

NBER WORKING PAPER SERIES

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Working Paper 20193  
<http://www.nber.org/papers/w20193>

NATIONAL BUREAU OF ECONOMIC RESEARCH  
1050 Massachusetts Avenue  
Cambridge, MA 02138  
June 2014

We thank Marios Angeletos, Max Croce, Guido Lorenzoni, Jonathan Parker, and Mike Woodford for helpful comments. We also thank Tony Zhang and Hongcen Wei for excellent research assistance. The authors have not received financial support from an interested party for the completion of this paper. The authors are not officers, directors, or board members of any relevant organization. No other party had the right to review the paper prior to its circulation. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

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NBER Working Paper No. 20193  
June 2014  
JEL No. C63,D83,E2,E3,E44,G11

### **ABSTRACT**

We introduce the information microstructure of a canonical noisy rational expectations model (Hellwig, 1980) into the framework of a conventional real business cycle model. Each household receives a private signal about future productivity. In equilibrium, the stock price serves to aggregate and transmit this information. We find that dispersed information about future productivity affects the quantitative properties of our real business cycle model in three dimensions. First, households' ability to learn about the future affects their consumption-savings decision. The equity premium falls and the risk-free interest rate rises when the stock price perfectly reveals innovations to future productivity. Second, when noise trader demand shocks limit the stock market's capacity to aggregate information, households hold heterogeneous expectations in equilibrium. However, for a reasonable size of noise trader demand shocks the model cannot generate the kind of disagreement observed in the data. Third, even moderate heterogeneity in the equilibrium expectations held by households has a sizable effect on the level of all economic aggregates and on the correlations and standard deviations produced by the model. For example, the correlation between consumption and investment growth is 0.29 when households have no information about the future, but 0.41 when information is dispersed.

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# 1 Introduction

An efficient allocation of goods and services depends on the ability of financial markets to aggregate dispersed information that is not available to any single economic agent in its totality (Hayek, 1945). The way in which asset prices and economic aggregates reflect this dispersed information has been the object of a large theoretical literature on “noisy rational expectations” going back to Grossman (1976) and Hellwig (1980).

This literature has produced a rich set of predictions. For example, inefficiencies may arise when prices transmit information that is costly to acquire (Grossman and Stiglitz, 1980; Verrecchia, 1982), when agents must form expectations about the expectations of others (Allen, Morris, and Shin, 2006; Bacchetta and Van Wincoop, 2008; Qiu and Wang, 2010; Angeletos, Lorenzoni, and Pavan, 2012), or when agents learn about actions that are strategic complements to their own actions (Amador and Weill, 2012; Goldstein, Ozdenoren, and Yuan, 2013).<sup>1</sup>

Although this field of research has received a great deal of attention in recent years, quantifying its results within the standard framework of dynamic stochastic general equilibrium (DSGE) models has proven difficult. This relative scarcity of quantitative applications is the result of a methodological barrier: the tools used to solve noisy rational expectations models are generally perceived to be incompatible with the quantitative machinery of DSGE models. Noisy rational expectations models typically combine normally distributed shocks with policy functions that are (log) linear in the expectation of the shocks that agents learn about. This combination ensures that aggregate variables (e.g., prices or the capital stock) inherit the normal distribution, allowing a straightforward application of the projection theorem when solving for equilibrium expectations. By contrast, policy functions in contemporary DSGE models are inherently non-linear in expectations of future variables (e.g., consumption, labor supply, and portfolio returns). As a result, aggregate variables are not normally distributed in these models, even if they feature normally distributed shocks. Consequently, the standard approach for solving noisy rational expectations models is not directly applicable.

In this paper, we develop an approach that breaks this methodological barrier and allows us to apply the standard toolkit for solving noisy rational expectations models *within* the standard DSGE framework that is typically used for welfare and policy analysis. We use our approach to quantitatively estimate the seminal noisy rational expectations model by Hellwig (1980).<sup>2</sup>

In noisy rational expectations models, households receive a private signal about future pro-

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<sup>1</sup>See Brunnermeier (2001) and Veldkamp (2011) for excellent textbooks on the subject.

