

# Information Flows and News Driven Business Cycles\*

Todd B. Walker<sup>†</sup> Eric M. Leeper<sup>‡</sup>

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## Abstract

How do information flows influence business cycle dynamics in models with anticipated (news shocks) and unanticipated innovations? To address this question, we show how alternative specifications of news affect the equilibrium by deriving the mapping between news shocks and the endogenous variables in a simple analytical model. News shocks are shown to add moving average (MA) components to endogenous variables. We then show how the additional MA components affect equilibrium dynamics. We generalize two popular forms of news processes to demonstrate how information flows impact equilibrium dynamics. To compare these news processes, we establish conditions under which the two processes have identical information content. We find that allowing news shocks to be correlated across time generates hump-shaped impulse response functions and helps mitigate the comovement problem.

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<sup>†</sup>Department of Economics, Indiana University, walkertb@indiana.edu

<sup>‡</sup>Department of Economics, Indiana University and NBER, eleeper@indiana.edu

## 1 INTRODUCTION

A burgeoning empirical and theoretical literature about the role of “news” in generating business cycles has developed in recent years. Although the idea that news shocks may be a source of fluctuations has a venerable past—Beveridge (1909) and Pigou (1927), for example—much of the recent interest was spurred by Beaudry and Portier’s (2006) provocative empirical finding that innovations in stock prices appear to reflect news about future productivity and, at the same time, account for a large fraction of business cycle fluctuations.<sup>1</sup> Coincident with news about technology were developments suggesting that fiscal actions—taxes and spending—may be well anticipated by private agents [Hall (1971), Poterba (1988), Ramey and Shapiro (1998) and Yang (2005)].

Surprisingly, despite the centrality of information structures to the news literature—whether it be news about technology or news about fiscal or monetary actions—there has been essentially no exploration of alternative, equally plausible, assumptions about how information about critical economic variables flows to agents. Instead, the canonical assumption of information flows about news takes the form

$$z_t = \rho z_{t-1} + \sum_{q=0}^Q \varepsilon_{q,t-q} \quad (1)$$

where  $z$  is the variable of interest—technology, taxes, government spending, short-term nominal interest rate—and  $\varepsilon_{q,t-q}$  is the “news” that arrives about  $z_t$  contemporaneously with  $q$  periods of foresight. Each  $\varepsilon_{q,t-q}$  is i.i.d. and governed by a distinct probability distribution for each  $q$ . Shock are also orthogonal at all leads and lags, so that  $\varepsilon_{q,t-q} \perp \varepsilon_{j,t-j}$  for  $j \neq q$ . We refer to the process in (1) “i.i.d. news.”

Information processes like (1), or minor variations on it, are canonical in the sense that they appears across a wide range of applications [Leeper (1989), Yang (2005), Beaudry and Portier (2004b), Christiano, Ilut, Motto, and Rostagno (2008), Fujiwara, Hirose, and Shintani (2008), Schmitt-Grohé and Uribe (2008), Jaimovich and Rebelo (2009), Kriwoluzky (2009), Mertens and Ravn (2009), Ramey (2009)].

This paper shows that many of the dynamic properties of equilibria under the canonical news process, (1), are *driven by the news process itself*. But this canonical news process is chosen largely arbitrarily, not grounded in either theory or empirics. Alternative, equally plausible processes for news, can deliver strikingly different equilibrium dynamics.

We introduce an alternative new process, which we call “correlated news,” that posits an

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<sup>1</sup>Many recent papers document the importance of news shocks [Beaudry and Portier (2006, 2004a), Schmitt-Grohé and Uribe (2008), Jaimovich and Rebelo (2009) Christiano, Ilut, Motto, and Rostagno (2008) Fujiwara, Hirose, and Shintani (2008), Barsky and Sims (2008)].

autoregressive moving average process of the form

$$z_t = \rho z_{t-1} + \sum_{q=0}^Q \zeta_q \varepsilon_{t-q} \quad (2)$$

where the  $\zeta_q$  parameters determine the relative importance of news at various horizons. Here  $\varepsilon_{t-q}$  is also i.i.d., but the shocks are governed by a single probability distribution, regardless of the horizon  $q$ .

The paper examines both a simple analytical model and a more complex DSGE model. Analytics allow us to show explicitly how equilibrium dynamics vary with assumptions about the news process. We then turn to a quantitative exercise using the DSGE model estimated by Schmitt-Grohé and Uribe (2008), which represents an early and influential attempt to bring theory to bear on the empirical question of the relative importance of anticipated versus unanticipated shocks in accounting for business cycle comovements. In both models we contrast outcomes under the canonical process with those under MA news.

The paper makes the following contributions:

- To understand how alternative specifications of news affect the equilibrium, we derive the mapping between news shocks and the endogenous variables in a simple analytical model. News shocks are shown to add moving average (MA) components to endogenous variables. We then show how the additional MA components affect equilibrium dynamics.
- We generalize the two forms of news processes—i.i.d. and correlated—to demonstrate how information flows impact equilibrium dynamics. To compare these news processes, we establish conditions under which the two processes have identical information content. If two identically informative processes generate different equilibrium dynamics, then those differences are attributable entirely to the more or less arbitrary selection of one new process over another.
- Compared to i.i.d. news, correlated news allows DSGE models to generate hump-shaped response functions with far less reliance on real rigidities, such as habit formation, variable capital utilization, and investment adjustment costs.
- Relative to i.i.d. news, correlated news helps to mitigate the “comovement problem,” the tendency for news about technological improvements to generate an economic downturn in the period before the improved technology is realized, a problem identified by Cochrane (1994) and recently studies by Jaimovich and Rebelo (2009) and Schmitt-Grohé and Uribe (2008), among others.

Existing work tends to posit a particular, arbitrarily chosen, news process and then derives and reports results that are conditional on that choice. Alternative news processes are not examined or even acknowledged. But news about technological improvements is intrinsically different from news about changes in tax legislation, and these differences may call for different assumptions about information flows in the two cases. Because equilibrium dynamics hinge critically on assumptions about information flows, the paper points to the need for more thoughtful modeling of how information flows into the economy.

## 2 ANALYTICAL EXAMPLE

This section examines the equilibrium dynamics associated with news shocks in a simple economic environment. The simplicity allows us to track the exact role played by news shocks. We able demonstrate how different types of news processes alter dynamics. The results and conclusions reached in this section extend to the more sophisticated model that section 4 studies.

**2.1 MODEL** We consider a standard growth model with log preferences and inelastic labor supply. Technology is subjected to a shock,  $A_t$ , and a proportional tax,  $\tau_t$ , is levied against income. With hours worked normalized to unity, the equilibrium conditions are

$$C_t + K_t = A_t K_{t-1}^\alpha + (1 - \delta) K_{t-1} \quad (3)$$

$$\frac{1}{C_t} = \beta E_t \frac{1}{C_{t+1}} [(1 - \tau_{t+1}) \alpha A_{t+1} K_t^{\alpha-1} + (1 - \delta)] \quad (4)$$

where  $C_t$ , and  $K_t$  denote time  $t$  consumption and capital,  $\alpha$  is capital's share of income,  $\beta$  is the representative agent's subjective rate of discount, and  $\delta$  is the depreciation rate of capital. As usual,  $\alpha, \beta, \delta \in (0, 1)$ . The government sets the tax rate according to an exogenous stochastic process and adjusts lump-sum transfers to satisfy the budget constraint,  $T_t = \tau_t Y_t$ , where  $Y_t$  is output. Government spending is identically zero.

Log linearizing equations (3)–(4) yields the equilibrium capital stock as the solution to

$$E_t k_{t+1} - \gamma_0 k_t + \gamma_1 k_{t-1} = \nu_0 E_t a_{t+1} - \nu_1 a_t + \varsigma E_t \hat{\tau}_{t+1} \quad (5)$$

where lower case denotes deviation from steady state ( $\hat{\tau}_t$  denotes the deviation from the

steady state tax rate) and the coefficients are defined as

$$\begin{aligned}\gamma_0 &= 2 - (1 - \beta(1 - \delta)) \left( \frac{(1 - \beta(1 - \delta) - \alpha\beta\delta(1 - \tau))(\alpha - 1)}{\alpha} - 1 \right) \beta^{-1}(1 - \tau)^{-1} - \delta \\ \gamma_1 &= \frac{1 - \beta(1 - \delta)}{\beta(1 - \tau)} + 1 - \delta \\ \nu_0 &= \frac{(1 - \beta(1 - \delta))(\beta(1 - \delta) + \alpha\beta\delta(1 - \tau))}{\alpha\beta(1 - \tau)} \\ \nu_1 &= \frac{1 - \beta(1 - \delta)}{\alpha\beta(1 - \tau)} \\ \varsigma &= \frac{\tau(1 - \beta(1 - \delta) - \alpha\beta\delta(1 - \tau))(1 - \beta(1 - \delta))}{\alpha\beta(1 - \tau)^2}\end{aligned}$$

and  $0 \leq \tau < 1$  is the steady state tax rate.

