Staggered Price-Setting, Staggered Wage-Setting, and Business Cycle Persistence*

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Abstract

Staggered price-setting and staggered wage-setting are commonly viewed as similar mechanisms in generating persistent real effects of monetary shocks. In this paper, we distinguish the two mechanisms in a dynamic stochastic general equilibrium framework. We show that, although the dynamic price-setting and wage-setting equations are alike, a key parameter governing persistence is linked to the underlying preferences and technologies in different ways. With reasonable parameter values, the staggered price mechanism by itself is incapable of, while the staggered wage mechanism plays an important role in generating persistence.

Key Words: Staggered contracts; Business cycle persistence; Monetary policy

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1. Introduction

How monetary policy shocks affect business cycle duration has been a challenging issue concerning economists and policy makers. Recent empirical studies reveal that monetary policy shocks can have long-lasting effects on aggregate activities (e.g., Gali (1992) and Christiano, et al. (1999)). Yet, it has been a difficult task to identify monetary transmission mechanisms that can generate such effects.[1]

In a seminal paper, Taylor (1980) proposes a mechanism to help solve the persistence issue. In his model, firms and unions do not synchronize their wage-setting decisions. Once a nominal wage is set, it remains fixed for a short period of time such as a year, that is, nominal wage-setting decisions are staggered. In a recent survey, Taylor (1999) presents a wide range of empirical evidence for the staggering of wage-setting and price-setting. Taylor (1980) shows that staggered wage-setting can lead to endogenous wage inertia and thereby persistence in employment movements following a temporary shock. He states the intuition as follows:

> Because of the staggering, some firms will have established their wage rates prior to the current negotiations, but others will establish their wage rates in future periods. Hence, when considering relative wages, firms and unions must look both forward and backward in time to see what other workers will be paid during their own contract period. In effect, each contract is written relative to other contracts, and this causes shocks to be passed on from one contract to another . . . contract formation in this model generates an inertia of wages which parallels the persistence of unemployment.

More recently, Chari, Kehoe, and McGrattan (CKM) (2000) carry this intuition to a general equilibrium environment. They find, perhaps surprisingly, that a staggered *price* mechanism by itself cannot generate persistent real effects of monetary shocks, an apparent puzzle in light of Taylor's insights. There are two interpretations of this puzzle. On one hand, CKM (2000) suggest that it is difficult to explain persistence based on staggered nominal contracts in a general equilibrium framework, and therefore "mechanisms to solve the persistence problem must be found elsewhere." On the other hand, Taylor (1999) conjectures that the findings of CKM (2000) "may indicate that the monopolistic competition (stationary market power) model may not be sufficient as a microeconomic foundation." Behind

[1] Although models with information lags and price stickiness are shown to be quite successful in generating output fluctuations driven by monetary shocks, the resulting effects are usually contemporaneous rather than persistent. See, for example, Lucas (1972), Lucas and Woodford (1993), Rotemberg (1996), and Yun (1996).

the two lines of arguments seems to be a common perception that a staggered price mechanism and a staggered wage mechanism have similar implications on persistence: either that they both contribute to generating persistence or that neither does so.[2]

The purpose of this paper is to suggest a third interpretation of the persistence puzzle. We find that, in a general equilibrium environment, staggered wage-setting can have quite different implications on persistence than staggered price-setting. With reasonable values of parameters in preferences and technologies, staggered price-setting by itself is incapable of, while staggered wage-setting has a great potential in generating real persistence even when the underlying price- and wage-setting rules are derived from the standard monopolistic competition framework. The two types of staggering mechanisms have different implications because the key parameter that governs persistence in the dynamic price-setting and the dynamic wage-setting equations is here a function of the underlying parameters in preferences and technologies of the economy. Although the two equations are apparently identical, this functional form and thereby the value of the persistence parameter differ in general across the two mechanisms.

To compare the implications on persistence of the two types of staggering mechanisms, we build on Blanchard and Kiyotaki (1987) and construct a dynamic stochastic general equilibrium model that features monopolistic competition in both the goods market and the labor market, with firms setting nominal prices for their products and households setting nominal wages for their labor skills. We derive the households' wage-setting and the firms' price-setting rules from their optimizing decisions and thus link these decision rules to the underlying preferences and technologies in the model. We show that a critical parameter governing persistence is the elasticity of relative wage (or price) with respect to aggregate demand in the wage (or price) equation. A greater value of this parameter corresponds to less persistence because it implies a greater response of wage (or price) decisions to aggregate demand shocks, and thus a faster adjustment of the wage (or price) index and a quicker return of aggregate output to steady state. When wage-setting decisions are staggered, the elasticity of relative wage with respect to aggregate demand is *less* than one under plausible parameter values, and it decreases with both the elasticity of substitution between differentiated labor skills in the production technology and the degree of relative risk aversion in labor hours in households' preferences. In contrast, when pricing decisions are staggered, the elasticity of relative price with respect to aggregate demand is typically

[2]This view has recently been emphasized by Taylor (1999), who states that "the equations are essentially the same for wage setting and price setting."

greater than one, and it increases with the degree of relative risk aversion in labor hours. Consequently, the staggered wage mechanism tends to generate persistence but the staggered price mechanism does not.

To understand the driving forces of these results, we compare the optimal responses of households and firms to a monetary shock with the two different types of nominal rigidities. When wage-setting decisions are staggered, imperfectly competitive households choose nominal wages to balance the expected marginal utility of leisure and of wage income within the duration of their wage contracts, taking into account the effects of the wage decisions on the demand for their labor services and thus their wage incomes as well. When an expansionary monetary shock occurs, the wage index does not increase proportionally because of the staggering of wage-setting decisions. The price level does not rise fully either, since profit maximization requires that prices equal a constant markup over the marginal cost determined by the wage index. Therefore, real aggregate demand rises, raising both households' income and firms' demand for labor services. The higher income reduces the households' marginal utility of income and the higher labor demand raises their marginal utility of leisure. Utility maximization requires that households who can renew contracts raise wages to re-balance their marginal utility of income and of leisure. Given that wage decisions are staggered, however, an increase in a household's nominal wage leads to an increase in its relative wage and a higher relative wage reduces both the demand for the corresponding type of labor services (substitution effect) and the associated wage income (income effect), which in turn lowers the marginal utility of leisure and raises the marginal utility of income. Both effects serve to restore the balance between the marginal utility of income and of leisure, and thus the optimal increase in relative wages is small. We find that, within a reasonable range of parameter values, the optimal percentage increase in relative wages is typically less than the percentage increase in aggregate demand. In consequence, the wage index rises slowly, and movements in aggregate output and employment are gradual and long-lasting. Moreover, the easier to substitute across labor skills and the more willing the households to smooth labor hours, the smaller the optimal wage adjustment and the greater the magnitude of output persistence. If we measure the magnitude of persistence by the ratio of output response at the end of the initial contract duration to that in the impact period (i.e., a "contract multiplier"), this ratio can be as high as 56% under reasonable parameter values.

The staggered price mechanism works differently. Under this mechanism, imperfectly competitive firms choose prices to maximize expected profits within the duration of their price contracts, taking into account the effects of the pricing decisions on the demand for their goods and thus their revenues as well. We show that the optimal price is a linear function of a firm's expected marginal costs within its contract duration. Thus a higher price will be set if the firm is expecting higher marginal costs. Staggered price-setting allows an expansionary monetary shock to raise real aggregate demand and thus firms' demand for labor services as well. Facing higher real income and greater demand for its labor skill, each household responds by raising its nominal wage accordingly. The increase in real wage and hence in the real marginal cost in this case is much sharper than in the case with staggered wage-setting because here, all wage decisions are synchronized and thus a higher nominal wage does not lead to a higher relative wage and it does not reduce the household's labor hours or its wage income. With reasonable parameter values, the equilibrium percentage increase in real wage will exceed the increase in aggregate demand, causing marginal cost to rise by more than aggregate demand does. In response, profit-maximizing firms will fully adjust their prices whenever they have a chance to renew contracts. Consequently, movements in aggregate output and employment, after their initial responses to the shock, are fast and transitory. In contrast to the staggered wage model, the contract multiplier is here negative for reasonable parameter values.

The inability of staggered price-setting *by itself* to generate real persistence raises a natural question: are there important interactions between the nominal rigidity in the form of staggered price-setting and some forms of real rigidity that may potentially contribute to generating persistence? To answer this question, we construct a model with real rigidity in the form of labor market segmentation. The model features a large number of firms producing differentiated products, each using a combination of differentiated labor skills that are specific to the firm. To derive price-setting and wage-setting rules, we assume again that there is monopolistic competition in the goods market and in the labor market within each sector. We find that introducing labor market segmentation does not change the implications of the staggered wage-setting mechanism on aggregate dynamics, but it does improve the ability of the staggered price-setting mechanism to generate persistent real effects of money. Under staggered wage-setting, firms make identical pricing decisions in a symmetric equilibrium and the equilibrium dynamics are therefore identical to those with a fully integrated labor market. Under staggered price-setting, the immobility of labor across firms creates a disincentive for firms to change their prices rapidly. In particular, with immobile labor, a rise in a firm's relative price reduces the demand for its workers, which in turn reduces the marginal disutility of working for those households who work for the firm and hence the need to raise their real wages. In consequence, the price adjustments are sluggish and the response of aggregate output is persistent. In this case, the magnitude of output persistence under staggered wage-setting does not necessarily exceed that under staggered price-setting. Yet, in a very natural baseline case as we have discussed above, staggered wage-setting in general has a greater potential in generating real persistence than does staggered price-setting. And under reasonable parameter values, the two types of staggering mechanisms are embodied with significantly different persistence implications.