<sup>2</sup>We choose the framework by Hellwig (1980) mainly because the results are classics and require relatively little introduction. However, we believe our methodological approach is applicable more broadly, and hope it paves the way for a more general, quantitative evaluation of the noisy rational expectations literature. In addition to the noisy rational expectations literature cited above, our approach may also be applicable to a range of related dispersed information models in which agents learn from observing aggregate variables such as the capital stock or investment flows.

ductivity and can infer information about the signals received by others from observing the equilibrium stock price. The model has three main qualitative predictions: First, in a frictionless environment in which the trading motives of all economic agents are known, asset prices perfectly reveal all dispersed information (the Grossman (1976) equilibrium). Second, the trading activity of “noise traders” who randomly demand an unknown quantity of stocks interferes with the market’s capacity to aggregate information and prevents the perfect revelation of information in equilibrium. When information is not perfectly revealed, households differ in their equilibrium expectation of future productivity. Third, noise trader demand that is solely contingent on variables that are observable by households does not affect equilibrium expectations as long as the equilibrium price function remains monotonic in the productivity shock.

In the first part of the paper, we set up a DSGE model with capital accumulation, flexible labor supply, and Epstein-Zin utility in which households receive private signals about a future productivity shock and can learn from the equilibrium stock price. In addition, outside “noise traders” engage in stochastic asset purchases in the stock market, as in Hellwig (1980).

We then introduce our solution method and formally derive the conditions under which the three main predictions of the classical noisy rational expectations model carry over to the DSGE framework. The main insight from this analysis is that, under an appropriate assumption on the distribution of noise trader demand shocks, we can solve for households’ equilibrium expectations as a function of only two variables: the standard deviation of noise trader demand and the standard deviation of idiosyncratic noise in households’ private signal. Jointly, the two variables fully determine the equilibrium posterior distribution of households’ expectations of the productivity shock. In fact, we are able to derive a monotonic transformation of noise trader demand such that households’ equilibrium expectations take the same form as in the linear model.

As a result, the three main qualitative insights from the linear model seamlessly carry over to the DSGE framework. In particular, the equilibrium stock price becomes perfectly revealing of the productivity shock if no noise traders are present. In addition, any policy interventions (e.g., open market operations) in the stock market do not affect the equilibrium informativeness of stock prices as long as they are fully contingent on observables.

In the third part of the paper, we estimate and quantitatively evaluate the model. Relative to a conventional DSGE model, we have two additional parameters: the standard deviation of noise trader demand and the standard deviation of idiosyncratic noise in households’ private signal. To get a benchmark value for the size of noise trader demand shocks, we calibrate their size to the asset purchase program of the Federal Reserve. Although this estimate may not be accurate, it serves as an interpretable reference. We then choose the remaining parameter to match the cross-sectional variance of the expectation of annual GDP growth from the Survey of Professional Forecasters. Based on these estimates, we analyze the comparative statics in the

model. In a final step, we estimate both the standard deviation of noise trader demand and the standard deviation of noise in the private signal to match a set of financial and business cycle moments.

Relative to the conventional DSGE literature, the choice of frequency of our calibration is of particular importance as it determines the horizon at which households learn about the future. In order to maximize transparency, we follow the existing DSGE literature and choose the monthly frequency, such that households receive private information about productivity a month in advance. However, we note that the quantitative effects of dispersed information are likely to be proportionally larger if households learned about shocks a year or a decade in advance.

We find that dispersed information about future productivity affects the quantitative results of our DSGE model in four ways. First, households' ability to learn about future productivity affects their behavior, and especially their consumption-savings decision. In our calibration, households receive private signals about the innovation to the long-run productivity shock one month in advance. In the limit in which the standard deviation of the noise trader demand shock goes to zero, the equilibrium stock price becomes perfectly revealing and all households hold the same expectation in equilibrium. We compare this limiting case of perfect information aggregation with a standard calibration in which households receive no information at all about future productivity and find the equity premium falls by 1% and the risk-free interest rate rises by 2% when the stock price perfectly reveals the productivity shock.

