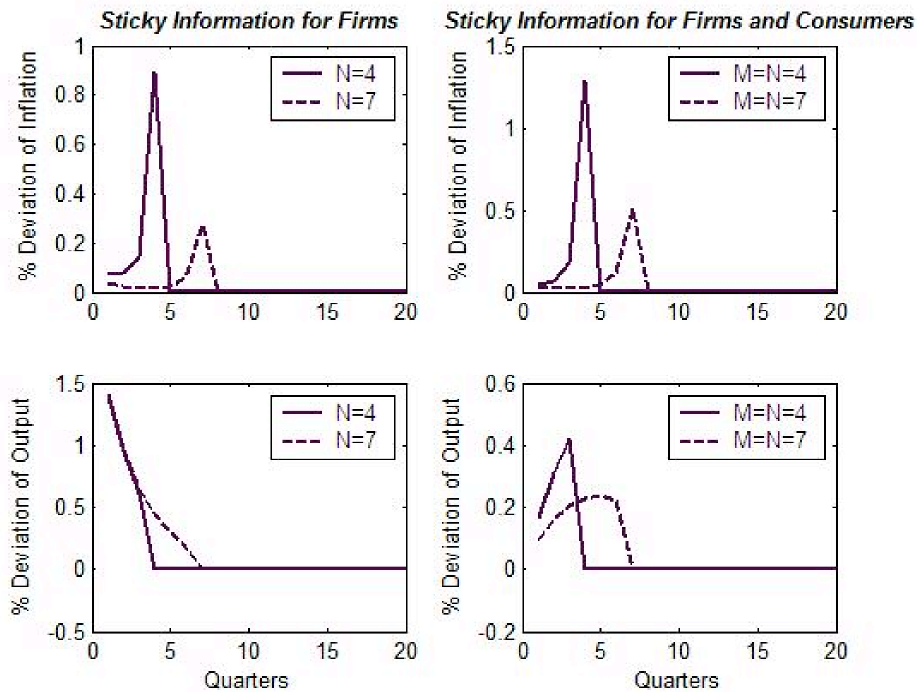
Figure 7: Response of the sticky information model with staggered information updating to a money growth shock



Note: This figure displays the impulse response of the sticky information model of section 3 in which the Poisson process for the arrival of information is replaced by fixed intervals. The shock is assumed to occur at $t=1$. N and M are the number of quarters firms and consumers, respectively, maintain the same information set. The shock is to the money growth rule. Strategic complementarity in consumption is $\phi=0.15$. All other parameters are at their baseline values.

Nonetheless, there remains a difference in the impact effect on inflation. With sticky information for firms only, inflation is rising immediately after the shock with a money growth rule, whereas it is falling with a Taylor rule. This occurs through the same mechanisms as with Poisson arrival rates, but these effects are overwhelmed by the jump in the price level when all firms acquire the same information and output is driven to zero. This will be the case as long as strategic complementarity in price setting is sufficiently high to keep initial changes in prices small relative the change in prices that must occur when information rigidity ends. Figure 9 plots the response of inflation when N=7 and M=1 with a Taylor rule for different levels of α (generated by changing the value of θ as necessary). For the baseline value of α=0.15, we have a very small impact effect on inflation, followed by a gradual decline due to the endogenous response of the central bank. This is followed by a large spike in inflation at $t=N$. With α=0.5, the impact effect is larger, though still somewhat less than the $t=N$ spike.

Figure 8: Response of the sticky information model with staggered information updating to a shock to the Taylor rule