To solve the linearized model, write the difference equation in capital as

$$(B^{-2} - \gamma_0 B^{-1} + \gamma_1)E_t k_{t-1} = E_t z_t$$

where  $B$  denotes the backshift operator, defined as  $B^{-j}E_t k_{t-1} = E_t k_{t-1+j}$ , and

$$z_t = \nu_0 E_t a_{t+1} - \nu_1 a_t + \varsigma E_t \hat{\tau}_{t+1}$$

Factor the quadratic as  $(\lambda_1 - B^{-1})(\lambda_2 - B^{-1})E_t k_{t-1} = E_t z_t$  so that  $\gamma_1 = \lambda_1 \lambda_2$  and  $\gamma_0 = \lambda_1 + \lambda_2$ . Note that  $\lambda_1 > 0$  and  $\lambda_2 > 0$ . Select  $\lambda_1 < 1$  and  $\lambda_2 = \frac{1 - \beta(1 - \delta) + \beta(1 - \delta)(1 - \tau)}{\beta(1 - \tau)} \frac{1}{\lambda_1} > 1$ . Operating on both sides with  $(\lambda_2 - B^{-1})^{-1}$  yields  $(\lambda_1 - B^{-1})E_t k_{t-1} = (\lambda_2 - B^{-1})^{-1}E_t z_t$  and therefore equilibrium capital accumulation obeys

$$k_t = \lambda_1 k_{t-1} - \lambda_2^{-1} E_t \sum_{i=0}^{\infty} \theta^i (\nu_0 a_{t+1+i} - \nu_1 a_{t+i} + \varsigma \hat{\tau}_{t+1+i}) \quad (6)$$

where

$$\theta = \frac{\beta(1 - \tau)\lambda_1}{1 - \beta\tau(1 - \delta)} \quad (7)$$

This equilibrium solution is well known and demonstrates that capital accumulation depends on the discounted expected values of future total factor productivity and tax rates.

**2.2 INFORMATION & SOLUTION** This section aims to make transparent how news affects the nature of equilibrium. The simplest information flows for taxes and technology posit

that they are serially uncorrelated and follow the (log-linearized) processes

$$\hat{\tau}_t = \varepsilon_{\tau,t-q}, \quad a_t = \varepsilon_{a,t-q} \quad (8)$$

where  $\varepsilon_j \sim N(0, \sigma_j^2)$  for  $j = a, \tau$ . We assume agents observe current and past innovations  $\{\varepsilon_{\tau,t-j}, \varepsilon_{a,t-j}\}_{j=0}^\infty$ , implying that they have perfect knowledge of future tax rates and technology when  $q > 0$ . For example, if  $q = 2$ , then at  $t$  agents have perfect knowledge of  $\hat{\tau}_{t+1}, \hat{\tau}_{t+2}$ ,  $a_{t+1}$  and  $a_{t+2}$ . Given (6) and (8), the equilibrium may be written as a function of  $q$ . It is instructive to separate the effects of tax news from those of technology news. For taxes, we obtain

$$k_t = \begin{cases} 0 & \text{for } q = 0 \\ \lambda_1 k_{t-1} - \lambda_2^{-1} \varsigma \sum_{j=1}^q \theta^{q-j} \varepsilon_{\tau,t-j+1} & \text{for } q > 0 \end{cases} \quad (9)$$

With no foresight about taxes,  $q = 0$ , a surprise change in the proportional income tax is lump sum, leaving capital unchanged. News that future taxes will rise depresses capital accumulation.

The equilibrium as a function of the technology shock is

$$k_t = \begin{cases} \lambda_1 k_{t-1} + \lambda_2^{-1} \nu_1 \varepsilon_{a,t} & \text{for } q = 0 \\ \lambda_1 k_{t-1} + \lambda_2^{-1} \nu_1 \varepsilon_{a,t-q} - \lambda_2^{-1} (\nu_0 - \theta \nu_1) \sum_{j=1}^q \theta^{q-j} \varepsilon_{a,t-j+1} & \text{for } q > 0 \end{cases} \quad (10)$$

As emphasized by Leeper, Walker, and Yang (2009) and shown by (9) and (10), foresight about taxes and technology introduce moving average (MA) components into endogenous equilibrium variables, even when the exogenous process generating the news (8) follows an i.i.d. process.<sup>2</sup> Additional MA components arise entirely from the expectational effects of foresight. The “hallmark of a rational expectations equilibrium,” in Sargent’s (1981) memorable phrase, is that endogenous variables take on the stochastic characteristics of the exogenous driving process with the mapping determined by the expectation operator. In the typical framework with i.i.d. technology and taxes, equilibrium capital would follow an AR(1) process and would be a function only of the technology shock. In models with news shocks, the expectational effects imply that innovations dated  $t - q$  matter for contemporaneous capital decisions. Forward looking agents will immediately adjust consumption and capital holdings in response to impending changes in taxes or technology  $q$  periods out. The time between when agents learn the news shock and when the shock actually hits the economy is

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<sup>2</sup>Leeper, Walker, and Yang (2008, 2009) emphasize that these MA coefficients can create problems for structural VAR estimation.

referred to as the “anticipation horizon.”

Comparing (6) with (9) and (10) shows that, while the tax rate  $\tau_t$  and technology process  $a_t$  are discounted in the usual manner, the innovations  $\varepsilon_a, \varepsilon_\tau$  are discounted in a seemingly perverse manner: the contemporaneous innovation receives the heaviest discount. To see this more clearly, assume full depreciation ( $\delta = 1$ ) and a three-period anticipation horizon ( $q = 3$ ), and note that optimal capital accumulation as a function of the tax shock follows

$$k_t = \alpha k_{t-1} - (1 - \theta)(\tau/(1 - \tau)) \left\{ \varepsilon_{\tau,t-2} + \theta \varepsilon_{\tau,t-1} + \theta^2 \varepsilon_{\tau,t} \right\}$$

where  $\theta < 1$ . The “perverse” discounting of the shocks over the anticipation horizon occurs because the contemporaneous innovation contains information about tax rates at time  $t + q$ , while  $t - q$  innovations are informative about the time  $t$  tax rate and technology. This discounting has important implications for characterizing the empirical aspects of models with news, to which we now turn.

### 3 EMPIRICAL ASPECTS OF INFORMATION FLOWS

This section derives empirical implications of the stylized news process for the simple growth model. The moving average terms in the solution for capital—due entirely to news shocks—have important implications for equilibrium dynamics. We illustrate how dynamics depend on information flows using the simple model under particular parameterizations. This section’s exercises are illustrative; quantitative impacts appear in section 4.

**3.1 EQUILIBRIUM DYNAMICS** Figure 1a plots the response of capital to a positive tax shock under one, two, and four quarters of foresight for  $\alpha = 0.36, \delta = 1, \beta = 0.99$ , and  $\tau = 0.25$ .<sup>3</sup> The paths of capital display the consequences of the perverse discounting associated with foresight. When taxes are levied on output, the optimal response is to decrease the capital stock throughout the anticipation horizon with a sharp decrease in the period immediately before the tax hike. For  $q = 4$ , the capital stock does not respond on impact because the contemporaneous innovation is so heavily discounted.

The figure shows that foresight about tax changes can change the serial correlation properties of endogenous variables, producing hump-shaped responses even in environments in which no humps exist in the absence of foresight. It is well known that many macro aggregates display this hump shape in response to various shocks. Rational expectations models typically account for this empirical pattern by adding internal propagation mechanisms such

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<sup>3</sup>With complete depreciation of capital, the equilibrium equations simplify even further, with  $\lambda_1 = \alpha$ ,  $\lambda_2^{-1} = \tau/(1 - \tau)(1 - \theta)$ ,  $\theta = \alpha\beta(1 - \tau)$ .

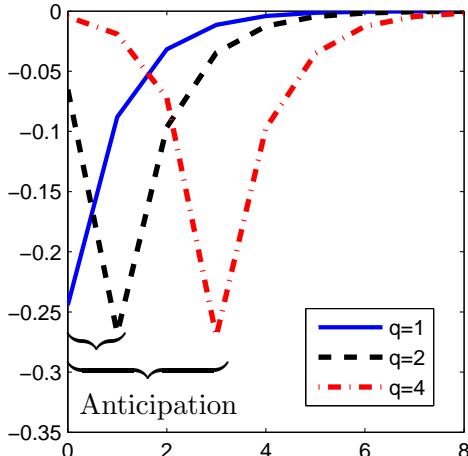


Figure 1a: Impulse Response

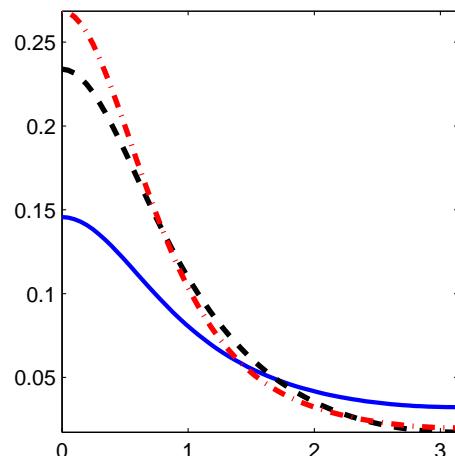


Figure 1b: Spectrum

Figure 1: Capital impulse responses to tax shocks and spectrum for one quarter of foresight ( $q = 1$ , unit impulse at  $t = 1$ ), two quarters of foresight ( $q = 1$ , unit impulse at  $t = 2$ ) and four quarters of foresight ( $q = 4$ , unit impulse at  $t = 4$ )

as habit formation, capital adjustment costs, learning by doing, and price or wage stickiness. That a very simple model of foresight can deliver hump-shaped impulse response functions with the propagation due entirely to expectational effects suggests a useful research question: how much of the propagation of economic shocks in time series data is due to agents responding to news about future realizations of taxes and technology?