There are several strands of literature that are related to our work. Following the lead of CKM (2000), there has been a growing literature on persistence, focusing on interactions between the nominal rigidity in the form of staggered price-setting and various forms of real rigidity. For example, Bergin and Feenstra (2000) show that the interactions between staggered price-setting and the real rigidity introduced through a non-CES aggregation technology and a roundabout input-output structure help generate real persistence; Kiley (1997) demonstrates that a high degree of increasing returns at the individual firm level helps produce persistence in a staggered price model; and Gust (1997) emphasizes that impediments to factor mobility across sectors contribute to propagating monetary shocks. Following the seminal work of Blanchard and Kiyotaki (1987) and Blanchard (1986), attempts have also been made to model staggered wage contracts in a dynamic general equilibrium environment. For example, Erceg (1997) analyzes a model with both staggered price and staggered wage contracts and studies the role of this double staggering mechanism in propagating monetary shocks, while Huang and Liu (1999) show that, in the absence of real rigidity, adding a staggered price mechanism on top of a staggered wage mechanism does not help magnify persistence. The work by Cho, Cooley, and Phaneuf (1997) evaluates the welfare effect of nominal wage contracts. The persistence issue has also been examined in general equilibrium models with state-dependent pricing rules. Dotsey, King, and Wolman (1999) provide a general equilibrium framework for analyzing the implications of state-dependent price-setting rules. Dotsey, et. al (1997) show that staggered price-setting can arise in a model with menu costs, and incorporating variable capacity utilization in such a model helps deliver persistence. The issue of real persistence is paralleled by the issue of inflation persistence. Ball (1994) demonstrates that, while the standard Taylor type of nominal contracts can potentially generate persistence in aggregate output and the price level, it encounters difficulties in generating persistence in the inflation rate. Ball (1995) shows that imperfect credibility of the central bank may help resolve the inflation persistence problem. Fuhrer and Moore (1995) find that a model with staggered contracts in relative wages (instead of nominal wages) can generate substantial inflation persistence. In summary, there has been a renewed interest in examining the role of staggered nominal contracts and their interactions with various forms of real rigidity in propagating monetary shocks (see also the survey by Taylor (1999)). Yet, little has been done to explore the microstructures that may distinguish the staggered wage mechanism from the staggered price mechanism. In this paper, we fill this gap by distinguishing the two mechanisms in their capabilities of generating persistence in a dynamic general equilibrium environment.

It is important to emphasize that we do not attempt to propose a single friction that is able to fully account for the dynamic output responses to monetary shocks. In fact, the recent work by Christiano, Eichenbaum, and Evans (1997) and Huang, Liu, and Phaneuf (2000) suggests that it is unlikely for a single-friction model to provide a complete account of the real effects of monetary shocks. To provide such an account may require a combination of frictions. Our work suggests that, in such a multi-friction model, staggered wage contracts can be an important contributing mechanism.

The rest of the paper is organized as follows. Section 2 illustrates the conventional wisdom on the equivalence of staggered price-setting and staggered wage-setting based on a simplified version of Taylor's (1980) model, briefly describes the CKM (2000) persistence puzzle, and demonstrates the difference in the key persistence parameter under the two types of staggering mechanisms. Section 3 formally explores the different implications of the two types of nominal rigidities in a fully specified dynamic general equilibrium model. Section 4 evaluates the robustness of the main results by allowing for capital accumulation in the model. Section 5 examines the interactions between the real rigidity in the form of labor market segmentation and the nominal rigidity associated with each of the two types of staggering mechanisms. Section 6 concludes the paper. The Appendix describes the baseline model with capital accumulation.

2. The conventional wisdom and the persistence puzzle

In a reduced form model, Taylor (1980) shows that staggered wage-setting is able to generate persistent fluctuations in employment and aggregate output following a temporary aggregate demand shock. The conventional wisdom holds that staggered wage-setting and staggered price-setting should have similar implications on the dynamics of aggregate output and the price level. Based on this perception, CKM (2000) try to carry Taylor's intuition into a general equilibrium environment by examining the ability of staggered price-setting (rather than staggered wage-setting) to generate output persistence when pricing rules are explicitly derived from individuals' optimizing behaviors. They find, perhaps surprisingly, that the staggered price mechanism by itself does not generate output persistence. In what follows, we show that the conventional wisdom about the equivalence of staggered price-setting and staggered wage-setting does not hold in general. With reasonable values of parameters in preferences and technologies, staggered wage-setting has a much greater potential in generating real persistence than does staggered price-setting.

2.1. The conventional wisdom

The conventional wisdom suggests that staggered price-setting has similar implications on aggregate dynamics as staggered wage-setting. The intuition is based on the following pair of models in the spirit of Taylor (1980).[3]

Model 1 (staggered price-setting):

In each period, a fraction $1/N$ of firms can set prices, and in doing so, they take into account the prevailing price which is an average of the N contractual prices determined in the current and the previous $N-1$ periods. Therefore, when setting new prices, firms look at both the future and the past pricing decisions because these are part of the prevailing price. When $N=2$, the model with staggered price-setting is described by the following equations:

$$\bar{p}_t = \frac{1}{2}(p_t + p_{t-1}), \tag{1}$$

$$p_t^* = \bar{p}_t + \gamma y_t, \tag{2}$$

$$p_t = \frac{1}{2}(p_t^* + \mathrm{E}_t p_{t+1}^*), \tag{3}$$

where $\bar{p}_t$ denotes the prevailing price level, p_t is the price set in period t for t and $t+1$, p_t^* is the price a firm would set if it could set it just for period t, y_t is aggregate output, and E_t is a conditional expectation operator based on information available up to date t. All variables are in log-terms.

Model 2 (staggered wage-setting):

In a model with staggered wage-setting, pricing decisions are synchronized. Thus, the price level is equal to each individual firm's price, which is in turn given by a constant markup over the nominal wage index. The following equations describe the model with staggered wage-setting:

$$\bar{P}_t = P_t = \mu_p \bar{W}_t, \tag{4}$$

$$\bar{w}_t = \frac{1}{2}(w_t + w_{t-1}), \tag{5}$$

[3] The authors are grateful to an anonymous referee for suggesting the style of exposition here.

$$w_t^* = \bar{p}_t + \gamma y_t, \tag{6}$$

$$w_t = \frac{1}{2}(w_t^* + \mathrm{E}_t w_{t+1}^*). \tag{7}$$

In these equations, the upper case variables $\bar{P}_t$, P_t, and W_t denote the price level, the price decision, and the wage index in level-terms while the lower case variables are in log-terms. The variable w_t is the wage set in period t for t and $t+1$ and w_t^* is the wage a household would set if it could set it just for period t.

Equation (4) says that the price P_t is a constant markup over the wage index $\bar{W}_t$ (with a markup parameter given by $\mu_p > 1$). Thus, given that firms' pricing decisions are synchronized, the price level is proportional to the wage index. Inspecting the two models reveals that if the value of the parameter γ did not depend on whether it is price-setting or wage-setting that is staggered, then the two models would imply the same aggregate dynamics.

2.2. The output dynamics and the persistence puzzle

In both models, a key parameter governing aggregate dynamics is γ. Equations (2) and (6) suggest that a greater value of γ implies a more sensitive response of price-setting or wage-setting decisions to changes in aggregate demand, thus faster adjustments in prices and wages, and a shorter-lived response of aggregate output. To generate output persistence requires a small value of γ. In this sense, the dynamic issue of persistence hinges upon the static issue of how small γ is.

To illustrate the role of γ in generating persistence, we solve the models by assuming a money demand equation given by $y_t = m_t - \bar{p}_t$, where m_t denotes the logarithm of the money stock. By combining equations (2) and (3) (or equations (6) and (7)), we obtain

$$x_t = \frac{1}{2}(\bar{p}_t + \mathrm{E}_t \bar{p}_{t+1}) + \frac{\gamma}{2}(y_t + \mathrm{E}_t y_{t+1}), \tag{8}$$

where x_t corresponds to p_t in the model with staggered price-setting (Model 1) or to w_t in the model with staggered wage-setting (Model 2). The system can then be reduced to a second order difference equation in x_t by substituting for $\bar{p}_t$ and y_t using (1) and the money demand equation, respectively. Under an additional assumption that m_t follows a random walk process, a simple solution to this difference equation can be obtained, and the implied output dynamic equation is given by

$$y_t = a y_{t-1} + \frac{1+a}{2}(m_t - m_{t-1}), \quad \text{where} \quad a = \frac{1-\sqrt{\gamma}}{1+\sqrt{\gamma}}. \tag{9}$$

Here, two special cases are noteworthy: if $\gamma = 1$, then $a = 0$ and there is no persistence; if $\gamma = 0$, then $a = 1$ and the output follows a random walk process. In general, a smaller γ corresponds to a greater value of a and hence a more persistent movement in aggregate output. The model can generate persistence if and only if $\gamma < 1$.

Equation (9) reveals that if γ is a structural parameter void of any distinctions between staggered price-setting and staggered wage-setting, then the two models are apparently identical, an observation that forms the basis of the conventional arguments. Yet, in a general equilibrium environment, γ is no longer a structural parameter. It is instead determined by fundamental parameters in preferences and technologies. An important question is then, with plausible values of the fundamental parameters and with γ so determined, can a model with staggered price (or wage) contracts generate persistent fluctuations in aggregate output? CKM (2000) try to answer this question and conclude that staggered *price*-setting does not generate output persistence because the magnitude of γ so determined is too large for empirically plausible parameter values. Based on this conclusion, it is commonly inferred that a dynamic general equilibrium model with staggered *wage*-setting cannot generate persistence either.

2.3. Different persistence implications of staggered price-setting and staggered wage-setting

Our main finding in this paper is that, in a general equilibrium environment, the value of γ depends on whether it is price-setting or wage-setting that is staggered. Thus, the two types of staggering mechanisms have different implications on the dynamic effects of monetary shocks on the price level and aggregate output. The formal model will be presented in Section 3. Here we summarize the results and highlight the difference in γ between the two mechanisms.