Second, when noise trader demand shocks limit the stock market's capacity to aggregate information, the model cannot generate the kind of disagreement observed in the data for any reasonable size of noise trader demand shocks. For example, in our standard specification, the cross-sectional standard deviation in households' expectations of future GDP growth is 0.05%, compared to 0.27% in the survey of economic forecasters. Similarly, when we choose the precision of households' private signal to maximize the cross-sectional variance in household expectations, the cross-sectional variation in households' holdings of stocks does not exceed 0.04% in our standard specification.

Third, even moderate heterogeneity in household behavior affects the correlations and standard deviations produced by the model, as well as the level of all economic aggregates. For example, the correlation between consumption growth and investment is 0.29 when households have no information about the future, 0.27 when they have perfect information about the future, but 0.41 in our standard specification.

Fourth, aside from their effect on information aggregation, noise trader demand shocks affect the model in their own right. When we choose the standard deviation of noise trader demand shocks to maximize the overall fit of the model we find that, with sufficiently (albeit unreasonably) large shocks, the model comes closer to matching the standard deviation of stock returns and stock prices, as well as the cross-sectional standard deviation of expectations of future GDP

growth observed in the data.

This last finding illustrates a number of difficulties that arise when transporting the concept of noise traders into a general equilibrium setting. The first difficulty is that the non-fundamental asset demand of noise traders has no clear counterpart in the data.

Second, noise traders effectively act as foreign agents, adding and subtracting resources from the economy at different points in time. When we change the standard deviation of noise trader demand shocks, we also directly change the volatility of all macroeconomic aggregates, which makes comparative statics with respect to the standard deviation of noise trader demand shocks somewhat difficult to interpret.

Finally, heterogeneous classes of agents, and in particular non-maximizing agents such as noise traders, make thinking about welfare difficult. For example, it is unclear whether one should include noise traders in a welfare measure, and if so, how to calculate their utility. On the other hand, performing welfare analysis based on the utility of rational households alone may lead to counterintuitive results as wealth transfers occur between the two groups in equilibrium.

In a related paper (Hassan and Mertens, 2010) we address these issues by removing noise traders from the model altogether, and instead work only with a single class of “near-rational” households. Near-rational households are perfectly rational in all dimensions of their behavior, but make small correlated errors when forming expectations about future productivity (they are on average slightly too optimistic in some states of the world and slightly too pessimistic in others). By the envelope theorem, such small errors are of little concern to an individual household, because they have only a lower-order effect on its own utility. However, as a result of these small errors being correlated across households, they affect the equilibrium stock price. As households (rationally) attempt to learn from the equilibrium price, the common component of households’ errors is amplified and has a first-order external effect on the market’s capacity to aggregate information. The model thus endogenously generates non-fundamental noise in the stock price through an information externality: a given household does not internalize the effect of its own error on the equilibrium expectation of other households in the economy. Having eliminated non-maximizing agents from the model, we are then able to address a number of welfare-related questions that we sidestep in the current paper. In particular, we show that a deterioration of the market’s capacity to aggregate information may cause large (first-order) aggregate welfare losses. Mertens (2009) analyzes a range of policies that may mitigate the information externality and improve the market’s capacity to aggregate information.

In the interest of maintaining a maximum comparability to the most standard noisy rational expectations model, we maintain the noise trader assumption in the current paper despite the difficulties with its normative interpretation, and focus on the positive predictions of the model throughout.

The solution method we use in this paper generalizes a solution method we use in earlier

work (Mertens, 2009; Hassan and Mertens, 2010). It builds on Judd (1998) and Judd and Guu (2001) in using an asymptotically valid higher-order expansion in all state variables around the deterministic steady state of the model in combination with a nonlinear change of variables (Judd (2002)). Tille and van Wincoop (2013) independently develop a similar solution method based on perturbation methods.<sup>3</sup> Albagli et al. (2011) develop an alternative approach in which they constrain each agent’s asset purchases, such that the optimality conditions of only one marginal agent holds in equilibrium.