Another perspective on how information flows affect a model's potential fit to data can be gleaned from the spectrum of the model's equilibrium. Hump-shaped and highly persistent response patterns are consistent with Granger's (1966) "typical spectral shape" of economic time series, with most of the spectral power at low frequencies, and declining smoothly as frequency increases. Figure 1b shows that the spectrum of the equilibrium changes with the degree of foresight. The additional MA terms make the equilibrium process more persistent, with low frequencies—those closer to the origin in the figure—relatively more important components of the overall variance. This can be seen easily when capital depreciates completely. The spectra of equilibrium capital dynamics for one and two quarters of foresight are given by

$$g_k^{q=1}(e^{-i\omega}) = \frac{[\tau^*(1-\theta)]^2}{1 - 2\alpha \cos \omega + \alpha^2}, \quad g_k^{q=2}(e^{-i\omega}) = \frac{[\tau^*(1-\theta)]^2(1 + 2\theta \cos \omega + \theta^2)}{1 - 2\alpha \cos \omega + \alpha^2} \quad (11)$$

where  $\tau^* = \tau/(1-\tau)$ ,  $\theta = \alpha\beta(1-\tau)$ , and  $\omega$  is frequency measured in cycles per period, with  $0 \leq \omega \leq \pi$ . The MA term coming from the additional quarter of foresight alters the spectrum by  $(1 + 2\theta \cos \omega + \theta^2)$ . The derivative of this term is  $-2\theta \sin \omega$  and because  $\theta > 0$ , the spectrum decreases on  $(0, \pi)$ . This additional MA term alters the spectrum of

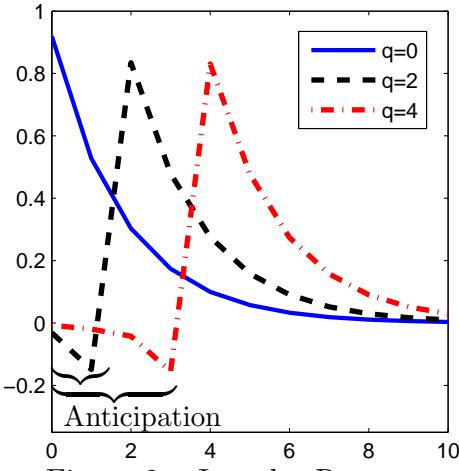


Figure 2a: Impulse Response

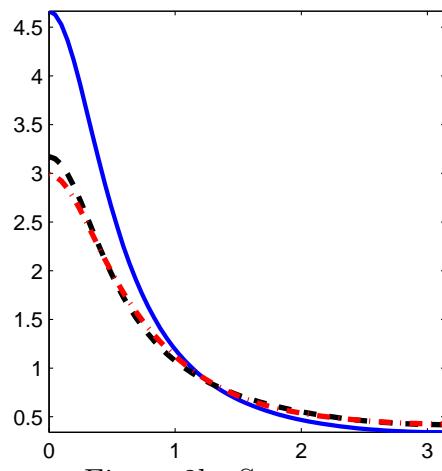


Figure 2b: Spectrum

Figure 2: Capital Impulse Responses to Technology Shock and Spectrum for  $q = 0, 2, 4$ 

the equilibrium so that lower frequencies become relatively more important. Expectational effects of foresight about taxes imply that all innovations dated  $t-q$  through  $t$ —discounted at rate  $\theta$ —are relevant for time  $t$  capital. As innovations are added to the equilibrium process, the time series characteristics change and the process becomes more persistent.

It is not always the case that foresight makes time series more persistent. The opposite is true for the response to a technology shock. Through tedious algebra one can show that  $\nu_0 - \theta\nu_1 > 0$ , and therefore capital responds *negatively* to an innovation in technology throughout the anticipation horizon (periods  $t$  through  $t-q-1$ ). Figure 2 plots the impulse response to a technology shock and the spectrum for  $q = 0, 2, 4$  and  $\alpha = 0.36, \delta = 0.05, \beta = 0.99$  and  $\tau = 0.25$ . With i.i.d. technology shocks and no foresight, future changes in technology are not forecastable and capital responds only to the contemporaneous innovation, declining at rate  $\lambda_1$  thereafter. With foresight, future changes in technology are known and an anticipated positive technology shock raises future income and wealth, but not current income. Agents smooth their consumption paths by raising current consumption and decreasing saving. Over the entire anticipation period capital responds negatively to positive news about technology.<sup>4</sup>

Figure 2b reinforces that foresight about technology makes the resulting time series *less* persistent. The spectrum is given by

$$g_k^{q=0}(e^{-i\omega}) = \frac{[\lambda_2^{-1}\nu_1]^2}{1 - 2\lambda_1 \cos \omega + \lambda_1^2}, \quad g_k^{q=1}(e^{-i\omega}) = \frac{[\lambda_2^{-1}\nu_1]^2(1 - 2\vartheta \cos \omega + \vartheta^2)}{1 - 2\lambda_1 \cos \omega + \lambda_1^2} \quad (12)$$

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<sup>4</sup>This pattern is exacerbated with elastic labor supply because higher wealth reduces labor supply, reducing current income.

where  $\vartheta = \lambda_2^{-1}(\nu_0 - \theta\nu_1) > 0$ . The additional term  $(1 - 2\vartheta \cos \omega + \vartheta^2)$  is due entirely to foresight and is increasing on  $(0, \pi)$ . Therefore foresight with respect to technology tilts the spectrum so that higher frequencies are given relatively more weight. The intuition behind this result is that the wealth effect induces more fluctuations in capital vis-a-vis the no-foresight AR(1) equilibrium.

Foresight's distinct effects on technology and tax news in the simple model deserve emphasis. Foresight with respect to technology generates results that are inconsistent with two of Prescott's (1986) three elements of the "business cycle phenomenon"—the periodicity of output (as shown by the reallocation of power to higher frequencies), and the comovement of other variables with output. News about improved technology raises future income but causes a current downturn, the so-called "comovement problem" in aggregate variables [Cochrane (1994), Jaimovich and Rebelo (2009) and Schmitt-Grohé and Uribe (2008)]. Foresight about taxes yields the opposite result: a more persistent equilibrium and, because lower expected taxes raise current economic activity, positive comovement.

In the case of technology foresight, most of the "fixups" to align theory with data are model specific. For example, to generate positive comovement following news of a positive technology shock, Jaimovich and Rebelo (2009) use Greenwood, Hercowitz, and Huffman (1988) preferences to minimize the wealth effects of anticipated technology on labor supply. This eliminates the comovement problem associated with technology news. More generally, habit formation, investment adjustment costs and other internal propagation mechanisms are now considered standard additions to DSGE models. The next section underscores the importance of understanding how *information* interacts with model dynamics, and argues that exploring alternative information processes may be a promising way to reconcile theory with data.

**3.2 TWO NEWS PROCESSES** Equilibrium dynamics are strongly influenced by the temporal properties of the news processes. We begin by contrasting two types of news processes that have been employed in the literature. The news shocks modeled as exogenous processes are typically assumed to be i.i.d. which take the form

$$x_t^{iid} = D(L)[\varepsilon_{1t} + \varepsilon_{2t-1}] \quad (13)$$

where  $\varepsilon_{1t}$  and  $\varepsilon_{2t}$  are uncorrelated at all leads and lags and drawn from distinct probability distributions,  $\varepsilon_{jt} \stackrel{i.i.d.}{\sim} N(0, \sigma_{\varepsilon,j}^2)$  for  $j = 1, 2$ . The  $D(\cdot)$  process is a polynomial in the lag operator  $L$ ,  $D_0 + D_1L + D_2L^2 + \dots$ , that satisfies square summability (i.e.,  $\sum_{j=0}^{\infty} D_j^2 < \infty$ ). Schmitt-Grohé and Uribe (2008) embed an expanded version of (13) in their estimated DSGE model with  $D(L)$  specified as an AR(1),  $D(L) = (1 - \rho L)^{-1}$ .

An alternative news process allows for the shocks to be temporally correlated. This process is given by

$$x_t^{tc} = D(L)(\zeta + (1 - \zeta)L)\varepsilon_t \quad (14)$$

where now the  $\varepsilon$ 's are drawn from the same distribution  $\varepsilon \stackrel{i.i.d.}{\sim} N(0, \sigma_\varepsilon^2)$ . The moving-average coefficient,  $\zeta \in (0, 1)$ , determines the relative weight of the shock at different time horizons. Leeper, Walker, and Yang (2009) employ a version of (14) to study tax news.

As argued in the introduction, the i.i.d. news process is the one typically employed by the burgeoning news literature. But little justification or motivation is provided for why news is modeled in this manner. Here we make two points. First, we argue that the alternative specification of news given by (14) is perhaps easier to motivate in terms of economic interpretations. Second, we show that allowing for correlation in the news process mitigates some of the empirical inconsistencies of i.i.d. news shocks described in the previous section.

By modeling the exogenous process with a unspecified distributed lag,  $D(\cdot)$ , we are able to derive results that are a function only of the correlation properties of the two shock processes. These results are general, even though they are derived within the framework of a highly stylized model.

**3.2.1 ECONOMIC INTERPRETATION** In order to compare (13) with (14), we need a metric to establish equivalency. For rational expectations models, a natural metric is equivalency of forecast errors. Fortunately, contrasting (13) with (14) is straightforward because both processes have the same number of free parameters— $\sigma_{\varepsilon,1}^2, \sigma_{\varepsilon,2}^2$  for the i.i.d. news process, and  $\sigma_\varepsilon^2, \zeta$  for the temporally correlated news process. We can then establish a result that equates the information content of the i.i.d. news process with that of the temporally correlated process. The following proposition answers the question: under what parameter settings would agents be indifferent between conditioning on (13) and (14)?<sup>5</sup>

**Proposition 1.** *The information content of  $x_t^{iid} = D(L)[\varepsilon_{1t} + \varepsilon_{2t-1}]$  is identical to that of  $x_t^{tc} = D(L)(\zeta + (1 - \zeta)L)\varepsilon_t$  when the following restrictions hold:*

$$\sigma_{\varepsilon,1}^2 = \sigma_\varepsilon^2 \zeta^2 \quad (15)$$

$$\sigma_{\varepsilon,2}^2 = \sigma_\varepsilon^2 (1 - \zeta) \left( \frac{2D_1\zeta + D_0(1 - \zeta)}{D_0} \right) \quad (16)$$

*Proof.* Let  $J(L) = D(L)(\zeta + (1 - \zeta)L)$  and let  $z^t$  denote the sequence of current and past

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<sup>5</sup>We define “indifference” in terms of equating variance of forecast errors.