To illustrate our points, we assume that the period-utility function is given by $U(C) - V(L)$, where C and L denote consumption and labor hours, and the usual Inada conditions hold.[4] Given this utility function, we show that, under staggered price-setting, the key persistence parameter γ is given by

$$\gamma_p = \xi_c + \xi_l, \tag{10}$$

where $\xi_c \equiv -U''C/U' > 0$ and $\xi_l \equiv V''L/V' > 0$ are relative risk aversion with respect to consumption and labor hours, respectively, both evaluated at steady state. On the other hand, under staggered wage-setting, γ is given by

$$\gamma_w = \frac{\xi_c + \xi_l}{1 + \theta_w \xi_l}, \tag{11}$$

[4] In the formal model presented in Section 3, we assume that real money balances enter individuals' utility function. Here, it is not essential to have money in the utility function because we have assumed a static money demand equation, an assumption that we will relax in Section 4.

where $\theta_w > 1$ is the elasticity of substitution between labor skills. It follows immediately that the conventional wisdom fails to hold in general. Particularly, since $\gamma_w \leq \gamma_p$ in light of (10) and (11), it is more likely to generate persistence under staggered wage-setting than is under staggered price-setting.

Indeed, with empirically plausible parameter values, staggered wage-setting tends to generate persistence while staggered price-setting does not. The parameter ξ_c corresponds to the relative risk aversion with respect to consumption. The general consensus is that the value of ξ_c is between 1 and 10, and it is typically set to 1 or slightly larger in most business cycle literature (e.g., Prescott (1986)). The parameter ξ_l corresponds to the inverse of the intertemporal elasticity of substitution in labor hours. Most empirical literature suggests that this elasticity is less than one, or equivalently, $\xi_l > 1$ (e.g., Pencavel (1986)). The parameter θ_w corresponds to the elasticity of substitution between differentiated labor skills. Available empirical evidence suggests a value of θ_w between 2 and 6 (see, for example, Griffin (1992, 1996)).[5] With $\xi_l > 1$, γ_p is necessarily greater than one so that, under staggered price-setting, the response of output oscillates around steady state and there is no persistence. In contrast, γ_w is less than one provided that $\xi_c < 1 + (\theta_w - 1)\xi_l$, a condition that holds for a broad range of plausible parameter values (e.g., it holds with $\xi_c = 1$, corresponding to log-utility in consumption). In consequence, under staggered wage-setting, the response of output is gradual and long-lasting.

Although from a purely theoretical point of view, it is possible to have both γ_p and γ_w less or greater than one, this requires extreme values of the fundamental parameters. For example, if ξ_c and ξ_l are both sufficiently small, then we can have $\gamma_w \leq \gamma_p < 1$. In this case, both types of staggering can generate persistence. On the other hand, if ξ_c is sufficiently large, then we can have $\gamma_p \geq \gamma_w > 1$. In this case, neither staggered price-setting nor staggered wage-setting leads to persistence.

To summarize, the conventional wisdom on the equivalence of staggered price-setting and staggered wage-setting can be justified only under extreme parameter values. In general, the two types of staggering mechanisms are embodied with different persistence implications. While the staggered price mechanism by itself is incapable of, the staggered wage mechanism has a much greater potential in generating real persistence.

[5]The estimate of θ_w by Griffin (1992, 1996) is based on firm level data representing different industries. As noted by Griffin (1992), the estimate tends to be biased downward for two reasons: (i) all firms in the data set are subject to Affirmative Action which restricts labor substitutability, and (ii) the employment data does not include employee characteristics such as workers' age, experience, and education. Griffin (1996) shows that, when Affirmative Action is explicitly accounted for, the estimate of θ_w is about 6.

3. A dynamic general equilibrium model with staggered contracts

In this section, we present a dynamic general equilibrium model and derive optimal price-setting and wage-setting rules. We then solve a log-linearized version of the model's equilibrium decision rules and show that staggered price-setting and staggered wage-setting have in general different implications on aggregate dynamics.

3.1. The model

The economy is populated by a large number of households and firms. There is a government conducting monetary policy. To derive firms' price-setting and households' wage-setting rules, we assume monopolistic competition in both the goods market and the labor market. In each period t, the economy experiences a realization of shocks s_t, while the history of events up to date t is $s^t \equiv (s_0, \cdots, s_t)$ with probability $\pi(s^t)$. The initial realization s_0 is given.

Each household is endowed with a differentiated labor skill indexed by $i \in [0, 1]$. The preferences of household i are represented by the utility function

$$\sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi(s^t) \left\{ U(C^*(i, s^t)) - V(L(i, s^t)) \right\}, \tag{12}$$

where $\beta \in (0, 1)$ is a discount factor, $C^*(i, s^t) \equiv [bC(i, s^t)^\nu + (1 - b)(M(i, s^t)/\bar{P}(s^t))^\nu]^{1/\nu}$ is a CES composite of consumption and real money balances, and $L(i, s^t)$ denotes hours worked. In each period t and each event s^t, the household faces a budget constraint given by

$$\begin{aligned} \bar{P}(s^t)C(i, s^t) + \sum_{s^{t+1}} D(s^{t+1}|s^t)B(i, s^{t+1}) + M(i, s^t) \leq \\ W(i, s^t)L^d(i, s^t) + \Pi(i, s^t) + B(i, s^t) + M(i, s^{t-1}) + T(i, s^t), \end{aligned} \tag{13}$$

where $B(i, s^{t+1})$ is i's holdings of a nominal bond that costs $D(s^{t+1}|s^t)$ dollars at s^t and pays one dollar in period $t + 1$ if s^{t+1} is realized, $W(i, s^t)$ is a nominal wage of i's labor skill, $L^d(i, s^t)$ is a demand schedule for i's labor, $\Pi(i, s^t)$ is its share of profits, and $T(i, s^t)$ is a lump-sum transfer it receives from the government.

The consumption good is a Dixit-Stiglitz (1977) composite of differentiated goods. It is given by

$$C(i, s^t) = \left[\int_0^1 C(i, j, s^t)^{\frac{\theta_p - 1}{\theta_p}} dj \right]^{\frac{\theta_p}{\theta_p - 1}}, \tag{14}$$

where $\theta_p > 1$ is the elasticity of substitution between the goods. Minimizing the expenditure $\int_0^1 P(j)C(i,j)dj$ on all goods subject to (14) yields the demand function of i for good j:

$$C^d(i,j,s^t) = \left(\frac{P(j,s^t)}{\bar{P}(s^t)}\right)^{-\theta_p} C(i,s^t), \tag{15}$$

where the price index is given by $\bar{P}(s^t) = \left(\int_0^1 P(j,s^t)^{1-\theta_p} dj\right)^{\frac{1}{1-\theta_p}}$. The total demand of all households for good j is the sum of all individual demand. That is,

$$Y^d(j,s^t) \equiv \int_0^1 C^d(i,j,s^t)di = \left(\frac{P(j,s^t)}{\bar{P}(s^t)}\right)^{-\theta_p} Y(s^t), \tag{16}$$

where $Y(s^t) \equiv \int_0^1 C(i,s^t)di$ denotes the aggregate demand for the composite good.

Each good $j \in [0,1]$ is produced using a composite of all types of labor skills as an input. The production function is

$$Y(j,s^t) = L(j,s^t), \quad \text{with} \quad L(j,s^t) = \left[\int_0^1 L(j,i,s^t)^{\frac{\theta_w - 1}{\theta_w}} di\right]^{\frac{\theta_w}{\theta_w - 1}}, \tag{17}$$

where $\theta_w > 1$ is the elasticity of substitution between differentiated labor skills. Minimizing the labor cost $\int_0^1 W(i)L(j,i)di$ subject to (17) results in the demand function of firm j for labor skill i:

$$L^d(j,i,s^t) = \left[\frac{W(i,s^t)}{\bar{W}(s^t)}\right]^{-\theta_w} L(j,s^t), \tag{18}$$

where $\bar{W}(s^t) = \left[\int_0^1 W(i,s^t)^{1-\theta_w} \, di\right]^{\frac{1}{1-\theta_w}}$ is a wage index. The total demand of all firms for labor skill i is thus given by

$$L^d(i,s^t) = \left[\frac{W(i,s^t)}{\bar{W}(s^t)}\right]^{-\theta_w} L(s^t), \tag{19}$$

where $L(s^t) \equiv \int_0^1 L(j,s^t)dj$ denotes the aggregate demand for the composite labor skill.

Households are price takers in the goods market and monopolistic competitors in the labor market. They set wages for their labor skills, taking the labor demand schedule (19) as given. On the other hand, firms are wage takers in the labor market and monopolistic competitors in the goods market. They set prices for their products, taking the goods demand schedule (16) as given.

We are interested in the dynamic effects of monetary policy on aggregate output fluctuations. For this purpose, we assume that newly created money is distributed to all households via lump-sum transfers so that $\int_0^1 T(i,s^t)di = M(s^t) - M(s^{t-1})$.

An equilibrium in this economy consists of allocations $C(i,s^t)$, $M(i,s^t)$, and $B(i,s^{t+1})$ and wages $W(i,s^t)$ for household $i \in [0,1]$; allocations $Y(j,s^t)$ and $L(j,s^t)$ and prices $P(j,s^t)$ for firm $j \in [0,1]$, together with prices $D(s^{t+1}|s^t)$, $\bar{P}(s^t)$, and $\bar{W}(s^t)$ that satisfy the following conditions: (i) taking the wages and all prices but its own as given, each firm's allocations and price solve its profit maximization problem; (ii) taking the prices and all wages but its own as given, each household's allocations and wage solve its utility maximization problem; (iii) money market and bond market clear; and (iv) monetary policy is as specified.

In what follows, we focus on a symmetric equilibrium in which all households in a given wage-setting cohort make identical wage decisions and all firms in a given price-setting cohort make identical pricing decisions. Since there are complete contingent bond markets, equilibrium consumption flows and real money balances are identical across all households.[6] Combining this observation with the market clearing conditions, we have $C(i,s^t) = \int_0^1 C(i,s^t)di \equiv Y(s^t)$ and $M(i,s^t) = M(s^t)$ for all i.