This paper is part of a large literature that strives for a richer representation of financial markets within otherwise standard DSGE models. Examples include Bernanke and Gertler (1989), Bernanke et al. (1999), Woodford and Curdia (2009), He and Krishnamurthy (2011), and Brunnermeier and Sannikov (2013). We add to this literature by providing a simple way to incorporate the notion that stock markets aggregate and transmit information into otherwise standard quantitative models.

Another closely related literature considers the effect of information about future fundamentals in the form of exogenous news shocks within DSGE models (Jaimovich and Rebelo, 2009; Barsky and Sims, 2011; Schmitt-Grohé and Uribe, 2012). Blanchard et al. (2013) estimate the relative contributions of noise shocks and information in the data. We add to this literature by providing a means to quantify the extent to which asset markets endogenously transmit news about future fundamentals.

The remainder of the paper is structured as follows. Section 2 introduces the classic noisy rational expectations model and describes the usual steps in solving the linear model. Section 3 sets up the quantitative DSGE model and shows how we can follow the same steps when solving for equilibrium expectations in the non-linear model. Section 4 characterizes the dynamic effects of dispersed information in general terms. Section 5 quantitatively analyzes and estimates the model. Section 6 concludes.

## 2 The Classic Noisy Rational Expectations Model

The model economy exists at two points in time  $t = 1, 2$ . It is populated by a continuum of identical households indexed by  $i \in [0, 1]$ . At  $t = 1$ , each household is endowed with  $N$  units of a numéraire good that can be stored until  $t = 2$  and  $K$  units of capital. At  $t = 2$ , each unit of capital returns  $\eta$  units of the numéraire

$$Y = \eta K, \quad \eta \sim N(\bar{\eta}, \sigma_\eta^2). \tag{1}$$

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<sup>3</sup>Also see Tille and van Wincoop (2008) and Devereux and Sutherland (2011).

Before trading commences, each household receives a private signal about productivity:

$$s_i = \eta + \nu_i, \quad (2)$$

where  $\nu_i$  represents *i.i.d.* draws from a normal distribution with zero mean and variance  $\sigma_\nu^2$ . Given  $s_i$ , each household chooses to purchase  $z_i$  units of capital to maximize expected utility from terminal wealth,

$$E_{1i} [U_i] = E_{1i} [w_{2i}] - \frac{\rho}{2} V_1[w_{2i}], \quad (3)$$

where  $E_{1i} [\eta] = E [\eta | s_i, Q]$  and  $V_1[w_{2i}]$  is the posterior variance of  $w_{2i}$  conditional on the private signal  $s_i$  and the stock price  $Q$ . The parameter  $\rho > 0$  determines the degree of absolute risk aversion. Terminal wealth is given by

$$w_{2i} = z_i(\eta - Q) + N. \quad (4)$$

Households thus optimally demand

$$z_i = \frac{E_{1i} [\eta] - Q}{\rho V_1[\eta]} \quad (5)$$

units of capital.

Market clearing requires that aggregate asset demand is equal to aggregate supply:

$$\int_0^1 z_i di + T(Q) + \tau = K, \quad (6)$$

where  $T(Q)$  reflects asset purchases by noise traders that follow some policy rule contingent on  $Q$  and  $\tau$  are asset purchases by noise traders that are stochastic from the perspective of households. Throughout, we focus on symmetric equilibria.

**Assumption L1** Contingent asset purchases by noise traders are a linear function of  $Q$

$$T(Q) = b_0 + b_1 Q. \quad (7)$$

**Assumption L2** Random asset purchases by noise traders follow the normal distribution

$$\tau \sim N(0, \sigma_\tau^2). \quad (8)$$

**Assumption L3** Households can condition their expectation on prices ( $Q$ ) but not on aggregate quantities ( $\int_0^1 z_i di$ ).