$z_t, \{z_{t-j}\}_{j=0}^{\infty}$ . We can establish this result by equating the variance of the forecast errors at horizons  $t+1$  and  $t+2$ . The Wiener-Kolmogorov optimal prediction formula yields

$$E[x_{t+1}^{iid} - E(x_{t+1}^{iid} | \{\varepsilon_1^t, \varepsilon_2^t\})]^2 = E[D(L)\varepsilon_{1t+1} - L^{-1}[D(L) - D_0]\varepsilon_{1t}]^2 = D_0^2\sigma_{\varepsilon,1}^2 \quad (17)$$

$$E[x_{t+1}^{tc} - E(x_{t+1}^{tc} | \{\varepsilon^t\})]^2 = E[F(L)\varepsilon_{t+1} - L^{-1}[F(L) - F_0]\varepsilon_t]^2 = D_0^2\zeta^2\sigma_{\varepsilon}^2 \quad (18)$$

$$\begin{aligned} E[x_{t+2}^{iid} - E(x_{t+2}^{iid} | \{\varepsilon_1^t, \varepsilon_2^t\})]^2 &= E[D(L)[\varepsilon_{1,t+2} + \varepsilon_{2,t+1}] - L^{-2}[D(L) - D_0 - D_1L]\varepsilon_{1t} \\ &\quad - L^{-1}[D(L) - D_0]\varepsilon_{2,t}]^2 = D_0^2[\sigma_{\varepsilon,1}^2 + \sigma_{\varepsilon,2}^2] + D_1^2\sigma_{\varepsilon,1}^2 \end{aligned} \quad (19)$$

$$\begin{aligned} E[x_{t+2}^{tc} - E(x_{t+2}^{tc} | \{\varepsilon^t\})]^2 &= E[F(L)\varepsilon_{t+2} - L^{-2}[F(L) - F_0 - F_1L]\varepsilon_t]^2 \\ &= \{D_0^2\zeta^2 + [D_1\zeta + (1 - \zeta)D_0]^2\}\sigma_{\varepsilon}^2 \end{aligned} \quad (20)$$

Equating (17) with (18) and (19) with (20) delivers the result.  $\square$

Since a majority of the work in the news shock literature posits an AR(1) specification for  $D(L)$ , we provide the following corollary to Proposition 1.

**Corollary 1.** *If  $D(L) = (1 - \rho L)^{-1}$ , then the information content of (13) and (14) is equivalent when  $\sigma_{\varepsilon,1}^2 = \sigma_{\varepsilon}^2\zeta^2$  and  $\sigma_{\varepsilon,2}^2 = \sigma_{\varepsilon}^2(1 - \zeta)(2\rho\zeta + 1 - \zeta)$*

As  $\zeta \rightarrow 1$ , agents have no foresight concerning future changes in  $x_t$  according to (14). The corresponding restriction for the i.i.d. process entails removing  $\varepsilon_{2,t-1}$  from the  $x_t$  process. Similarly, as  $\zeta \rightarrow 0$ , agents observe  $x_{t+1}$  without error, implying  $\sigma_{\varepsilon,1}^2 = 0$ . Notice also that as the AR(1) process becomes less persistent ( $\rho \rightarrow 0$ ), the intuitive result emerges that the variance of the two-step-ahead forecast error for the MA process ( $\sigma_{\varepsilon}^2(1 - \zeta)^2$ ) must exactly equal the variance of  $\varepsilon_{2,t}$ .

One crucial difference between the two information structures is the temporal correlation in the agents' innovations. An extreme case of the correlation structure emerges if we set  $D(L) = 1$ . Under this assumption, the process in (13) posits that at date  $t$  agents read two different newspapers because the shocks  $\varepsilon_{1t}$  and  $\varepsilon_{2t-1}$  are drawn from different distributions. The first reveals  $\varepsilon_{1t}$ —news about  $x_t$ —and the second reveals  $\varepsilon_{2t}$ —news about  $x_{t+1}$ . But at  $t+1$ ,  $\varepsilon_{1t}$  is no longer informative about  $x$  at any date. In contrast, the process in (14) has agents at date  $t$  read a single newspaper to learn  $\varepsilon_t$ , which gives news about both  $x_t$  and  $x_{t+1}$ . In the next period, yesterday's news continues to be informative about  $x_{t+1}$ , but today's news causes agents to update their beliefs about  $x_{t+1}$ .

This simplified example is not illustrative of the literature because it excludes the possibility for news to be correlated through an autoregressive component. The following lemma delivers a more general result.

**Lemma 1.** *The temporal correlation in the agents' innovations between date  $t + 1$  and  $t + 2$  conditional on date  $t$  information for (13) and (14) is given by*

$$E[(x_{t+1}^{iid} - E(x_{t+1}^{iid} | \{\varepsilon_1^t, \varepsilon_2^t\}))(x_{t+2}^{iid} - E(x_{t+2}^{iid} | \{\varepsilon_1^t, \varepsilon_2^t\}))]^2 = D_0 D_1 \sigma_{\varepsilon,1}^2 \quad (21)$$

$$E[(x_{t+1}^{tc} - E(x_{t+1}^{tc} | \{\varepsilon^t\}))(x_{t+2}^{tc} - E(x_{t+2}^{tc} | \{\varepsilon^t\}))]^2 = D_0(\zeta D_1 + (1 - \zeta)D_0)\sigma_\varepsilon^2 \quad (22)$$

*Proof.* Follows immediately from the proof of Proposition 1.  $\square$

Lemma 1 can be used to establish a specific result for  $D(L) = (1 - \rho L)^{-1}$ .

**Proposition 2.** *If  $D(L) = (1 - \rho L)^{-1}$  with  $\rho \in (0, 1)$  and assuming an identical information structure as given by Proposition 1, then the temporal correlation in the agents' innovations at time  $t + 1$  and  $t + 2$  is stronger for the temporally correlated news process in (14) than for i.i.d. news process in (13).*

*Proof.* Substituting into (21) and (22) gives

$$\begin{aligned} E[(x_{t+1}^{iid} - E(x_{t+1}^{iid} | \{\varepsilon_1^t, \varepsilon_2^t\}))(x_{t+2}^{iid} - E(x_{t+2}^{iid} | \{\varepsilon_1^t, \varepsilon_2^t\}))]^2 &= \rho \sigma_{\varepsilon,1}^2 \\ E[(x_{t+1}^{tc} - E(x_{t+1}^{tc} | \{\varepsilon^t\}))(x_{t+2}^{tc} - E(x_{t+2}^{tc} | \{\varepsilon^t\}))]^2 &= (\zeta \rho + 1 - \zeta) \sigma_\varepsilon^2 \end{aligned}$$

Replacing  $\sigma_{\varepsilon,1}^2$  with  $\sigma_\varepsilon^2 \zeta^2$  according to Proposition 1 implies the inequality  $\rho \zeta^2 < (\zeta \rho + 1 - \zeta)$ .  $\square$

Proposition 2 shows that while both processes are able to accommodate temporal correlation in agents' innovations, (14) will always be more highly correlated. We are not suggesting that more correlation is necessarily better, but it is easy to motivate correlation in news shocks. Different dynamic properties of alternative new processes argue that there is probably not one, single process that is appropriate in all settings. The choice of news process should be guided by the phenomena under study. For example, with respect to fiscal policy, less correlated news shocks could imply information arrives concerning two separate pieces of legislation that affect tax rates differently at nearly the same horizon. It seems more likely that the news process should be heavily temporally correlated, as in (14). This is because fiscal policy is subject to substantial lags due to the legislative process and implementation of changes in tax policy.<sup>6</sup> While a proposed tax change may undergo slight revision as it is debated and passed in the House and Senate, there are no revisions during the implementation lag. Temporal correlation in the news process is probably most appropriate when examining fiscal foresight.

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<sup>6</sup>Yang (2008) estimates the median lag time to be three to four quarters, while Mertens and Ravn (2008) estimate it to be six quarters.

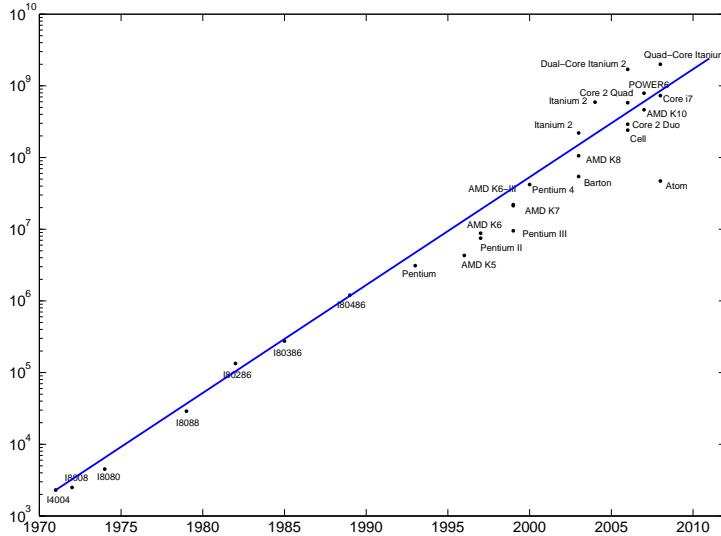


Figure 3: Moore's Law for the number of CPU transistors (logarithmic scale).