We now derive the optimal price-setting and wage-setting rules. In each period t, a fraction $1/N_p$ of firms can set new prices and a fraction of $1/N_w$ of households can set new wages. Once a price (or wage) is set, it remains fixed for N_p (or N_w) periods. We denote by N the duration of price or wage contracts.

Under staggered price contracts, all firms are divided into $N_p = N$ cohorts based on the timing of their pricing decisions while households synchronize their wage decisions (i.e., $N_w = 1$). If firm j can set a new price in period t, it solves

$$\text{Max}_{P(j,s^t)} \quad \sum_{\tau=t}^{t+N-1} \sum_{s^\tau} D(s^\tau|s^t)[P(j,s^t) - \bar{W}(s^\tau)]Y^d(j,s^\tau), \tag{20}$$

[6]We assume, without loss of generality, that the initial wealth is identical across households. Thus, with the complete insurance provided by the contingent bonds, equilibrium consumption flows and real money balances will also be identical across households. Yet, as pointed out by an anonymous referee, a move from a complete-insurance economy to a no-insurance one would potentially lead to different equilibrium dynamics because, with incomplete insurance, households' consumption will in general depend on their own incomes that may differ across households when wage decisions are staggered. An important question is whether such a move will fundamentally change our main results. To solve a model with no insurance, however, we need to keep track of a non-degenerate income distribution among households on a period-by-period basis. This will make analytical solutions impossible and also pose enormous computational difficulties. In fact, in our view, developing techniques to solve such a model would be the subject of a paper in itself. Given that our objective is to clarify a common perception about the equivalence between the two types of staggering mechanisms and that existing literature focuses on full-insurance economies, we choose to articulate our points with a full-insurance model. We believe that a model of staggered wage-setting with incomplete insurance is an extremely important subject for future research.

subject to (16). The resulting optimal pricing rule is given by

$$P(j, s^t) = \frac{\theta_p}{\theta_p - 1} \frac{\sum_{\tau=t}^{t+N-1} \sum_{s^\tau} D(s^\tau|s^t)\bar{W}(s^\tau)Y^d(j, s^\tau)}{\sum_{\tau=t}^{t+N-1} \sum_{s^\tau} D(s^\tau|s^t)Y^d(j, s^\tau)}. \tag{21}$$

Thus a firm's optimal price is a constant markup over a weighted average of marginal costs within the duration of price contracts, where the marginal cost is given by the nominal wage index since the firm's production requires all types of labor as inputs. If a firm can set a new price and expects a rise in its marginal cost, it will respond by setting a higher price for the entire contract duration.

Similarly, under staggered wage contracts, all households are divided into $N_w = N$ cohorts based on the timing of their wage-setting decisions while firms synchronize their pricing decisions (i.e., $N_p = 1$). If a household can set a new wage, its utility maximization problem will include a choice with respect to its nominal wage. The optimal wage decision rule derived from the first order conditions for the household's problem is given by

$$W(i, s^t) = \frac{\theta_w}{\theta_w - 1} \frac{\sum_{\tau=t}^{t+N-1} \sum_{s^\tau} \beta^{\tau-t}\pi(s^\tau|s^t)(-V_l(i, s^\tau))L^d(i, s^\tau)}{\sum_{\tau=t}^{t+N-1} \sum_{s^\tau} \beta^{\tau-t}\pi(s^\tau|s^t)[U_c(i, s^\tau)/\bar{P}\,(s^\tau)]L^d(i, s^\tau)}, \tag{22}$$

where $-V_l(i, s^\tau)$ and $U_c(i, s^\tau)$ denote the marginal utility of leisure and of consumption, $L^d(i, s^\tau)$ is the demand function for household i's labor skill given by (19), and $\pi(s^\tau|s^t) = \pi(s^\tau)/\pi(s^t)$ is the conditional probability of s^τ given s^t, for $\tau \geq t$. Therefore, the household's optimal wage is a constant "markup" over the ratio of weighted marginal utilities of leisure to marginal utilities of income within the duration of wage contracts, with the weights given by normalized demand for its labor services. If the household expects an increase in the marginal utility of leisure or a fall in the marginal utility of income within the next N periods, it will respond by setting a higher nominal wage.

3.2. A comparison of the two types of staggering mechanisms

To gain further insights into the dynamic wage-setting and pricing decision rules, we log-linearize the decision rules around a deterministic steady state. The linearized version of the price-setting equation (21) is given by

$$p_t = \sum_{j=1}^{N-1} b_j p_{t-j} + \mathrm{E}_t \sum_{j=1}^{N-1} b_j p_{t+j} + \frac{\gamma_p}{N-1} \mathrm{E}_t \sum_{j=0}^{N-1} y_{t+j}, \tag{23}$$

where the lower-case variables denote log-deviations of the corresponding upper-case variables from their steady state values and the event argument s^t is replaced by the time subscript t to save notations. We have also set $\beta = 1$ to simplify the expressions. The weights on lagged and forward prices in (23) are given by $b_j = \frac{N-j}{N(N-1)}$ and the coefficient γ_p in front of current and future outputs is a parameter determined by fundamental parameters in preferences and technologies. Similarly, by setting $\beta = 1$, the log-linearized version of the wage-setting equation (22) can be written as

$$w_t = \sum_{j=1}^{N-1} b_j w_{t-j} + \mathrm{E}_t \sum_{j=1}^{N-1} b_j w_{t+j} + \frac{\gamma_w}{N-1} \mathrm{E}_t \sum_{j=0}^{N-1} y_{t+j}, \tag{24}$$

where the weights b_j are the same as in (23) and γ_w is a parameter that is linked to preference and technology parameters, not necessarily in the same way as is γ_p.

The intertemporal backward- and forward-looking effects emphasized by Taylor (1980) are reflected by the weights b_j on the lagged and forward prices or wages. Obviously, such intertemporal effects are identical across the two types of staggering mechanisms. The distinctions between the two mechanisms lie with the distinctions between γ_p and γ_w, the elasticity of relative price and relative wage with respect to the expected changes in future outputs.

In a simple model of staggered contracts such as Taylor's (1980), it is presumed that $\gamma_p = \gamma_w$ so that the linearized price-setting and wage-setting rules are apparently identical, with appropriate interpretations of notations. This idea forms the basis of the conventional wisdom that staggered price-setting and staggered wage-setting have similar implications on the dynamics for the price level and real output.

In a general equilibrium environment such as the one presented here, the γ's are no longer a structural parameter. They are instead determined by the fundamental parameters in the model. In particular, they are linked to the fundamental parameters in different ways, as in equations (10) and (11). As we have argued there, with empirically plausible values of the fundamental parameters, γ_p is necessarily greater than one so that, in response to a change in aggregate demand, firms quickly adjust their prices whenever they can renew their contracts. Thus, there is no output persistence under staggered price-setting. In contrast, γ_w is less than one for a broad range of plausible parameter values and it decreases with both θ_w, the elasticity of substitution between differentiated labor skills, and ξ_l, the relative risk aversion in labor hours. Thus, the staggered wage mechanism has a great potential in generating real persistence.

To illustrate the intuition behind the different dynamic implications of the two mechanisms, it is helpful to examine the linkage between the γ's and the fundamental parameters in further details. Indeed, as is clear from the price-setting and wage-setting rules in (23) and (24), the dynamic issue of how large the output persistence is hinges upon the static issue of how small the γ's are. Here we adopt an intuitive approach to derive the γ's. A more formal derivation is available upon request.

Under staggered price-setting, the optimal pricing decision depends on the current and future marginal costs within the contract duration, and the marginal cost in each period is determined by the wage index since labor is the only input in production. Given that wages are flexible, the wage index coincides with the individual wage decision in a symmetric equilibrium, and the optimal wage decision rule (22) reduces to

$$\frac{\bar{W}(s^t)}{\bar{P}(s^t)} = \frac{\theta_w}{\theta_w - 1} \frac{-V_l(G(s^t)Y(s^t))}{U_c(Y(s^t))}, \tag{25}$$

where we have used the relations in (16), (17), and (19) to replace $L(i, s^t)$ by $G(s^t)Y(s^t)$, with $G(s^t) \equiv \int_0^1 [P(j, s^t)/\bar{P}(s^t)]^{-\theta_p} dj$, so that the marginal disutility of working depends explicitly on aggregate output. We have also used the goods market clearing condition to replace $C(i, s^t)$ with $Y(s^t)$ and imposed a money demand equation $M(s^t) = \bar{P}(s^t)Y(s^t)$ so that the marginal utility of consumption depends only on aggregate output.

When aggregate demand increases, households face higher demand for their labor skills and hence the marginal disutility of working rises, while with higher income, they consume more and thus the marginal utility of consumption falls. The rise in the marginal disutility of working and the fall in the marginal utility of consumption reinforce each other to induce the households to raise their wages, as shown by equation (25). Since wage decisions are synchronized, a change in an individual household's wage does not affect its relative wage or its hours worked. Therefore, it is only the aggregate demand effect that determines the households' wage decisions. The magnitude of the effect of aggregate demand on real wages is determined by the curvatures of the utility function, and in particular, it is measured by the sum of the relative risk aversion in consumption and the relative risk aversion in labor hours. This can be seen by examining the log-linearized version of (25):

$$\bar{w}_t - \bar{p}_t = (\xi_c + \xi_l)y_t, \tag{26}$$

where ξ_c and ξ_l are the steady state relative risk aversion with respect to consumption and leisure. Thus, a one percent increase in aggregate output leads to a $\xi_c + \xi_l$ percent increase in real wage, and hence in the real marginal cost. If a firm could set a price just for period t, then such a price would also increase by the same percentage. With staggered price-setting, the optimal price is a weighted average of such static pricing decisions. In consequence, the elasticity of the optimal price with respect to aggregate output (i.e., γ_p) is given by $\xi_c + \xi_l$, as in (10).