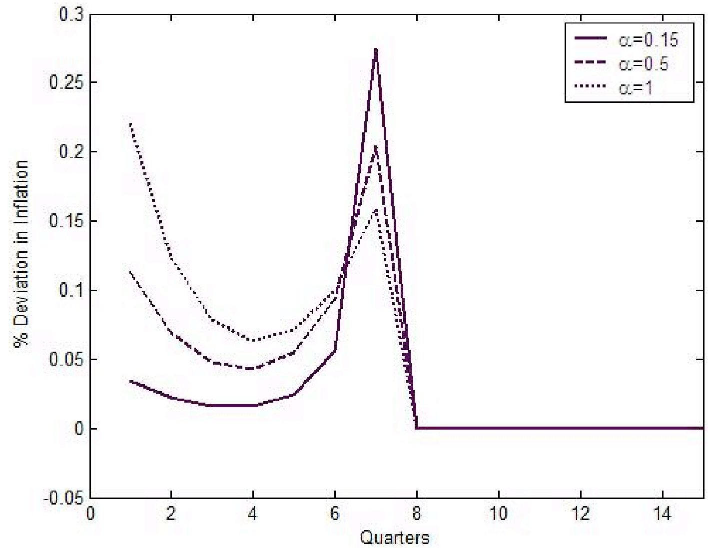
Note: This figure displays the impulse response of the sticky information model of section 3 in which the Poisson process for the arrival of information is replaced by fixed intervals. The shock is assumed to occur at *t=1*. *N* and *M* are the number of quarters firms and consumers, respectively, maintain the same information set. The shock is to the Taylor rule. Strategic complementarity in consumption is $\phi=0.15$. All other parameters are at their baseline values.

Finally, with neither strategic complementarity nor substitutability in price setting (α=1), the peak response of inflation occurs on impact. While inflation still rises at $t=N$, this spike is now smaller than the impact effect.

5 Discussion and relation to the previous literature

This paper has focused on the determinants of inflation inertia in the sticky information model. Particular emphasis has been placed on the role of strategic complementarity in price setting, which matters not just for the persistence of real effects as in sticky price models, but also for the qualitative "hump-shaped" response of inflation. The results have shown that integrating the sticky information approach into more developed aggregate demand settings can affect the model's ability to deliver inflation inertia. In particular, the assumption of

Figure 9: Sensitivity of inflation response under fixed duration of information rigidity for firms and a Taylor rule.



Note: This figure shows the response of inflation to a one-unit shock to the Taylor rule in the model of section 3, but where the Poisson process for the arrival of information is replaced with a fixed duration between information updates (the length of which is $N=7$). There is no sticky information for consumers and all parameters are at their baseline levels.

forward-looking consumers and a Taylor rule to capture the endogenous response of consumers and policy-makers makes inflation inertia hard to deliver for typical parameter values. Including sticky information for consumers can help yield output inertia and therefore makes it easier to achieve inflation inertia, but the results remain very sensitive to parameter values. These results are useful to sort the conflicting results found in previous papers regarding the robustness of MR's original findings.

Closest to MR is Reis (2005) whose primary purpose is to develop microfoundations for the time-dependent sticky information model of MR. After showing that aggregating across firms facing costs to the acquisition of information leads to a Poisson process for the arrival of information at the aggregate level, he presents a model in which labor is supplied individually to firms and applies the SIPC to this setup. As emphasized by Woodford (2003), this approach generates strategic complementarity in price setting for standard parameter values. In his case, this leads to α=0.11, nearly the same value as in MR. Since aggregate demand is modeled as in MR, his results closely replicate those of MR.

Keen (2004) considers a more general model with utility-maximizing consumers, a money demand equation, and shocks to the growth rate of money. Unlike Reis (2006), he assumes that labor and capital are supplied to aggregate factor markets, from which all firms do their hiring and renting. This yields, for most parameter values, strategic substitutability in price setting (α>1). In response to money growth shocks, Keen finds that the sticky information model leads to immediate jumps in inflation unless the persistence of money growth shocks is much higher than estimated values. With Taylor rules, he finds that the sticky information model is incapable of generating inflation inertia. His results are thus largely due to the absence of "enough" strategic complementarity in price setting, which follow from his assumption of economy-wide input markets. The assumption of purely forward-looking consumers also makes it harder for his model to deliver inflation inertia.

Trabandt (2005) and Korenok and Swanson (2004) each consider a similar model to Keen (2004), but one in which labor is individually supplied to firms, thereby generating significant strategic complementarity in price setting. Their models also include forward-looking consumers and a money demand equation combined with an exogenous AR(1) process for the growth rate of money. As argued in section 4.1, this combination can generate inflation inertia in response to a money growth shock despite the presence of forward-looking consumers, as conclude both papers. Hence, the different assumptions about factor markets, and therefore strategic complementarity in price setting, lead these authors to reach a very different conclusion than Keen (2004).