The news process appropriate for modeling technology diffusion is quite different from the fiscal example. Extensive theoretical and empirical work finds that technology adoption follows an *S*-shaped diffusion function [Griliches (1957), Geroski (2000), and Rogers (2003)]. Griliches (1957) found that the period of time that from 10 percent to 90 percent of fields became planted with hybrid corn varied tremendously from state to state: 4 years in Iowa; 9 years in Wisconsin; 19 years in Kentucky. Mansfield (1989) studied how many years it took for one-half of the population of potential users to adopt certain technologies, finding times that ranged from 1 year for tin containers to 15 years for coke ovens. As Geroski (2000, p. 618) emphasizes, “most innovations fail (i.e., they do not diffuse at all), and it seems reasonable to insist that any serious model of diffusion ought to include failure as a possible outcome.”

Rotemberg (2003) emphasizes that the slow diffusion of technology can have important short-run consequences through expectation formation. Business cycle fluctuations occur because agents must update the probability of success, failure, and rate of diffusion of technology. An upward revision to long-run output generates wealth effects that lower marginal utility today. Moore’s Law graphically illustrates of this expectational channel. Figure 3 plots the number of CPU transistors over time. The solid line is Moore’s Law, which posits that the number transistors should double every two years. The exponential trend represents the expected increase in computing power over time, while the realizations represent innovations in agents’ information sets. That Moore’s Law has been a very good approximation to actual data suggests that future changes in CPU technology are correlated. Figure 3 also shows that realizations both above the trend and below the trend tend to cluster; from 1995

through 2003, for example, many of the processors could not keep pace with Moore's Law. Technology diffusion seems to call for both strong temporal correlation and high persistence in the innovations to agents information sets.

**3.2.2 GENERALIZATION AND DYNAMIC IMPACT** We now examine the dynamic implications of the two news processes by incorporating an information structure that nests both (13) and (14) into the simple model of section 2.

Assume that the log-linearized tax and technology news separately evolve according to<sup>7</sup>

$$x_t^{gen} = D(L)[\varepsilon_{1,t}^{gen} + \varepsilon_{2,t-1}^{gen}] \quad (23)$$

where each shock in (23) is a linear combination of two i.i.d. disturbances

$$\begin{aligned} \varepsilon_{1t}^{gen} &= \sigma_{11}\eta_{1t} + \sigma_{12}\eta_{2t} \\ \varepsilon_{2t}^{gen} &= \sigma_{21}\eta_{1t} + \sigma_{22}\eta_{2t}. \end{aligned}$$

The  $\eta_{it}$ 's are assumed to be distributed as standard normal and are uncorrelated at all leads and lags. This implies that the innovations are distributed as bivariate normal according to

$$\begin{bmatrix} \varepsilon_{1t}^{gen} \\ \varepsilon_{2t}^{gen} \end{bmatrix} = N \left[ \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{bmatrix} \sigma_{11}^2 + \sigma_{12}^2 & \varrho\sigma_{11}\sigma_{12} \\ \varrho\sigma_{11}\sigma_{12} & \sigma_{21}^2 + \sigma_{22}^2 \end{bmatrix} \right]$$

where  $\varrho = (\sigma_{11}\sigma_{21} + \sigma_{12}\sigma_{22})/\sigma_1\sigma_2$  controls the correlation among the innovations and  $\sigma_1^2 \equiv \sigma_{11}^2 + \sigma_{12}^2$ ,  $\sigma_1 \equiv \sqrt{\sigma_1^2}$ .

Agents are assumed to observe current and past innovations  $\{\eta_{1,t-j}, \eta_{2,t-j}\}_{j=0}^\infty$ , which, according to (23), implies that agents have foresight about future values of tax rates and technology. The ratio of the variances ( $\varpi \equiv (\sigma_{11}^2 + \sigma_{12}^2)/(\sigma_{21}^2 + \sigma_{22}^2)$ ) governs the importance of news at different horizons. For example, as  $\varpi \rightarrow 0$ , the process is given by  $x_t^{gen} = D(L)\varepsilon_{2t-1}^{gen}$ , and agents perfectly observe tax rates and the technology process one period ahead.

By changing the correlation in the innovations, the generalized process nests i.i.d. news ( $\varrho = 0$ )

$$x_t^{iid} = D(L)[\sigma_{11}\eta_{1t} + \sigma_{22}\eta_{2t-1}] = D(L)[\varepsilon_{1t} + \varepsilon_{2t-1}]$$

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<sup>7</sup>Here we abstract from the MA coefficients  $\zeta$  and  $1 - \zeta$  for clarity. Including the MA coefficients would not change the results we derive.

where  $\varepsilon_{1t}$  and  $\varepsilon_{2t}$  are now uncorrelated at all leads and lags. And  $\varrho = 1$  yields

$$x_t^{tc} = D(L)[(\sigma_{11}\eta_{1t} + \sigma_{22}\eta_{2t}) + \sigma_{11}\eta_{1t-1} + \sigma_{22}\eta_{2t-1}] = D(L)[\varepsilon_t + \varepsilon_{t-1}]$$

where now the  $\varepsilon$ 's are drawn from the same Gaussian distribution with variance  $\sigma_{11}^2 + \sigma_{22}^2$ .

As might be expected, the temporal properties of news have important implications for economic behavior. Section 2 demonstrated how news with respect to technology leads to dynamic equilibrium behavior that is inconsistent with data. In order to analyze how temporal correlation in the shocks might mitigate these findings, we solve the simple model assuming the process for technology follows the generalized process (23). We focus on the solution for  $\eta_{2t}$  because it represents the news shock for the i.i.d. news case, but this is without loss of generality given the symmetric structure of the innovations. The generality of the solution is preserved by following Whiteman (1983) and solving the model in the frequency domain as a distributed lag in  $\eta_{2,t}$ , leading to the next proposition.

**Proposition 3.** *The optimal capital sequence is a function of  $\eta_{2t}$ ,  $k_t = F(L)\eta_{2t}$ , which in equilibrium is given by*

$$k_t = F(L)\eta_{2t} = \left( \frac{D(L)H(L) - D(\lambda_1)H(\lambda_1)}{(L - \lambda_1)(L - \lambda_2)} \right) \eta_{2t} \quad (24)$$

where  $H(L) = (\sigma_{12} + L\sigma_{22})(\nu_0 - L\nu_1)$

*Proof.* Recall the model is given by

$$E_t k_{t+1} - \gamma_0 k_t + \gamma_1 k_{t-1} = \nu_0 E_t a_{t+1} - \nu_1 a_t$$

Substituting for the  $k_t$  and  $a_t$  processes and taking expectations yields the functional difference equation in the  $z$ -transform in  $\eta_{2,t}$ ,

$$\begin{aligned} z^{-1}[F(z) - F_0] - \gamma_0 F(z) + \gamma_1 z F(z) &= \nu_0(z^{-1}[D(z) - D_0]\sigma_{12} + D(z)\sigma_{22}) \\ &\quad - \nu_1(D(z)[\sigma_{12} + \sigma_{22}z]) \end{aligned}$$

Collecting terms in  $F(z)$  and factoring the quadratic so that  $\gamma_1 = \lambda_1\lambda_2$  and  $\gamma_0 = \lambda_1 + \lambda_2$  yields

$$F(z)[(z - \lambda_1)(z - \lambda_2)] = F_0 - \nu_0 D_0 \sigma_{11} + D(z)H(z)$$

The function  $F(z)$  must be analytic on the open unit disc in order for the  $F(L)\eta_{2,t}$  sequence to be square summable. This will be true if the free parameter  $F_0$  is set to remove the pole

at  $z = \lambda_1$ . Evaluating at  $z = \lambda_1$  and solving for  $F_0$  delivers (24).  $\square$

We can use this generalized solution to examine how the properties of the equilibrium change as the correlation in the shock varies. Foresight with respect to technology generates a powerful wealth effect that produces a negative response to capital (and subsequently output) over the anticipation horizon, as the previous section shows. Because we assume only one quarter of foresight in this example, the anticipation horizon occurs on impact. Evaluating  $F(L)$  at  $L = 0$  delivers the anticipation effect associated with observing  $\eta_{2,t}$ , which is

$$F_0 = \frac{D_0\sigma_{12}\nu_0 - D(\lambda_1)H(\lambda_1)}{\lambda_1\lambda_2} \quad (25)$$

The following proposition shows that as the temporal correlation in the innovation increases, the anticipation effect subsides.

**Proposition 4.** *If  $D(L) = (1 - \rho L)^{-1}$  and  $\sigma_{22} > \sigma_{11}$ , then the anticipation effect associated with i.i.d. news ( $\sigma_{12} = 0$ ) is greater than the anticipation effect associated with correlated news ( $\sigma_{12} > 0$ ).*

*Proof.* Notice that eliminating the correlation in the shocks  $\sigma_{12} = 0$ , yields the inequality  $F_0^{\sigma_{12}=0} < F_0$  if  $D_0\nu_0 - D(\lambda_1)(\nu_0 - \lambda_1\nu_1) > 0$ . If we impose  $D(L) = (1 - \rho L)^{-1}$ , the inequality holds because  $\nu_0\lambda_1 \left[ \frac{1-\rho}{1-\lambda_1\rho} \right] > 0$ ,  $\nu_0, \lambda_1 > 0$  and  $\lambda_1 \in (0, 1)$ . We also need the variance of the news shock  $\sigma_{22}^2$  to be larger than the contemporaneous shock  $\sigma_{11}^2$  for the result to hold due to the equivalent representation of (24) in  $\eta_{1t}$ .  $\square$

Figure 4 shows the extent to which adding correlation in the shock mitigates the anticipation effect. This result holds for any AR(1) specification. Figure 4 makes clear that the anticipation effect can even be reversed in this simple setting. By changing the size and sign of the anticipation effect, temporally correlated news shocks can mitigate the anticipation effect and the comovement problem. Given the simplicity of the model, we do not interpret these results quantitatively. We now turn to a more sophisticated model to get a better sense of the quantitative effects.