Under staggered wage-setting, the optimal wage decision is given by (22), which involves current and future marginal disutilities of working and marginal utilities of consumption within the contract duration. To gain intuition, however, it is useful to think of a static "optimal" wage that a household would set if it could set it just for the current period (denote it by $W^*(s^t)$). By imposing $N = 1$ in the dynamic wage decision rule (22), we obtain the static wage decision rule given by

$$\frac{W^*(s^t)}{\bar{W}(s^t)} = \frac{\theta_w \theta_p}{(\theta_w - 1)(\theta_p - 1)} \frac{-V_l((W^*(s^t)/\bar{W}(s^t))^{-\theta_w} Y(s^t))}{U_c(Y(s^t))}, \tag{27}$$

where we have used the equilibrium conditions that $P(j, s^t) = \bar{P}(s^t)$ (since prices are flexible) and that the optimal price is a constant markup over the wage index, so that $\bar{P}(s^t) = \mu_p \bar{W}(s^t)$, with $\mu_p \equiv \theta_p/(\theta_p - 1)$. Other equilibrium conditions we have used to obtain (27) include (16), (17), (19), the market clearing condition $C(i, s^t) = Y(s^t)$ (for all $i \in [0, 1]$), and the money demand equation $M(s^t) = \bar{P}(s^t)Y(s^t)$.

In light of equation (27), there is a similar effect of aggregate demand on households' wage decisions in this case as in the case with staggered price-setting: when aggregate demand rises, the marginal disutility of working will rise while the marginal utility of consumption will fall, forcing the household to raise its wage. One might therefore conjecture that a household's optimal wage should also increase by $\xi_c + \xi_l$ percent for each percentage increase in aggregate demand. But this neglects a key difference between (25) and (27) that lies in the arguments of $-V_l(\cdot)$: Under staggered price-setting, wages are flexible and a change in an individual household's wage affects neither its relative wage nor its hours worked; Under staggered wage-setting, however, a change in a household's nominal wage will result in a change in its relative wage and thus its hours worked. A higher relative wage reduces the household's employed hours and therefore reduces its marginal disutility of working. Through this relative wage effect, the optimal change in a household's wage is less than $\xi_c + \xi_l$ percent. By how much it is less depends on how rapidly the household's employed hours fall as its relative wage rises (measured by θ_w) and on how fast the marginal disutility of working falls as the employed hours fall (measured by ξ_l). Given that the households would like to avoid excessive fluctuations in their employed hours (i.e., $\xi_l > 0$), they choose to keep their wages in line with others.

To make this intuition more transparent, we examine a log-linearized version of equation (27) given by

$$w_t^* - \bar{w}_t = \frac{\xi_c + \xi_l}{1 + \theta_w \xi_l} y_t, \tag{28}$$

which says that a one percent increase in aggregate output leads to a $(\xi_c+\xi_l)/(1+\theta_w\xi_l)$ percent increase in the relative wage. Since the optimal dynamic wage decision w_t in (24) is a weighted average of the static wages $w^*_{t+\tau}$ for $\tau \in \{0, 1, \dots, N-1\}$, we conclude that the elasticity of optimal wage with respect to aggregate output is given by $\gamma_w = (\xi_c + \xi_l)/(1 + \theta_w\xi_l)$, as in (11).

To summarize, under staggered price-setting, firms face quickly changing labor costs and respond by quickly adjusting their prices. In contrast, under staggered wage-setting, a relative wage consideration prevents households from changing their wages too quickly. Therefore, while staggered price-setting is incapable of, staggered wage-setting has a great potential in generating real persistence.

3.3. Some numerical examples

We now illustrate our results in Section 3.2 by considering a commonly used within-period utility function given by

$$U(C^*) - V(L) = \frac{{C^*}^{1-\sigma}}{1-\sigma} - \frac{L^{1+\eta}}{1+\eta}, \tag{29}$$

With this utility function, we have $\xi_c = \sigma$ and $\xi_l = \eta$. The special case with $\sigma = 1$ corresponds to log-utility in consumption, while in the case with $\sigma = 0$, the utility function implies zero income effect in households' wage-setting decisions. In Table 1, we display the contrast between γ_p and γ_w for a plausible range of parameter values with log-utility (the upper panel) and with zero-income-effect utility (the lower panel). The table confirms our conclusion that staggered wage-setting and staggered price-setting in general lead to different persistence implications and that staggered wage-setting tends to generate persistence while staggered price-setting does not.

Table 2 displays the range of parameter values within which staggered wage-setting can generate real persistence (i.e., the conditions under which $\gamma_w < 1$). The table shows that, for given values of θ_w and σ, there always exists a plausible range of η values that allows $\gamma_w < 1$; and for given values of θ_w and η, there is always a plausible range of σ values that permits $\gamma_w < 1$.

4. The model with intertemporal links

To establish the distinctions between the two types of staggering mechanisms in a general equilibrium environment, we have so far abstracted from intertemporal links such as capital accumulation. With no capital, a change in aggregate output implies a one-for-one change in consumption, and thus there may be a substantial income effect in households' wage decisions. With capital, the change in consumption is attenuated and the income effect is weakened. An important question is whether incorporating capital and thus weakening the income effect will overturn the analytical results obtained in the baseline model. We now show that it does not.

To obtain equilibrium dynamics in the model with capital, we first log-linearize the equilibrium conditions under each of the two types of staggering mechanisms, and then solve the linearized system of equations based on calibrated parameters. The details of the model specification and the parameter calibration are described in the Appendix. The calibrated parameter values are summarized in Table 1. All parameter values are standard except for θ_w, the elasticity of substitution among differentiated labor skills. Based on the micro-studies by Griffin (1992, 1996), we conduct our numerical experiments with different values of θ_w ranging from 2 to 6.

In our simulation, we assume that the money supply grows at a rate $\mu(s^t)$, which follows a stationary stochastic process given by

$$\ln \mu(s^t) = \rho \ln \mu(s^{t-1}) + \varepsilon_t, \tag{30}$$

where $0 < \rho < 1$, and ε_t has an i.i.d. normal distribution with zero mean and finite variance. To compute the impulse responses of key variables in the model following a monetary shock, we choose the magnitude of the initial innovation term ε_0 so that the money stock rises by 1% one year after the shock.

Figure 1 plots the impulse response functions of output under the two types of staggering, with four price- or wage-setting cohorts (i.e., $N = 4$). Under staggered price-setting, aggregate output initially rises, and then returns to steady state as soon as the initial contract expires (i.e., one year after the shock). Thus, there is no persistence. This finding is consistent with CKM (2000). In contrast, under staggered wage-setting, the response of aggregate output dies out gradually following its initial increase, and the greater the value of θ_w, the more persistent the output response. To measure the magnitude of persistence, we define a "contract multiplier" as the ratio of the output response at the end of the initial contract duration to that in the impact period. The contract multiplier is negative under the staggered price mechanism whereas it increases from 23% to 43% and then to 56% when θ_w rises from 2 to 4 and then to 6 under the staggered wage mechanism. Thus, when capital is incorporated into the baseline model, our basic conclusion about the distinctions between the two types of staggering mechanisms stands firm: the weakened income effect in households' wage decisions introduced through capital accumulation does not weaken the ability of staggered wage-setting to produce persistence, neither does it overturn the inability of staggered price-setting in generating persistence. This finding is consistent with the numerical results displayed in Table 1, which shows that reducing the income effect to zero through parameter restrictions helps lower the values of both γ_w and γ_p, but for plausible parameter values, it does not reverse the inequality $\gamma_w < 1 \leq \gamma_p$.

Figures 2 and 3 display the impulse responses of the key variables under the two alternative forms of staggering, where we have set $\theta_w = 4$. Under both types of staggering, consumption, investment, and employment are all procyclical; investment is more volatile than output, which is in turn more volatile than consumption; and the nominal interest rate and the inflation rate are both procyclical. These are all standard features of a monetary business cycle model without nominal rigidities (e.g. Cooley and Hansen (1995)). Except for the lack of "liquidity effect," these features are broadly consistent with the business cycle facts in the U.S. economy. Nonetheless, the two types of staggering mechanisms differ in two key aspects. First, the impulse responses of both real and nominal variables under staggered wage-setting are more persistent than those under staggered price-setting. Second, real wage is strongly procyclical when pricing decisions are staggered, while it is weakly countercyclical when wage-setting decisions are staggered. Evidence on the cyclicality of real wage is mixed. As surveyed by Abraham and Haltiwanger (1995), existing empirical studies do not suggest systematically procyclical or countercyclical real wages.[7]

To summarize, the basic insights elaborated by our analytical solutions in Sections 3 stand up to the incorporation of such intertemporal links as capital accumulation and interest-rate-sensitive money demand. While the staggered price mechanism by itself is incapable of, the staggered wage mechanism plays an important role in generating persistence.

5. Interactions between staggered nominal contracts and real rigidities

[7] Although the weak cyclicality of real wages is commonly viewed as a salient feature of the business cycle, recent empirical studies suggest that the cyclical behaviors of real wages depend on the level of data aggregation and on the sources of the shocks. If microdata instead of aggregate data are used, then there is evidence that real wages are procyclical (e.g., Bils (1985) and Solon, Barsky, and Parker (1994)). On the other hand, if the response of real wages to aggregate demand shocks is disentangled from that to aggregate supply shocks, then real wages are countercyclical in response to aggregate demand shocks but procyclical in response to aggregate supply shocks (e.g., Fleishman (1999)). Since monetary shocks are the only driving force of fluctuations in our models, we need to compare the models' predictions on real wage behaviors with the response of real wages to *monetary* shocks in the data to assess the model's empirical relevance. While the work by Bernanke and Carey (1996) suggests countercyclical behaviors of real wages following monetary shocks, the recent study by Christiano, et al. (1999) shows that, in response to monetary shocks, real wages are acyclical or weakly procyclical. One way to induce acyclical real wages in our model is to have pricing and wage decisions both staggered.

The inability of staggered price-setting by itself to generate persistent real effects of money naturally raises the question of whether there are important interactions between the nominal rigidity in the form of staggered price-setting and some forms of real rigidity that may help generate persistence. To provide an answer to this question, we modify the model presented in Section 3 by incorporating a type of real rigidity in the form of labor market segmentation. We find that such a model modification does improve the ability of staggered price-setting to generate output persistence, though it does not change the implications of staggered wage-setting on the dynamics for the price level and aggregate output.