## 2.1 Solving the Model

The standard approach to solving this “CARA-Gaussian” model proceeds in three steps. Because the steps in the solution of the DSGE model are generalized versions of these same steps, we derive them in detail to show the analogy in the procedure.

### Step 1: Guess Equilibrium Price Function

We guess that the equilibrium price function is linear in  $\eta$  and  $\tau$

$$Q = \pi_0 + \pi_1\eta + \gamma\tau, \quad (9)$$

where  $\pi_0$ ,  $\pi_1$ , and  $\gamma$  are endogenous coefficients to be solved below.

### Step 2: Bayesian Expectation Formation

Plugging (5) into (6) and rearranging terms yields

$$\hat{q} \equiv \int_0^1 E_{1i}[\eta] di + \tau\rho V_1[\eta] = \rho V_1[\eta] (K - T[Q]) + Q. \quad (10)$$

Note that all variables on the right-hand side of the equation are known at  $t = 1$ . Observing  $Q$  is thus equivalent to observing the average expectation of  $\eta$  across households with some error  $\tau\rho V_1[\eta]$ . Without loss of generality, we refer to this monotonic transformation of the stock price as  $\hat{q}$ .

Assuming our guess in (9) is correct, we can show that the rational expectation of  $\eta$  given the private signal and  $\hat{q}$  takes a linear form

$$E_{1i}[\eta] = \alpha_0 + \alpha_1 s_i + \alpha_2 \hat{q}, \quad (11)$$

where the constants  $\alpha_0$ ,  $\alpha_1$ , and  $\alpha_2$  are Bayesian weights households give to the prior, the private signal, and the monotonic transformation of the market price of capital, respectively.

Plugging the definition in (10) into (11), integrating on both sides, solving for  $\int E_{1i}[\eta] di$ , and then adding  $\tau\rho V_1[\eta]$  on both sides yields

$$\hat{q} = \frac{\alpha_0}{1 - \alpha_2} + \frac{\alpha_1}{1 - \alpha_2} \eta + \frac{1}{1 - \alpha_2} \tau\rho V_1[\eta].$$

Observing the stock price is thus also equivalent to observing an unbiased signal of  $\eta$

$$\left( \hat{q} - \frac{\alpha_0}{1 - \alpha_2} \right) \frac{1 - \alpha_2}{\alpha_1} = \eta + \frac{\rho V_1[\eta]}{\alpha_1} \tau. \quad (12)$$

We thus have a prior and two independent, unbiased signals of  $\eta$ . It follows that the posterior variance is the inverse of the sum of the precision of these three elements<sup>4</sup>

$$V[\eta|s_i, Q] = V_1[\eta] = \left( \sigma_\eta^{-2} + \sigma_\nu^{-2} + \left( \frac{\alpha_1}{\rho V_1[\eta]} \right)^2 \sigma_\tau^{-2} \right)^{-1}. \quad (13)$$

Moreover, the conditional expectation of  $\eta$  is the precision-weighted sum of the signals and the prior mean divided by the posterior precision

$$E[\eta|s_i, Q] = \frac{\sigma_\eta^{-2} \bar{\eta} + \sigma_\nu^{-2} s_i + \left( \frac{\alpha_1}{\rho V_1[\eta]} \right)^2 \sigma_\tau^{-2} \left( \eta + \frac{\rho V_1[\eta]}{\alpha_1} \tau \right)}{V_1[\eta]^{-1}}. \quad (14)$$

Matching coefficients (14) with (11) yields

$$\alpha_1 = \frac{V_1[\eta]}{\sigma_\nu^2}. \quad (15)$$

Plugging into (13) yields

$$V_1[\eta] = \left( \frac{1}{\sigma_\eta^2} + \frac{1}{\rho^2 \sigma_\nu^4 \sigma_\tau^2} + \frac{1}{\sigma_\nu^2} \right)^{-1}. \quad (16)$$