## 4 SCHMITT-GROHÉ-URIBE MODEL

The intuition for the simple model extends naturally to more complex environments. In order to demonstrate this point, we now turn to the model of Schmitt-Grohé and Uribe (2008, 2010) (SGU). We examine this model because SGU is among the small handful of papers

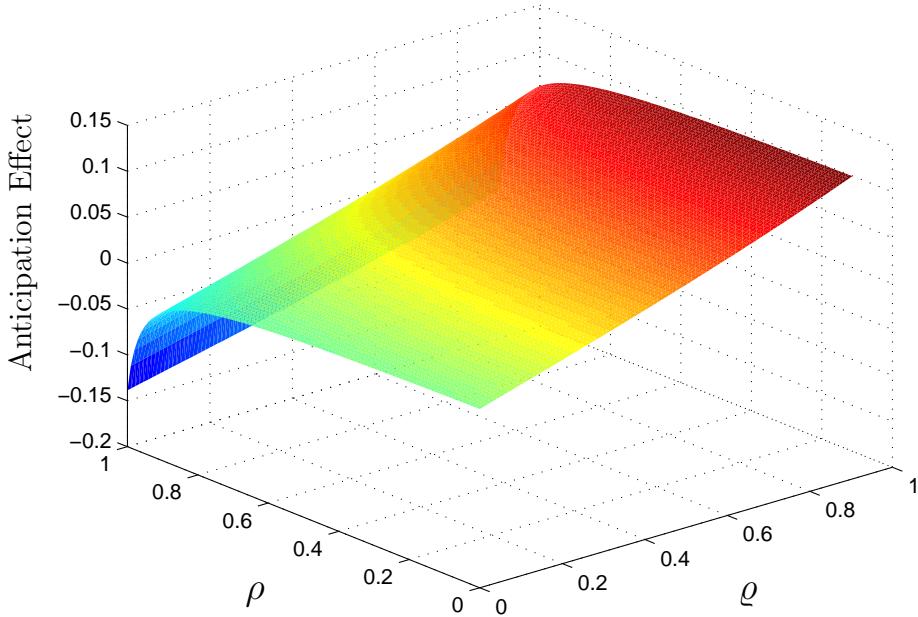


Figure 4: Anticipation Effect ( $F_0$ ) for various AR(1) coefficients ( $\rho$ ) and temporal correlation ( $\varrho$ )

in the literature that estimate a DSGE model with news.<sup>8</sup> SGU use the i.i.d. information structure, so we shall compare the implications of that information structure to those that emerge when the innovations are temporally correlated.

**4.1 MODEL DETAILS** The model economy includes several features commonly added to real business cycle (RBC) models, which are designed to capture the sluggish response to innovations found in estimated VARs [Burnside, Eichenbaum, and Fisher (2004)]. These real rigidities include habit formation, capacity utilization, and investment adjustment costs. We employ SGU's (2008) model structure with the only difference being how information is modeled. We highlight this key distinction in the next section.

A representative household derives utility from consumption,  $C_t$  and leisure,  $\ell_t$ , and maximizes

$$E_0 \sum_{t=0}^{\infty} \beta^t \frac{\{(C_t - \theta_c C_{t-1})(\ell_t - \theta_\ell \ell_{t-1})^\chi\}^{1-\sigma} - 1}{1 - \sigma} \quad (26)$$

where  $\beta$  is the discount factor,  $\theta_c$  and  $\theta_\ell$  determine the degree of internal habit formation,  $\chi$  controls the marginal rate of substitution between consumption and leisure, and  $\sigma$  determines

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<sup>8</sup>Davis (2007) and Fujiwara, Hirose, and Shintani (2008) are other examples.

the intertemporal elasticity of substitution. While habit formation in consumption is a common assumption, habit formation in leisure is somewhat unorthodox. The motivation is to induce adjustment costs in hours worked. This is an important assumption in models with news shocks because an anticipated increase in productivity induces a strong wealth effect over the anticipation horizon and causes an immediate negative response in hours worked. Habits in leisure ensure that households begin adjusting labor supply at the moment they receive the news.<sup>9</sup>

The capital stock evolves according to

$$K_{t+1} = [1 - \delta(u_t)]K_t + I_t \left[ 1 - S\left(\frac{I_t}{I_{t-1}}\right) \right] \quad (27)$$

where  $I_t$  denotes gross investment and  $u_t$  measures capacity utilization in period  $t$ , chosen optimally by households (owners of physical capital). The effective amount of capital services supplied to firms at time  $t$  is given by  $u_t K_t$ . The depreciation rate is assumed to be an increasing, convex function of the rate of utilization,

$$\delta(u) = \delta_0 + \delta_1(u - 1) + \frac{\delta_2}{2}(u - 1)^2 \quad \delta_i > 0. \quad \forall i$$

Investment adjustment costs follow Christiano, Eichenbaum, and Evans (2005) and also follow a quadratic specification

$$S(x) = \frac{\kappa}{2}(x - \mu^i)^2, \quad k > 0$$

where  $\mu^i$  denotes the steady state growth rate of investment. Analogous to the role played by habit formation, investment adjustment costs and a utilization-contingent depreciation rate induce elongated and smooth impulse responses to innovations impacting capital.

The production technology is given by

$$Y_t = z_t(u_t K_t^\alpha X_t h_t^{1-\alpha}) \quad (28)$$

where  $z_t$  is a transitory productivity shock,  $X_t$  is a permanent productivity shock, and  $h_t$  denotes hours worked,  $h_t = 1 - \ell_t$ .

The government consumes an exogenous and stochastic quantity of goods  $G_t$ . The re-

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<sup>9</sup>The condition that consumption and leisure enter the utility function multiplicatively ensures that adjustment costs do not fade over time [King, Plosser, and Rebelo (1988)].

source constraint is given by

$$C_t + A_t I_t + G_t = Y_t \quad (29)$$

where  $A_t$  is the rate of transformation between consumption and investment goods, and is assumed to be exogenous and stochastic.  $A_t$  represents the relative price of investment goods in terms of consumption goods.

The social planner's problem is solved by maximizing (26) subject to (27)–(29) by choosing  $C_t, h_t, \ell_t, K_{t+1}, u_t, Y_t$  and  $I_t$  given  $K_0$  and the exogenous processes for  $G_t, X_t, A_t$  and  $z_t$ . SGU show the first-order conditions are given by

$$\begin{aligned} U_1(\cdot) - \theta_c \beta E_t U_1(\cdot) &= \Lambda_t \\ U_2(\cdot) - \theta_\ell \beta E_t U_2(\cdot) &= \Lambda_t z_t X_t F_2(\cdot) \\ Q_t \Lambda_t &= \beta E_t \Lambda_{t+1} [z_{t+1} u_{t+1} F_1(\cdot) + Q_{t+1} (1 - \delta(u_{t+1}))] \\ z_t F_1(\cdot) &= Q_t \delta'(u_t) \\ A_t \Lambda_t &= Q_t \Lambda_t \left[ 1 - S\left(\frac{I_t}{I_{t-1}}\right) - \left(\frac{I_t}{I_{t-1}}\right) S'\left(\frac{I_t}{I_{t-1}}\right) \right] + \beta E_t Q_{t+1} \Lambda_{t+1} \left(\frac{I_{t+1}}{I_t}\right)^2 S'\left(\frac{I_{t+1}}{I_t}\right) \end{aligned}$$

where  $\Lambda_t Q_t$  and  $\Lambda_t$  is the Lagrange multiplier on (27) and (29), respectively.  $Q_t$  is the relative price of installed capital in period  $t$  available for production in period  $t+1$  in terms of period  $t$  consumption goods (Tobin's marginal  $q$ ).

**4.2 INFORMATION FLOWS** The model consists of four exogenous shock processes—stationary neutral productivity shock  $z_t$ , nonstationary neutral productivity shock  $X_t$ , investment specific shock  $A_t$ , and a government spending shock  $G_t$ . We examine two alternative specifications for the news process. The first is a simplification of the one examined in Schmitt-Grohé and Uribe (2008) and is given by

$$x_t = \rho x_{t-1} + \varepsilon_{x,t}^0 + \varepsilon_{x,t-1}^1 + \varepsilon_{x,t-2}^2 + \varepsilon_{x,t-3}^3 \quad (30)$$

where  $\varepsilon_{x,t}^j$  denotes the  $j$ -period anticipated changes in the level of  $x_t$ .<sup>10</sup> These shocks are assumed to be independent across time and anticipation horizon  $E\varepsilon_{x,t}^j \varepsilon_{x,t-m}^k = 0$  for  $k, j = 0, 1, 2, 3$  and  $E\varepsilon_{x,t}^j \varepsilon_{x,t}^k = 0$  for any  $k \neq j$ . The information set of the agent is still assumed to be current and past realizations of the exogenous shocks  $\varepsilon_{x,t}^j$ . By observing  $\varepsilon_{x,t}^2$ , for example, agents know precisely how this shock will impinge upon  $x_{t+2}$  and agents will respond as soon

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<sup>10</sup>In an updated version, Schmitt-Grohé and Uribe (2010) model news according to  $x_t = \rho x_{t-1} + \varepsilon_{x,t}^0 + \varepsilon_{x,t-4}^4 + \varepsilon_{x,t-8}^8$ . For our purposes, it is sufficient to examine (30) as the conclusions reached in this section will extend to alternative specifications for i.i.d. news.