In the model, there is a continuum of firms producing differentiated goods indexed in the interval $[0, 1]$. A firm j's production requires a composite of labor skills that are specific to j, with the production function given by (17). The firm-specific labor skills are differentiated and are supplied by a continuum of households indexed in the interval $[0, 1]$. A different firm uses a different set of labor skills. The utility function of a household i is similar to (12). Based on this model, we consider two types of nominal contracts: one with staggered pricing decisions among all firms, the other with staggered wage decisions among all those households who work for a specific sector.[8]

It is straightforward to verify that the demand schedule for good j is given by (16). The demand schedule for labor skill i that is specific to sector j is given by (18), with $W(i, s^t)$ and $\bar{W}(s^t)$ replaced by $W(j, i, s^t)$ and $\bar{W}(j, s^t)$, respectively, since the labor skill is specific to sector j. Taking the demand schedules as given, each firm sets a price for its product and each household sets a wage for its labor skill. Under staggered price contracts, the optimal price-setting rule is similar to (21) in the model with an integrated labor market, but with the overall wage index $\bar{W}(s^t)$ replaced by a sector specific wage index $\bar{W}(j, s^t)$. Under staggered wage contracts, the optimal wage-setting rule is given by (22), but with $W(i, s^t)$ and $L^d(i, s^\tau)$ replaced by $W(j, i, s^t)$ and $L^d(j, i, s^\tau)$, respectively. The log-linearized price-setting and wage-setting equations are similar to (23) and (24) in the previous model, with possibly different values for the γ's.

Under staggered wage-setting, pricing decisions are flexible so that all firms make identical pricing decisions in a symmetric equilibrium. Thus, staggered wage-setting produces the same equilibrium dynamics as in the case with a fully integrated labor market. In particular, the persistence parameter is here given by

$$\gamma_w^{sl} = \frac{\xi_c + \xi_l}{1 + \theta_w \xi_l}, \tag{31}$$

[8] Although the same equilibrium *price-setting* rules can be obtained in an environment where each firm uses only one type of labor (e.g., Edge (2000)), such an environment is not appropriate for modeling wage-setting behaviors.

which is identical to γ_w in (11). It follows that staggered wage-setting has the same implications on persistence, regardless of whether the labor markets are segmented or not.

The implications of staggered price-setting on aggregate dynamics, however, does depend on whether the labor markets are integrated or segmented. With segmented labor markets, staggered price-setting may also generate persistence. To understand the intuition, we begin with examining the households' wage decision rule. Since wages are flexible, all workers in a given sector make identical wage decisions. The optimal wage-setting rule implies that the real wage, and hence the real marginal cost facing firms in sector j is given by

$$\frac{W(j,s^t)}{\bar{P}(s^t)} = \frac{\theta_w}{\theta_w - 1} \frac{-V_l(L(j,s^t))}{U_c(Y(s^t))} = \frac{\theta_w}{\theta_w - 1} \frac{-V_l\left([P(j,s^t)/\bar{P}(s^t)]^{-\theta_p} Y(s^t)\right)}{U_c(Y(s^t))}, \tag{32}$$

where the second equality follows from the demand schedule (16) and the production function (17). To gain insights, it is useful here to think of a static "optimal" pricing decision rule. In particular, let $P^*(j,s^t)$ denote the price that firm j would set if it could set it just for period t. Then $P^*(j,s^t) = \mu_p W(j,s^t)$, where $\mu_p \equiv \theta_p/(\theta_p - 1)$ is a markup, and equation (32) can be written as

$$\frac{P^*(j,s^t)}{\bar{P}(s^t)} = \frac{\theta_w \theta_p}{(\theta_w - 1)(\theta_p - 1)} \frac{-V_l\left([P^*(j,s^t)/\bar{P}(s^t)]^{-\theta_p} Y(s^t)\right)}{U_c(Y(s^t))}. \tag{33}$$

This equation resembles equation (27), suggesting that staggered price-setting here can also lead to persistence for similar reasons as in the case with staggered wage-setting. Following an aggregate demand shock, firms that can adjust prices will respond by setting a higher price. With immobile labor, however, a rise in a firm's relative price reduces the demand for its workers. This in turn reduces the marginal disutility of working for those households who work for the firm and hence the need to raise their real wages, creating a disincentive for the firm to increase its price, as indicated by equations (32) and (33). How large the disincentive is depends on how fast the employed hours fall as the firm's relative price rises and on how rapid the marginal disutility of working falls as the employed hours fall.

To further demonstrate the similarity between the intuition here and that in the case with staggered wage-setting, we examine a log-linearized version of equation (33)

$$p_t^* - \bar{p}_t = \frac{\xi_c + \xi_l}{1 + \theta_p \xi_l} y_t, \tag{34}$$

which closely resembles equation (28). In response to a one percent increase in aggregate output, the firm's relative price will rise by $(\xi_c + \xi_l)/(1 + \theta_p \xi_l)$ percent. Thus, the key persistence parameter, the elasticity of relative price with respect to aggregate output, is given by

$$\gamma_p^{sl} = \frac{\xi_c + \xi_l}{1 + \theta_p \xi_l}, \tag{35}$$

which is similar to the expression for γ_w in the case with staggered wage-setting. Here, θ_p and ξ_l appear in the denominator of the expression for γ_p^{sl} for reasons similar to the appearance of θ_w and ξ_l in the denominator of γ_w. Since $\gamma_p^{sl} < 1$ for reasonable parameter values, staggered price-setting, when coupled with the labor market segmentation, can generate real persistence.

This section shows that γ_p does not always exceed γ_w in the case with segmented labor markets. Yet, the key result of the paper is that they are in general different and that in a very natural baseline case presented in Section 3, γ_p is unambiguously larger (and larger by wide margin) than γ_w for plausible parameter values.

6. Conclusion

We have shown that, with optimizing individuals, staggered wage contracts and staggered price contracts have in general different implications on persistence. Although the dynamic price-setting and the dynamic wage-setting equations are apparently identical, the key parameter that governs persistence in the two equations is linked to preferences and technologies in different ways, resulting in different predictions on how aggregate output responds to monetary shocks. For plausible parameter values, the staggered price-setting mechanism *by itself* is incapable of, while the staggered wage-setting mechanism plays an important role in generating persistence. The difference between the two mechanisms cannot possibly be uncovered unless individuals' optimizing behaviors are explicitly modelled.

Our analysis has implications not just for staggered nominal contracts, but for other models of nominal rigidity. For example, menu costs are commonly viewed as an important source of nominal price rigidity (e.g., Mankiw (1985) and Akerlof and Yellen (1985)). With small menu costs of adjusting prices, however, some forms of real rigidity are needed for monetary shocks to generate large real effects (e.g., Ball and Romer (1990)). Our analysis suggests that, in a general equilibrium environment, the response of relative wages to aggregate demand shocks in general differs from that of relative prices, and that, in the absence of real rigidity, the nominal wage rigidity (in the form of staggered wage contracts) tends to generate larger real effects than does the nominal price rigidity. For this reason, we suspect that if menu costs are applied to wage-setting, then the nominal wage rigidity (in the form of wage adjustment costs) can be an important mechanism in propagating monetary shocks. Indeed, staggering in nominal contracts and menu costs are closely related. For example, staggering in pricing decisions can arise as an equilibrium outcome when firms face heterogeneous menu costs of adjusting prices (e.g., Dotsey, et al. (1997, 1999)). Similarly, if households (or unions) face a non-degenerate distribution of wage adjustment costs, then it is likely to have endogenous staggering in wage decisions. For the reasons discussed in our current paper, such staggering in wage-setting can potentially lead to large and persistent real effects of money. This possibility is worth investigating in future work.

Appendix. The model with capital accumulation

This appendix presents a model of staggered nominal contracts with capital accumulation. The model is identical to the baseline model presented in Section 3 with two exceptions. First, firms' production requires both labor and capital as inputs. Second, households' problems now involve decisions on capital accumulation.

A.1. The model

We begin with the firms' problems. Each firm $j \in [0,1]$ has access to a Cobb-Douglas production function

$$Y(j,s^t) = K(j,s^t)^{\alpha} L(j,s^t)^{1-\alpha}, \tag{36}$$

where $K(j,s^t)$ is the firm's capital input, $L(j,s^t) = \left[\int_0^1 L(j,i,s^t)^{\frac{\theta_w - 1}{\theta_w}} di\right]^{\frac{\theta_w}{\theta_w - 1}}$ is a composite of labor skills used by the firm, and $\alpha \in (0,1)$ is the share of the capital input. Let $R^k(s^t)$ denote the nominal rental rate on capital. By minimizing the production cost $R^k(s^t)K(j) + \int_0^1 W(i,s^t)L(j,i)di$ subject to (36), we obtain the demand functions for $L(j,s^t)$, $K(j,s^t)$, and $L(j,i,s^t)$. The resulting marginal cost function is $MC(s^t) = \tilde{\alpha}\bar{W}(s^t)^{1-\alpha}R^k(s^t)^{\alpha}$, where $\tilde{\alpha} = \alpha^{-\alpha}(1-\alpha)^{\alpha-1}$. It is straightforward to verify that, under staggered price-setting, the optimal pricing decision rule is given by (21), with $\bar{W}(s^{\tau})$ replaced by the marginal cost function $MC(s^{\tau})$.