### Step 3: Verification of the Price Guess

Plugging (7), (14), and (15) into both sides of the second equality in (10), solving for  $Q$  and collecting terms by  $\eta$  and  $\tau$  yields

$$Q = \frac{(\sigma_\eta^{-2} \bar{\eta} - \rho(K - b_0)) V_1[\eta]}{1 - \rho V_1[\eta] b_1} + \frac{\sigma_\nu^{-2} (1 + \rho^{-2} \sigma_\nu^{-2} \sigma_\tau^{-2}) V_1[\eta]}{1 - \rho V_1[\eta] b_1} \eta + \frac{(\rho^{-1} \sigma_\nu^{-2} \sigma_\tau^{-2} + \rho) V_1[\eta]}{1 - \rho V_1[\eta] b_1} \tau \quad (17)$$

Matching coefficients with (9), plugging in (16) and simplifying yields

$$\pi_1 = \frac{\sigma_\eta^2 (\rho^2 \sigma_\nu^2 \sigma_\tau^2 + 1)}{\sigma_\eta^2 - \rho^2 \sigma_\nu^2 \sigma_\tau^2 (\sigma_\eta^2 (b_1 \rho \sigma_\nu^2 - 1) - \sigma_\nu^2)} \quad \text{and} \quad \gamma = \rho \sigma_\nu^2 \pi_1, \quad (18)$$

verifying the guess (9).

## 2.2 Three Classical Results

From (16), we can readily read off the three main qualitative predictions of the noisy rational expectations model.

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<sup>4</sup>See Appendix A for a formal derivation using the projection theorem.

**Result 1.** *Absent stochastic noise trader demand, the stock price becomes perfectly revealing*

$$\lim_{\sigma_\tau \rightarrow 0} V_1[\eta] = 0.$$

**Result 2.** *Noise trading reduces the market's capacity to aggregate information,*

$$\frac{\partial V_1[\eta]}{\partial \sigma_\tau} > 0.$$

*When information aggregation is less than perfect, households put weight on their private signal and thus hold heterogeneous expectations in equilibrium. (This follows directly from (15).)*

**Result 3.** *Noise traders' contingent asset purchases have no effect on price informativeness. (Note that  $T(Q)$  does not feature in (16).)*

### 3 A DSGE Model with Dispersed Information

We now generalize Results 1-3 to the context of a quantitative DSGE model. To this end, we set up a decentralization of the real business cycle model by Croce (2013). We choose this model because it performs well on matching quantities as well as asset prices and can readily be solved using perturbation methods. However, in principle, we believe our method is applicable to any DSGE model in which equilibrium policy functions are smooth.

#### 3.1 Setup

Technology is characterized by a linear homogeneous production function that uses capital,  $K_t$ , and labor,  $N_t$ , as inputs

$$Y_t = K_t^\alpha (e^{a_t} N_t)^{1-\alpha}, \quad (19)$$

where  $Y_t$  stands for output of the consumption good. The growth rate of labor productivity,  $\Delta a_{t+1} = \log(A_{t+1}/A_t)$ , has a long-run risk component,  $\omega$ , and a short-run risk component,  $\varphi$ ,

$$\Delta a_{t+1} = \mu_a + \omega_t + \sigma_\varphi \varphi_{t+1}. \quad (20)$$

where the long-run component follows

$$\omega_t = \rho \omega_{t-1} + \sigma_\eta \eta_t. \quad (21)$$

Both shocks to productivity,  $\varphi$  and  $\eta$ , are *i.i.d.* standard normal.

The equation of motion of the capital stock is

$$K_{t+1} = (1 - \delta_k)K_t + I_t - G_t K_t, \quad (22)$$

where  $I_t$  denotes aggregate investment and  $\delta_k$  is the rate of depreciation. Furthermore, convex adjustment costs to capital arise following Jermann (1998)

$$G_t = \frac{I_t}{K_t} - \left( \frac{v_1}{1 - \frac{1}{\xi}} \left( \frac{I_t}{K_t} \right)^{1 - \frac{1}{\xi}} + v_0 \right), \quad (23)$$

where  $v_1$ ,  $v_2$ , and  $\xi$  are positive constants.