Andres et al (2005) estimate a dynamic model with a sticky information Phillips Curve by full information maximum likelihood. They use their parameter estimates to consider the response to a shock to the Taylor rule. Given their parameter estimates, real marginal costs adjust very rapidly in response to the shock, a result equivalent to having little strategic complementarity in price setting. Despite having substantial internal habit formation in the consumption Euler equation, the response of inflation to a temporary shock to the interest rate is immediate. This result is similar to that found in section 4.2, where even the presence of sticky information consumers is insufficient to yield inflation inertia in response to an interest rate shock unless there are significant strategic complementarities in both consumption and price setting, a feature absent in their parameter estimates.

Collard and Dellas (2004) follow Dupor and Tsuruga (2005) in using fixed durations of information rigidity. Aggregate demand consists of forward-looking consumers and a money demand equation with monetary policy described by a money growth rule. Like Keen (2004), they assume economy-wide labor and capital markets, implying α>1 for their parameter values. They find that the peak response of inflation to monetary shocks is immediate. As shown in section 4.3,

Table 1: Summary of whether previous studies found inflation inertia using sticky information models

<table>
<tr><th></th><th></th><th colspan="2">Price Setting Behavior</th></tr>
<tr><th></th><th></th><th>Strategic Complements</th><th>Strategic Substitutes</th></tr>
<tr><td rowspan="2">Policy Response</td><td>Exogenous Process</td><td>Mankiw Reis (2002): YES
Reis(2004): YES
Trabandt(2005): YES
Korenok Swanson (2004): YES</td><td>Keen (2004): NO</td></tr>
<tr><td>Endogenous Response</td><td></td><td>Keen (2004): NO
Collard Dellas (2004): NO
Andres et al (2005): NO</td></tr>
</table>

Note: Yes/No indicates whether author(s) found inflation inertia in response to monetary shock. Exogenous process for policy response includes money growth rules and exogenous nominal income growth processes. Endogenous response means Taylor rule.

this result hinges again upon the implied level of strategic complementarity in price setting.

I summarize the results of these previous studies in Table 1. The critical role played by strategic complementarity in price setting is clear in the results found. Unfortunately, all of the papers that find an inertial response of inflation in response to monetary shocks do so in response to money growth or nominal income growth shocks but do not explicitly model the endogenous response of monetary policy-makers. Section 4.1 shows that the remaining box in the table has no clear-cut answer and the results are highly sensitive to parameter estimates.

6 Conclusion

This paper considers whether the sticky information model of MR can robustly deliver inflation inertia. It identifies strategic complementarity in price setting as a critical determinant for observing gradual hump-shape responses of inflation in response to monetary shocks. In addition, integrating the SIPC into more developed models of aggregate demand leads to contradictory conclusions, even in the presence of real rigidities. Whereas money growth rules combined with forward-looking consumers yield responses that closely resemble the original results of MR, the inclusion of a Taylor rule designed to capture the endogenous response of monetary policy-makers generally produces a time path of inflation that peaks in the same period as the shock occurs. The addition of sticky information in consumption yields an inertial response of output and increases the parameter space in which inflation can be inertial. However, under the baseline parameters considered in the model, inflation continues to peak on impact in response to an interest rate shock. These results allow us to sort out the conflicting conclusions drawn by previous studies regarding the robustness of MR's findings.

Because of the sensitivity of the sticky information model for firms to the assumptions of the rest of the model, future work should consider more carefully the implications of sticky information for other sectors of the economy. One of the attractive features of the sticky information model is that if information delays exist for firms, they should matter for other sectors of the economy, such as factor markets. This paper considers one such extension for consumers, but the approach used here could feasibly be extended to wage setting decisions.[15] More interesting still would be applying sticky information to the investment decisions of firms, since investment is typically considered to be the primary mechanism through which interest rate changes affect the economy.

[15] See Mankiw and Reis (2005) for a model with sticky information in price and wage-setting as well as consumption.