We next specify the households' problems. The utility function is the same as in the baseline model. The budget constraint is now given by

$$\begin{aligned} & \bar{P}(s^t)C(i,s^t) + \bar{P}(s^t)I(i,s^t)\left[1 + \phi\left(\frac{I(i,s^t)}{K(i,s^{t-1})}\right)\right] + \sum_{s^{t+1}} D(s^{t+1}|s^t)B(i,s^{t+1}) + M(i,s^t) \\ \leq \quad & W(i,s^t)L^d(i,s^t) + R^k(s^t)K(i,s^{t-1}) + \Pi(i,s^t) + B(i,s^t) + M(i,s^{t-1}) + T(i,s^t), \end{aligned} \tag{37}$$

where $I(i,s^t)$ and $\phi(I(i,s^t)/K(i,s^{t-1}))$ are the investment and the capital adjustment cost of household i in s^t, respectively. Capital accumulation is governed by

$$I(i,s^t) = K(i,s^t) - (1-\delta)K(i,s^{t-1}), \tag{38}$$

where $\delta \in (0,1)$ is a capital depreciation rate.

Household i maximizes utility choosing $C(i,s^t)$, $I(i,s^t)$, $M(i,s^t)$, and $B(i,s^{t+1})$, subject to (37)-(38) and a borrowing constraint $B(i,s^t) \geq -\bar{B}$ for some large positive number $\bar{B}$, taking prices $P(s^t)$, $\bar{W}(s^t)$, $R^k(s^t)$, and $D(s^{t+1}|s^t)$ and initial conditions $K(i,s^{-1})$, $M(i,s^{-1})$, and $B(i,s^0)$ as given. If the household is a member of the cohort that can set new wages, it also chooses a nominal wage $W(i,s^t)$ for the duration of its wage contract. To simplify notations, we denote by $Q(i,s^t)$ the investment-capital ratio $I(i,s^t)/K(i,s^{t-1})$ and by $H(Q)$ the effective cost of capital $1+\phi(Q)+Q\phi'(Q)$. The first order conditions are

$$U_c(i,s^t) = \lambda(i,s^t)\bar{P}(s^t), \tag{39}$$

$$U_m(i,s^t)/\bar{P}(s^t) = \lambda(i,s^t) - \beta \sum_{s^{t+1}} \pi(s^{t+1}|s^t)\lambda(i,s^{t+1}), \tag{40}$$

$$D(s^{t+1}|s^t) = \beta\pi(s^{t+1}|s^t)\lambda(i,s^{t+1})/\lambda(i,s^t), \tag{41}$$

$$\begin{aligned} U_c(i,s^t)H(Q(i,s^t)) = {} & \beta \sum_{s^{t+1}} \pi(s^{t+1}|s^t)U_c(i,s^{t+1})\{R^k(s^{t+1})/\bar{P}(s^{t+1}) + \\ & (1-\delta)H(Q(i,s^{t+1})) + Q(i,s^{t+1})^2\phi'(Q(i,s^{t+1}))\}, \end{aligned} \tag{42}$$

$$\begin{aligned} & \sum_{\tau=t}^{t+N-1} \sum_{s^\tau} \beta^{\tau-t}\pi(s^\tau|s^t)[-V_l(i,s^\tau)]\frac{\partial L^d(i,s^\tau)}{\partial W(i,s^t)} \\ & = \sum_{\tau=t}^{t+N-1} \sum_{s^\tau} \beta^{\tau-t}\pi(s^\tau|s^t)\lambda(i,s^\tau)L^d(i,s^\tau)(1-\theta_w), \end{aligned} \tag{43}$$

where $U_c(i,s^t)$, $U_m(i,s^t)$, and $-V_l(i,s^t)$ denote the marginal utility of consumption, real money balances, and leisure, respectively, $\lambda(i,s^t)$ is the Lagrangian multiplier associated with the budget constraint, and $\pi(s^\tau|s^t) = \pi(s^\tau)/\pi(s^t)$ is the conditional probability of s^τ given s^t, for $\tau \geq t$.

Equations (39)-(42) are standard first order conditions with respect to the household's choice of consumption, money balances, bond holdings, and capital investment, respectively. Equation (43) corresponds to the wage setting rule. The left-hand side of this equation is the expected present value of marginal utility gains due to an increase in wage and thus reduced labor hours during the contract periods, while the right-hand side is the expected present value of marginal utility losses due to unemployed hours and thus a lower wage income. The wage is set to balance the gains and the losses at the margin. Since there are complete contingent asset markets, each household's consumption and money balance decisions depend only on initial distributions of wealth. Without loss of generality, we assume that the initial holdings of wealth are identical across households. This assumption, along with the assumption that consumption and leisure are additively separable in the utility function, implies that the equilibrium consumption and money balances are identical across households for each realization of s^t. That is, $C(i, s^t) = C(s^t)$ and $M(i, s^t) = M(s^t)$. In consequence, $\lambda(i, s^t) = \lambda(s^t)$ for all i, and thus the wage decision rule implied by (43) depends only on aggregate variables.

Capital market clearing requires that $K(s^{t-1}) \equiv \int_0^1 K(i, s^{t-1})\, di = \int_0^1 K(j, s^t)\, dj$, and goods market clearing implies that

$$C(s^t) + I(s^t)\left[1 + \phi\left(\frac{I(s^t)}{K(s^{t-1})}\right)\right] = K(s^{t-1})^{\alpha} L(s^t)^{1-\alpha}. \tag{44}$$

Note that, in each period t, firms' decisions on capital demand are made after the realization of s^t, while the capital stock available for rent is chosen by households in s^{t-1}.

The rest of the optimization conditions is the same as in Section 3. Given the money supply process (30), an equilibrium can be defined analogously. We solve a log-linearized version of the equilibrium decision rules using standard computation methods.[9]

A.2. The calibration

We assume that the capital adjustment cost function is given by $\phi(I/K) = (\psi/2)(I/K)^2$ and the utility function is given by (29). The parameters to be calibrated include the subjective discount factor β, the preference parameters b, ν, and η, the capital share α, the depreciation rate δ, the adjustment cost parameter ψ, the monetary policy parameter ρ, and the parameters θ_w and θ_p in the aggregation technologies. The calibrated values are summarized in Table 1.

In our baseline model, we set $N = 4$ so that a period in the model corresponds to a quarter. Following the standard business cycle literature, we choose $\beta = 0.96^{1/4}$. To assign values for b and ν, we use the implied money demand equation

$$\log\left(\frac{M(s^t)}{P(s^t)}\right) = -\frac{1}{1-\nu}\log\left(\frac{b}{1-b}\right) + \log(C(s^t)) - \frac{1}{1-\nu}\log\left(\frac{R(s^t)-1}{R(s^t)}\right),$$

where $R(s^t) = \left(\sum_{s^{t+1}} D(s^{t+1}|s^t)\right)^{-1}$ is the gross nominal interest rate. The regression of this equation as performed in CKM (2000) implies that $\nu = -1.56$ and $b = 0.98$ for quarterly U.S. data with a sample range from quarter one in 1960 to quarter four in 1995. The serial correlation parameter ρ of money growth rate is set to 0.57, based on quarterly U.S. data on M1 from quarter three in 1959 to quarter two in 1995 (see also CKM (2000)).

[9] The details of computation methods are available from the authors upon request.

We next choose $\alpha = 0.33$ and $\delta = 1 - 0.92^{1/4}$ so that the baseline model predicts an annualized capital-output ratio of 2.6 and an investment-output ratio of 0.21. The parameter η is set to 2, corresponding to an intertemporal elasticity of substitution in labor hours equal to 0.5, which is consistent with most empirical labor literature. We adjust ψ so that the model predicts a standard deviation of aggregate investment that is 3.23 times as large as that of output, in accordance with the U.S. data. Following CKM (2000), we set $\theta_p = 10$ in the staggered price model, corresponding to a steady state markup of 11%. Based on the micro-studies by Griffin (1992, 1996), we consider values of θ_w in the range from 2 to 6.

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Table 1. Values of the key persistence parameters: $\{\gamma_p, \gamma_w\}$

	Log-utility in consumption ($\sigma = 1$)			
	$\eta = 1$	$\eta = 2$	$\eta = 5$	$\eta = 10$
$\theta_w = 2$	$\{2, 0.67\}$	$\{3, 0.60\}$	$\{6, 0.55\}$	$\{11, 0.52\}$
$\theta_w = 4$	$\{2, 0.40\}$	$\{3, 0.33\}$	$\{6, 0.29\}$	$\{11, 0.27\}$
$\theta_w = 6$	$\{2, 0.29\}$	$\{3, 0.23\}$	$\{6, 0.19\}$	$\{11, 0.18\}$
	Zero-income-effect utility $\{\sigma = 0\}$			
	$\eta = 1$	$\eta = 2$	$\eta = 5$	$\eta = 10$
$\theta_w = 2$	$\{1, 0.33\}$	$\{2, 0.40\}$	$\{5, 0.45\}$	$\{10, 0.48\}$
$\theta_w = 4$	$\{1, 0.20\}$	$\{2, 0.22\}$	$\{5, 0.24\}$	$\{10, 0.24\}$
$\theta_w = 6$	$\{1, 0.14\}$	$\{2, 0.15\}$	$\{5, 0.16\}$	$\{10, 0.16\}$

Table 2. The range of parameter values so that $\gamma_w < 1$

	The range of η values, given other parameters			
	$\sigma = 1$	$\sigma = 2$	$\sigma = 5$	$\sigma = 10$
$\theta_w = 2$	$(0, \infty)$	$(1, \infty)$	$(4, \infty)$	$(9, \infty)$
$\theta_w = 4$	$(0, \infty)$	$(0.33, \infty)$	$(1.33, \infty)$	$(3, \infty)$
$\theta_w = 6$	$(0, \infty)$	$(0.2, \infty)$	$(0.8, \infty)$	$(1.8, \infty)$
	The range of σ values, given other parameters			
	$\eta = 1$	$\eta = 2$	$\eta = 5$	$\eta = 10$
$\theta_w = 2$	$(0, 2)$	$(0, 3)$	$(0, 6)$	$(0, 11)$
$\theta_w = 4$	$(0, 4)$	$(0, 7)$	$(0, 16)$	$(0, 31)$
$\theta_w = 6$	$(0, 6)$	$(0, 11)$	$(0, 26)$	$(0, 51)$

Table 3.