A representative firm purchases capital and labor services from households. As it rents services from an existing capital stock, the firm's objective collapses to a period-by-period maximization problem

$$\max_{K_t, N_t} Y_t - d_t K_t - w_t N_t, \quad (24)$$

where  $K_t$  and  $N_t$  denote factor demands for capital and labor, respectively. First-order conditions with respect to capital and labor pin down the market-clearing wage,

$$w_t = (1 - \alpha) \frac{Y_t}{N_t}, \quad (25)$$

and the rental rate of capital,  $d_t = \alpha \frac{Y_t}{K_t}$ . Both factors receive their marginal product. Because the production function is linear homogeneous, the representative firm makes zero economic profits from producing the consumption good.

The representative firm owns an investment goods sector that converts the consumption good into units of capital, while incurring adjustment costs. It takes the price of capital as given and then performs instantaneous arbitrage:

$$\max_{I_t} Q_t (I_t - G_t K_t) - I_t. \quad (26)$$

Taking the first-order condition of (26) gives us the equilibrium price of capital.

$$Q_t = \frac{1}{1 - G'_t}. \quad (27)$$

Due to decreasing returns to scale in converting consumption goods to capital, the investment goods sector earns positive profits in each period. Profits are paid to shareholders as a part of

dividends per share:<sup>5</sup>

$$D_t = d_t + Q_t \left( G'_t \frac{I_t}{K_t} - G_t \right). \quad (28)$$

A continuum of households on the interval  $i \in [0, 1]$  has Epstein and Zin (1989) preferences over the consumption bundle  $\tilde{C}_{it}$

$$U_{it} = \left( (1 - \delta) \tilde{C}_{it}^{1 - \frac{1}{\psi}} + \delta E_{it} [U_{it+1}^{1 - \gamma}]^{\frac{1 - \frac{1}{\psi}}{1 - \gamma}} \right)^{\frac{1}{1 - \frac{1}{\psi}}}, \quad (29)$$

where the parameters  $\psi$  and  $\gamma$  measure the households' intertemporal elasticity of substitution and relative risk aversion, respectively. The consumption bundle  $\tilde{C}_{it}$  is a CES aggregate of consumption and leisure

$$\tilde{C}_{it} = \left( o C_{it}^{1 - \frac{1}{\xi_i}} + (1 - o) (A_{t-1} (1 - n_{it}))^{1 - \frac{1}{\xi_i}} \right)^{\frac{1}{1 - \frac{1}{\xi_i}}}, \quad (30)$$

where the weight of leisure scales with aggregate productivity,  $A$ , to ensure the existence of a balanced growth path. At the beginning of every period, each household receives a private signal about the shock to long-run productivity:

$$s_{it} = \eta_{t+1} + \nu_{it}, \quad (31)$$

where  $\nu_{it}$  represents *i.i.d.* draws from a normal distribution with zero mean and variance  $\sigma_\nu^2$ .

Given  $s_{it}$  and their knowledge about the state of the economy, households maximize life-time utility (29) by choosing a time path for consumption, labor, and their holdings of stocks  $\{C_{it}, n_{it}, k_{it}\}_{t=0}^\infty$ . Each household's optimization is subject to a budget constraint:

$$Q_t k_{it+1} = Q_{t-1} R_t k_{it} + H_{it} - C_{it} + w_t n_{it}, \quad (32)$$

where  $Q_t$  denotes the price of capital,  $H_{it}$  transfers from state-contingent claims discussed below, and  $w_t$  the wage rate. The returns to capital are defined as

$$R_{t+1} = \frac{(1 - \delta_k) Q_{t+1} + \alpha \frac{Y_{t+1}}{K_{t+1}} + Q_{t+1} \left( G'_{t+1} \frac{I_{t+1}}{K_{t+1}} - G_{t+1} \right)}{Q_t}. \quad (33)$$