Table 1: Calibrated Parameters

Parameter	Value	Description
$\beta$	0.973	Subjective Discount Factor
$\sigma$	2	Intertemporal Elasticity of Substitution
$\alpha$	0.3	Capital Share
$\delta_0$	0.025	Steady-state depreciation rate
$\mu$	1	Steady-state capital utilization rate
$\mu^y$	1.0045	Steady-state gross per capita GDP growth rate
$\mu^a$	0.9957	Steady-state gross rate of price of investment
$G/Y$	0.2	Steady-state share of government consumption in GDP

Table 1: Calibrated parameters taken from Schmitt-Grohé and Uribe (2008).

as the shock is observed. Agents do not have perfect foresight, however, because  $x_t$  also contains a contemporaneous innovation.

The alternative functional form is the correlated news process discussed above and is given by

$$x_t = \rho x_{t-1} + \phi_0 \varepsilon_{x,t} + \phi_1 \varepsilon_{x,t-1} + \phi_2 \varepsilon_{x,t-2} + \phi_3 \varepsilon_{x,t-3} \quad (31)$$

where  $\varepsilon_x$  is normally distributed with mean zero and variance  $\sigma_{\varepsilon_x}^2$ . We assume agents observe current and past realizations of the shocks  $\{\varepsilon_{x,t-j}\}_{j=0}^\infty$ , and interpret the moving-average parameters as weights with restrictions  $\sum_j \phi_j = 1$  and  $\phi_j \geq 0$ . Given that (31) is a function of past shocks, we allow for the possibility that by observing the shocks directly, agents receive “news” about the future path of the  $x_t$  process.

**4.3 SOLUTION AND CALIBRATION** The model is linearized around steady state values (see Appendix A of SGU (2008)) and calibrated according to the calibrated parameters and posterior means found in SGU. Table 1 reports the calibrated parameters, which follow standard values found in the literature. SGU use quarterly data ranging from 1955:Q1 to 2006:Q4 to estimate the model using Bayesian methods. The observable variables include the GDP deflator, real per capita GDP, real per capita consumption, real per capita investment, real per capita government expenditures, per capita hours and a relative price of investment goods, following Fisher (2005). Table 2, taken from Schmitt-Grohé and Uribe (2008), contains the prior and posterior moments for parameter values of interest. For a more thorough discussion of the estimation procedure see Schmitt-Grohé and Uribe (2008).

**4.4 INFORMATION FLOWS, PROPAGATION, AND COMOVEMENT** The model includes the typical propagation mechanisms that better align theory with the hump-shaped gradual

Table 2: Selected Estimated Parameters

Parameter	Prior Distribution			Posterior Distribution		
	Distribution	Mean	Std. Dev.	Mean	5 percent	95 percent
$\theta_c$	Beta	0.5	0.1	0.85	0.83	0.88
$\theta_\ell$	Beta	0.5	0.1	0.56	0.5	0.63
$\kappa$	Gamma	4.0	1.0	5.1	4.2	6.2
$\delta_2$	Uniform	5.0	2.9	0.11	0.08	0.14

Table 2: Posterior estimates of preference and technology parameters taken from Schmitt-Grohé and Uribe (2008).

impulse response functions seen in the data. These propagation mechanisms include habit formation, investment adjustment costs, and variable capacity utilization. The intuition described in section 3 demonstrates that news shocks may either augment or diminish the persistence of the endogenous variables. How these propagation mechanisms interact with news shocks will hinge on [i] how the news is modeled and [ii] the optimal responses of agents to the news shocks (i.e., will the MA coefficients enter positively or negatively). If news is correlated across time, the endogenous variables will inherit this property and will display impulse response functions that are smoother and hump-shaped. If the news shock reallocates spectral power to higher frequencies, then the propagation mechanisms will have to work harder (i.e., require higher values for the parameters in table 2).<sup>11</sup>

As Schmitt-Grohé and Uribe (2008) note, the estimated friction parameters from the model with news shocks are relatively high compared to the literature. The habit formation parameter ( $\theta_c$ ) has a very tight posterior around the mean of 0.85; the lower tail of the posterior distribution is three standard deviations above the prior mean. This indicates that the data strongly favor a relatively high value for  $\theta_c$  (relative to the prior specification). A similar, but less pronounced, pattern applies to the investment adjustment cost parameter,  $\kappa$ . The prior distribution is in line with standard assumptions, as in Justiniano, Primiceri, and Tambalotti (2008), but the posterior mean is a full standard deviation above the prior mean. As a frame of reference, Justiniano, Primiceri, and Tambalotti (2008) have the same prior distribution but an estimate of the posterior mode of 2.42. Christiano, Eichenbaum, and Evans (2005) estimate  $\kappa$  to be 2.42 in a flexible-price model. Of course these estimates are not strictly comparable due to differences in model and the absence of news, but it is hard to imagine that model structure alone would generate this kind of discrepancy.

In an updated version of their paper, Schmitt-Grohé and Uribe (2010) estimate a news process that allows for up to eight quarters of foresight. The additional degrees of foresight pushed the posterior median estimate of  $\kappa$  to 9.11 with a standard deviation of 1.05, and the

<sup>11</sup>See Kano and Nason (2009) for a more thorough explanation of the spectral properties of habit formation.

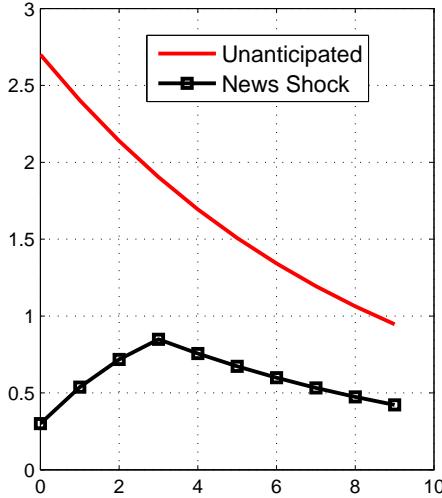


Figure 5a: Stationary Technology Shock

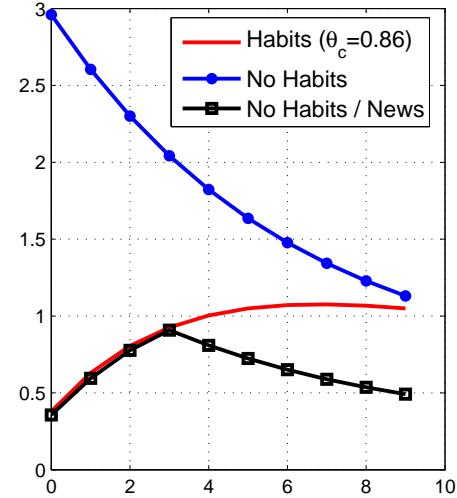


Figure 5b: Consumption

Figure 5: Consumption response to an anticipated (solid) and unanticipated stationary technology shock with habit formation (square) and without habit formation (circle)

habit formation parameter was again tightly estimated with a median of 0.91 and standard deviation of 0.01. These estimates further corroborate our hypothesis that models with i.i.d. news shocks must rely more heavily on propagation mechanisms.

Figure 5 shows how an alternative information structure might change these posterior estimates. This figure plots the impulse response of an unanticipated shock and a news process given by  $z_t = 0.9z_{t-1} + 0.485\varepsilon_t + 0.345\varepsilon_{t-1} + 0.148\varepsilon_{t-2} + 0.022\varepsilon_{t-3}$ . Figure 5a shows that this news process is hump-shaped, which assumes a strong correlation in the agents innovations as shown by Proposition 2. Figure 5b plots the response to the unanticipated shock assuming no habits and habit formation with  $\theta_c = 0.85$ . Habit formation alters the monotonically decreasing impulse response to one that changes gradually and is hump-shaped. This figure also shows that the correlated news process can replicate the impulse response function associated with habit formation for the first three quarters. That is, as noted in section 3, coupling foresight with a correlated news process generates MA coefficients that imply a smooth, hump-shaped impulse response function. The impulse response produced by habit formation cannot be matched exactly; to do that the degree of foresight would have to extend beyond two years—a period of foresight at least as long as the quarter where the maximum of the impulse response occurs for the model with habit formation. Nonetheless, the figure demonstrates a general phenomenon: there is a tradeoff between the correlated news process and the degree of habit formation.

To examine this tradeoff, we solve the model using the i.i.d. news process, (31), calibrating all of the parameters to the posterior estimates and calibrated values of SGU, with the

exception of the AR and MA coefficients of (31) and the habit formation parameter. Our target statistics,  $\hat{\Psi}$  in (32) below, are the path of consumption following a stationary neutral productivity shock, as estimated by SGU in their model with habit formation and the new process in (30). We choose the parameters of the new process in (31) and the habit formation parameter by solving

$$\min_{\Theta} [\hat{\Psi} - \Psi(\Theta)]' V^{-1} [\hat{\Psi} - \Psi(\Theta)] \\ \text{subject to } \theta_c \in (0, 1), \quad \phi_j \in (0, 1), \quad \sum_j \phi_j = 1 \quad (32)$$

where  $\Theta = \{\theta_c, \rho, \phi_j\}$  and  $V$  are the posterior means of the variances of the stationary neutral technology taken from table 3 in SGU's paper. We normalize the covariance matrix so that if the MA coefficients were all set to unity, the two information structures would have identical covariance matrices if  $\rho = 0.5$ . We included the first 50 elements of the impulse response function. Because there is an inherent indeterminacy between the news process and the habit formation parameter, the minimization was conducted in two steps. First, the AR and MA coefficients were estimated assuming no habit formation  $\theta_c = 0$ ; then a search for the habit formation parameter that minimized the distance between the two impulse response functions was performed, taking the AR and MA coefficients as given. We then increased the degree of foresight and repeated the estimation.