Calibrated parameter values in the model with capital

Preferences:	
$\frac{1}{1-\sigma}C^{*1-\sigma} - \frac{1}{1+\eta}L(i)^{1+\eta}$	$\sigma = 1, \quad \eta = 2$
where $C^* = \left[bC^\nu + (1-b)(M/\bar{P})^\nu\right]^{1/\nu}$	$b = 0.98, \quad \nu = -1.56$
Technologies: $Y(j) = K^\alpha L^{1-\alpha}$	$\alpha = 0.33$
Composite labor: $L = \left[\int L(i)^{\frac{\theta_w - 1}{\theta_w}} di\right]^{\frac{\theta_w}{\theta_w - 1}}$	$\theta_w \in \{2, 4, 6\}$
Composite good: $Y = \left[\int Y(j)^{\frac{\theta_p - 1}{\theta_p}} dj\right]^{\frac{\theta_p}{\theta_p - 1}}$	$\theta_p = 10$
Capital accumulation:	
$K_t = I_t + (1-\delta)K_{t-1}$	$\delta = 1 - 0.92^{1/4}$
$\phi(I_t/K_{t-1}) = \frac{\psi}{2}(I_t/K_{t-1})^2$	ψ adjusted
Money growth: $\log\mu(s^t) = \rho\log(\mu(s^{t-1})) + \varepsilon_t$	$\rho = 0.57$
Subjective discount factor	$\beta = 0.96^{1/4}$
Number of price- or wage-setting cohorts	
Staggered wage model	$N_p = 1$, $N_w = 4$
Staggered price model	$N_p = 4$, $N_w = 1$

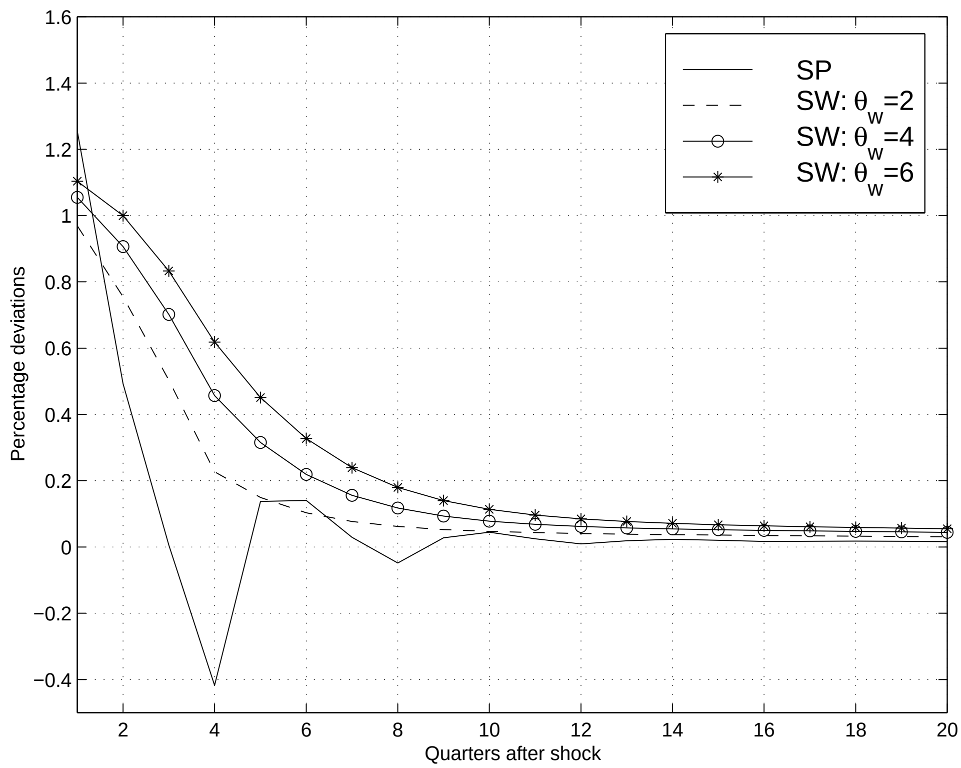

Figure 1:—The impulse responses of aggregate output under staggered price-setting (SP) versus staggered wage-setting (SW)

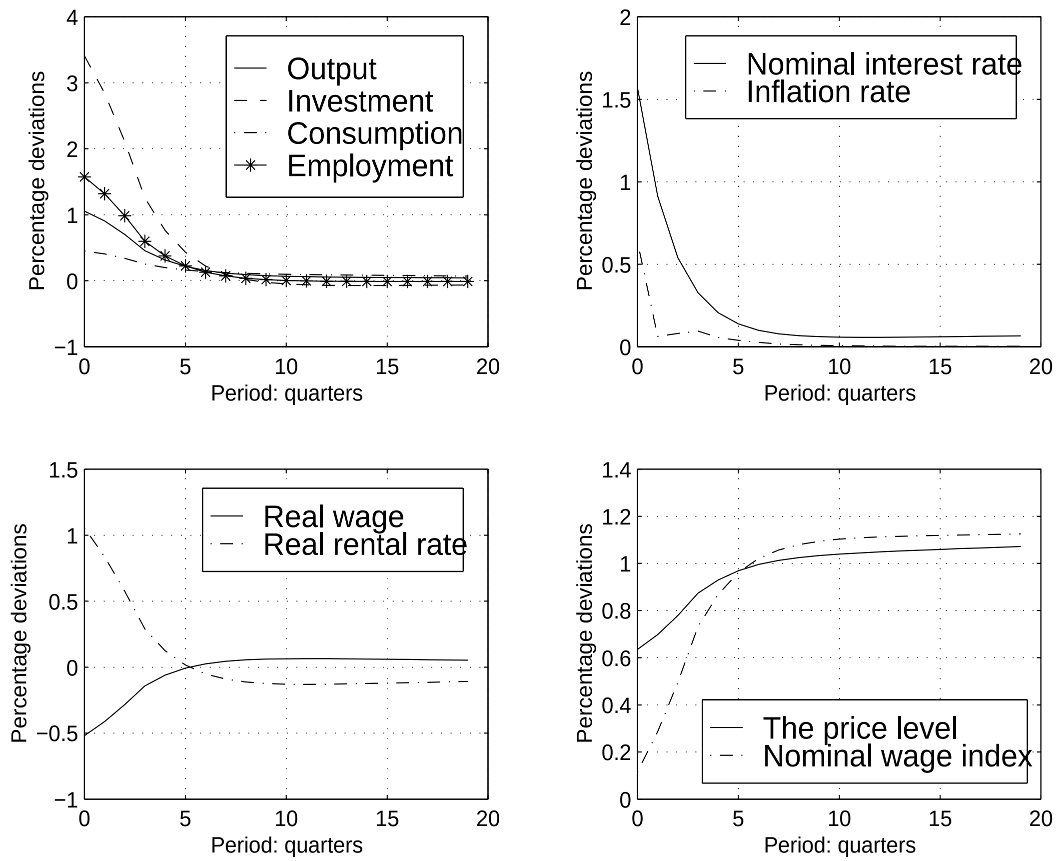

Figure 2:—Impulse responses under staggered wage-setting

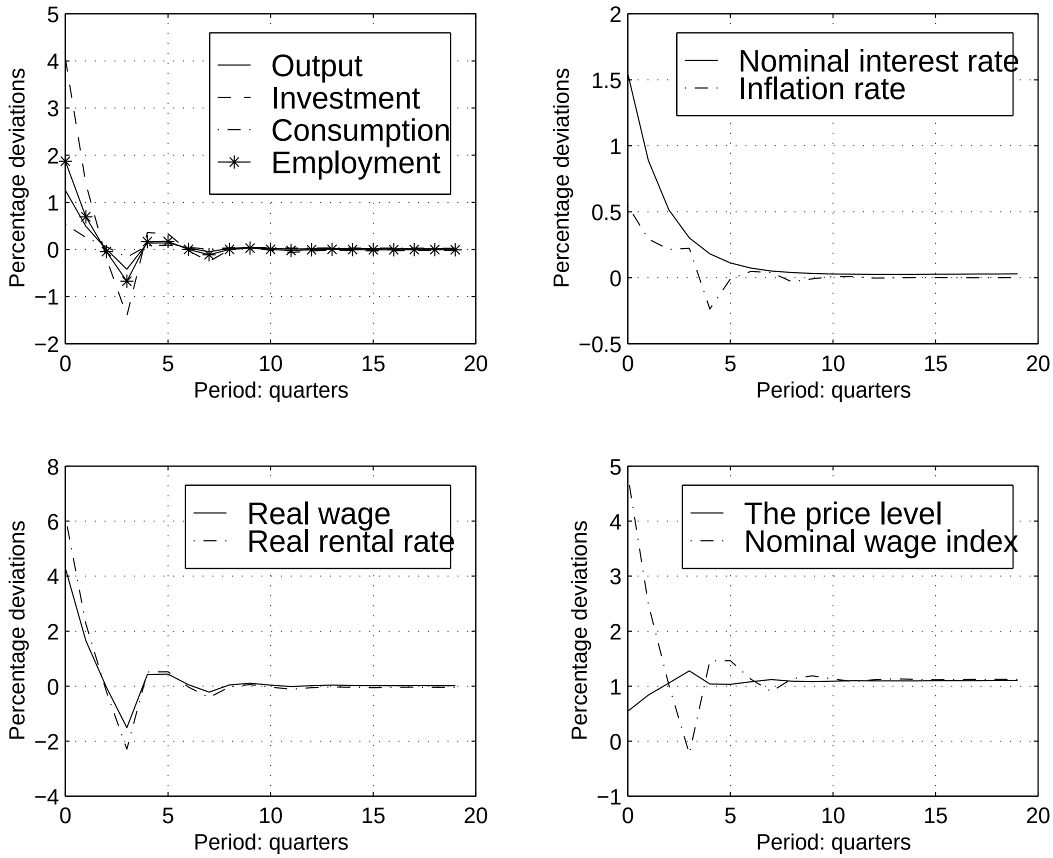

Figure 3:—Impulse responses under staggered price-setting