Appendix 1: The Identical Response of the SIPC and NKPC to Permanent Level Shocks to M

Suppose the money supply is m_t=*-log(0.9)* for all $t<0$ and is zero for all $t \geq 0$.[16] M-R show that the solution for the time path of prices under sticky-information is[17]

$$p_t = \frac{\left(-\log 0.9\right)\mu^{t+1}}{1-(1-\alpha)\left(1-\mu^{t+1}\right)} \tag{A1.1}$$

so that when α=1, this reduces to

$$p_t = \left(-\log 0.9\right)\mu^{t+1}. \tag{A1.2}$$

They also show that the solution for the time path of prices under sticky prices is[18]

$$p_t = \theta p_{t-1} + (1-\theta)^2 \sum_{i=0}^{\infty} \theta^i E_t\, m_{t+i} \tag{A1.3}$$

where $0<\theta<1$ and

$$\frac{\left(1-\theta\right)^2}{\theta} = \frac{\alpha\left(1-\lambda\right)^2}{\lambda}. \tag{A1.4}$$

Note that when $\alpha=1$, $\theta=\lambda$. Then plugging in the time path of money into (A1.3) and extrapolating it forward (for $t>0$), it is easy to show that it reduces to (A1.2) when $\mu=\lambda$. The time path of output must be identical since it is determined by the quantity equation.

Appendix 2: Deriving the Sticky Information IS Curve

From the text, we have that the linearized consumption must follow

$$c_t = \left(1-\lambda\right)\sum_{j=0}^{\infty} \lambda^j c_{t,t-j},$$

which combined with (9) and (10) yields

$$c_t = \frac{\left(1-\lambda\right)}{\lambda}\phi x_t^C + \left(1-\lambda\right)\sum_{j=0}^{\infty} \lambda^j c_{t,t-1-j}. \tag{A.2.1}$$

This can be rewritten as

$$c_t = \frac{\left(1-\lambda\right)}{\lambda}\phi x_t^C - c_{t-1} + \left(1-\lambda\right)\sum_{j=0}^{\infty} \lambda^j \left(c_{t,t-1-j} - c_{t-1,t-1-j}\right). \tag{A.2.2}$$

[16] I use the same money supply numerical examples as in M-R as they simplify the math but WLOG.
[17] Like M-R, I assume throughout that the economy is in steady state.
[18] The underlying NKPC is $\pi_t = E_t\pi_{t+1} + \frac{(1-\lambda)^2\alpha}{\lambda} y_t$ where 1-λ is the fraction of firms who change prices each quarter.

Note that $c_{t,t-1-j} - c_{t-1,t-1-j} = E_{t-1-j}\left[\left(1-\sigma\phi\right)\Delta c_t + \phi\left(i_{t-1} - \pi_t\right)\right] \equiv E_{t-1-j}\Psi_t$. Then (A.2.2) can also be rewritten as

$$x_t^C = \frac{\lambda}{\left(1-\lambda\right)\phi}\Delta c_t - \frac{\lambda}{\phi}\sum_{j=0}^{\infty}\lambda^j E_{t-1-j}\Psi_t \tag{A.2.3}$$

and, taking the one period ahead expectation,

$$E_t x_{t+1}^C = \frac{\lambda}{\left(1-\lambda\right)\phi}E_t\Delta c_{t+1} - \frac{\lambda}{\phi}\sum_{j=0}^{\infty}\lambda^j E_{t-j}\Psi_{t+1}\,. \tag{A.2.4}$$

Taking the difference between (A.2.4) and (A.2.3) yields

$$E_t\Delta x_{t+1}^C = \frac{\lambda}{\left(1-\lambda\right)\phi}E_t\Delta^2 c_{t+1} - \frac{\lambda}{\phi}\sum_{j=0}^{\infty}\lambda^j\left[E_{t-j}\Psi_{t+1} - E_{t-1-j}\Psi_t\right] \tag{A.2.5}$$

From the text we also had

$$E_t\Delta x_{t+1}^C = -\sigma E_t\Delta c_{t+1} + i_t - E_t\pi_{t+1}\,. \tag{A.2.6}$$

Multiplying both sides of (A.2.6) by ϕ and adding $E_t\Delta c_{t+1}$ to both sides yields

$$\mathrm{E}_t\Psi_{t+1} = \phi E_t\Delta x_{t+1}^C + E_t\Delta c_{t+1} \tag{A.2.7}$$

Then substituting (A.2.7) and (A.2.6) into (A.2.5) and rearranging yields equation (15) in the text.

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