Figure 6 shows the tradeoff between the habit formation parameter and the degree of foresight as the degree of foresight is increased from 1 to 12 quarters. To a certain extent the picture reaffirms the estimates of SGU. Even when the news process is temporally correlated, the decrease in the habit formation parameter is slow, falling only from 0.85 to 0.79 with four quarters of foresight. However, the next several quarters of foresight leads to a dramatic decrease in the habit formation parameter (from 0.79 to 0.38). Intuitively, expanding the degree of foresight increases the degrees of freedom available to the estimator, implying a better fit to SGU's estimated impulse response function for consumption, with less reliance on the persistence induced by habit formation. With three years of foresight, the habit formation parameter falls to 0.2, a number much smaller than empirical estimates. The upshot of this exercise is simply that the results here suggest that by modeling news as correlated, the real frictions of the model would not have to work as hard to fit the data.

This exercise is merely suggestive.<sup>12</sup> However, the figure does raise questions about the propagation mechanisms driving standard DSGE models. Informational frictions, which are

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<sup>12</sup>A more definitive approach to examining this tradeoff would be to estimate the SGU model using the temporally correlated news process (31), and then use formal model comparison to let the data decide which news process is preferred.

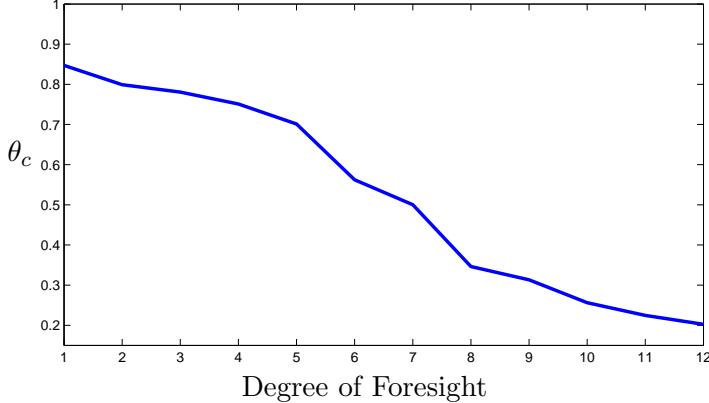


Figure 6: Tradeoff between Foresight and Habit Formation

rarely modeled, could be a driving force behind the propagation and amplification of shocks, rather than the familiar propagation mechanisms. We take seriously Lucas's warning about theorists bearing free parameters. Although the result in figure 6 certainly relies on free parameters, should it be dismissed so freely? Figure 3 of Moore's Law suggests that several years of potentially noisy foresight about technological improvements may be perfectly plausible, and studies of technology diffusion corroborate this. Our argument, though, is less precise: the tradeoff between information specification and conventional forms of producing propagation in DSGE models argues forcefully for studying the nature of information flows in various contexts. Such studies could reveal the degree of foresight and lead to more plausible characterizations of how news about important economic factors arrives.

As advocated throughout this paper, we offer an informational approach to mitigating the comovement problem. Figure 7 plots the responses of macro aggregates to the non-stationary neutral technology shock under two information structures—a i.i.d. news process given by

$$\begin{aligned} \ln X_t^{iid} &= \ln X_{t-1} + \ln \mu_t^x \\ \ln(\mu_t^x / \mu^x) &= \rho_x \ln(\mu_{t-1}^x / \mu^x) + \varepsilon_{1,t} + \varepsilon_{2,t-1} \end{aligned} \tag{33}$$

and a temporally correlated news process

$$\begin{aligned} \ln X_t^{iid} &= \ln X_{t-1} + \ln \mu_t^x \\ \ln(\mu_t^x / \mu^x) &= \rho_x \ln(\mu_{t-1}^x / \mu^x) + (\zeta + (1 - \zeta)L)\varepsilon_t \end{aligned} \tag{34}$$

As explained by Schmitt-Grohé and Uribe (2008), the  $\mu^x$  parameter determines the drift in the level of the nonstationary component of labor augmenting technological change.

We examine this particular shock for two reasons. First, Schmitt-Grohé and Uribe (2008)

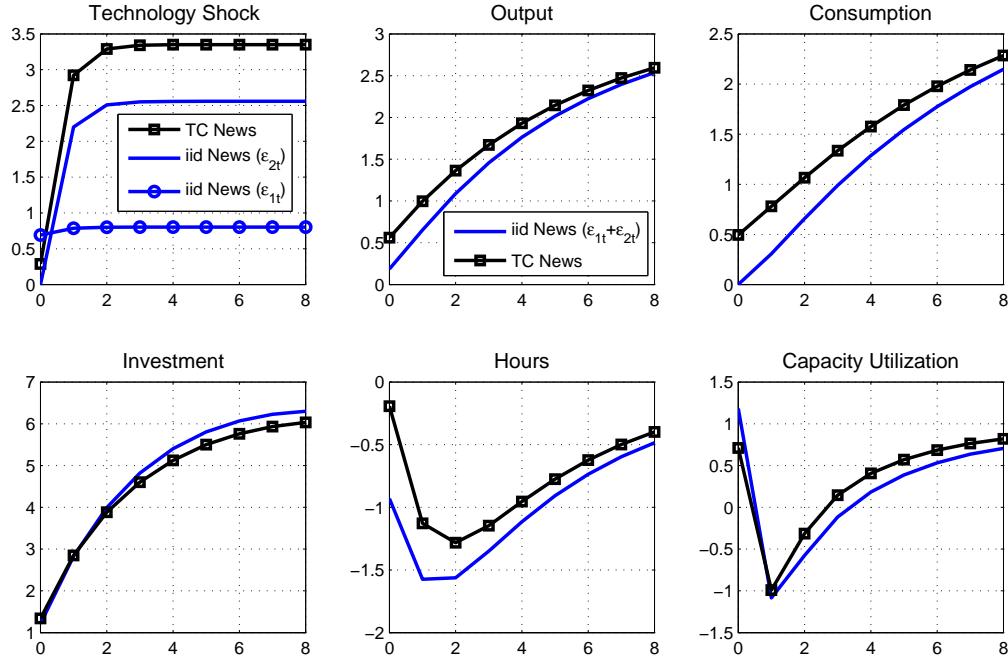


Figure 7: Impulse response functions to a nonstationary technology shock: i.i.d. news sum of  $\varepsilon_{1t}, \varepsilon_{2t}$  (solid) and correlated news (square)

find that 18 percent of the variance of output can be attributed to one-quarter anticipated changes in the growth rate of the nonstationary productivity shock. Third most among all shocks in the model. Second, one-quarter anticipated changes in the growth rate of this productivity shock generate a comovement problem as hours declines on impact due to the positive wealth effect associated with anticipated increase in permanent TFP. This result runs counter to the conclusions reached in Beaudry and Portier (2006), who find that output, investment, consumption, and employment all increase in response to anticipated changes in permanent TFP. Jaimovich and Rebelo (2009) obtain positive comovements of output, consumption, investment and hours by minimizing the wealth effect through Greenwood, Hercowitz, and Huffman (1988) preferences. Jaimovich and Rebelo generalize the Greenwood, Hercowitz, and Huffman's specification of preferences by including a parameter that controls the strength of the wealth elasticity of labor supply. This parameter can be set to ensure that hours worked increase over the anticipation horizon.

In order to compare the two information processes on an equal footing, we use Proposition 1 to calibrate (34) according to the posterior means of (33) estimated by SGU. The estimates from Schmitt-Grohé and Uribe (2008) are:  $\rho_x = 0.14$ ,  $\sigma_{\varepsilon,1} = 0.69$ ,  $\sigma_{\varepsilon,2} = 2.2$ , which translates into  $\zeta = 0.25$  and  $\sigma_\varepsilon = 2.79$  for (34) according to Corollary 1. We also plot the combined impulse response for  $\varepsilon_{1,t}$  and  $\varepsilon_{2,t}$  in (33). The *tc* news process does not generate

a pure anticipation effect due to the correlation in the anticipated and unanticipated shocks. By plotting the sum of the impulse response functions for (33), we ensure that it too does not generate a pure anticipation effect.

Figure 7 shows that the anticipation effect on hours is mitigated under the temporally correlated news process relative to i.i.d. news. The temporal correlation does not reverse the qualitative nature of the wealth effect; hours falls, just not as much as with i.i.d. news. Moreover, because of the frictions in the model, the responses of output, consumption, and investment are not that different across the information structures. The correlated news structure alters hours worked dramatically (the combined i.i.d. response is nearly five times the response of the correlated news process), but does not alter the other variables that much. This suggests that the GHH preference structure (or alternative mechanism to alleviate comovement) may not have to work as hard with a correlated news process.

## 5 CONCLUDING REMARKS

We have shown how news shocks alter equilibrium dynamics analytically in a simple model and numerically in the model of Schmitt-Grohé and Uribe (2008). News shocks are able to produce hump-shaped responses even in environments in which no humps exist in the absence of foresight. News shocks that create a hump-shaped response alter the spectral composition of the equilibrium by shifting relative variance to lower frequencies. That news shocks create these dynamic effects without any additional propagation mechanism suggests that information structures can help to reconcile theory and data.

How information enters the economy is crucial for understanding the dynamic impacts of news. We have demonstrated that temporally correlated shocks produce different equilibrium outcomes than i.i.d. shocks. A smooth process for news is consistent with hump-shaped impulse response functions and is able to produce positive comovement in macroeconomic aggregates in response to news shocks. Moreover, news shocks with temporal correlation are easily motivated. Agents learn about changes in technology and fiscal policy in a more gradual manner. News about technological advancements or future changes in tax rates received today will most likely be correlated with the information about these objects that arrives next quarter.

To be clear, this paper is not advocating one news process over another. Neither is it arguing that news shocks should replace commonly used frictions and propagation mechanisms. We are arguing, however, that the news generating process should be subject to the same constructive criticism that has helped shape the development of modern macroeconomic DSGE models. Just as in the development of structural changes to DSGE models, data should be the deciding factor in choosing among alternative news processes.

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