Foreign noise traders engage in open market operations in the stock market using an independent source of wealth. In each period, they purchase  $T^k(S_t) + T_{t+1}^\tau$  units of capital, where

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<sup>5</sup>Alternatively, profits may be paid to households as a lump-sum transfer; this assumption matters little for the quantitative results of the model.

the first term follows a policy rule that is a function of the vector of observable state variables  $S_t$ , and the second term,  $T_{t+1}^\tau$ , is random from the perspective of the households.<sup>6</sup> Despite being determined in period  $t$ , we denote noise trader demand by an index  $t + 1$  since it interferes in the market for capital  $K_{t+1}$ . The market clearing conditions for the stock, labor, and goods markets are

$$K_{t+1} = \int k_{it+1} di + T^k(S_t) + T_{t+1}^\tau, \quad (34)$$

$$N_t = \int n_{it} di, \quad (35)$$

and

$$Y_t + \varsigma_t = C_t + I_t, \quad (36)$$

where  $\varsigma_t$  stands for the net value of noise traders' purchases,

$$\varsigma_t = Q_t (T^k(S_t) + T_{t+1}^\tau) - Q_{t-1} R_t (T^k(S_{t-1}) + T_t^\tau). \quad (37)$$

Noise traders therefore trade goods with households and have a non-zero trade balance with the economy. The trade balance corresponds to financial claims which are held in the form of noise traders' ownership of capital.

Solving this model poses two main challenges. First, equilibrium quantities are non-linear functions of the underlying shocks. Maintaining the assumption of normally distributed shocks inevitably leads to a non-normal distribution of equilibrium variables. As a result, we can no longer solve for conditional distributions in closed form based on these quantities. Second, information dispersion results in a distribution of choices and state variables, which generates a non-degenerate distribution of wealth across households. To focus our attention on the first challenge, we side-step the second challenge by introducing contingent claims that households can use to insure against the idiosyncratic risk they face due to their private signal.<sup>7</sup>

At the beginning of each period (and before receiving their private signal), households can trade claims that are contingent on the state of the economy and on the realization of the noise they receive in their private signal,  $\nu_{it}$ . These claims are in zero net supply and pay off at the beginning of the next period. Since they are traded before any information about  $\eta_{t+1}$  is known, their prices cannot reveal any information about future productivity. Contingent claims trading thus completes markets between periods, without affecting households' signal extraction problem.

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<sup>6</sup>We introduce  $T^k(S_t) = 0$  to show that result 1 continues to hold in the DSGE model. In our calibration we set  $T^k(S_t) = 0$ .

<sup>7</sup>See Mertens and Judd (2013) for a perturbation-based approach to solving incomplete markets models with substantial heterogeneity.

In equilibrium, all households choose to hold these securities with net payoff

$$H_{it} = \begin{cases} Q_{t-1}R_t (K_t - T^k [S_{t-1}] - T_t^\tau) - Q_{t-1}R_t k_{it} & \text{if } \{\tilde{C}_{it}, n_{it}, k_{it}\} = \arg \max (29)|_{H_{it}=0}, \\ 0 & \text{otherwise} \end{cases} \quad (38)$$

such that all households enter each period with the same amount of wealth.<sup>8</sup> From (34), it follows immediately that these claims are in zero net supply

$$\int H_{it} di = 0. \quad (39)$$

## 3.2 Equilibrium

**Definition 1.** *Given a time path of shocks, an equilibrium in this economy is a time path of quantities, signals, and prices with the following properties:*

1. *The time path of households' consumption, stock holdings, and labor supply maximizes (29) given the vector of prices and signals.*
2. *The demand for capital and labor services solve the representative firm's maximization problem (24) given the vector of prices.*
3. *The time path of capital investment solves the investment good sector's problem (26) given the vector of prices.*
4. *The time paths of stock prices, wages, and stock returns clear the markets for stocks, labor services, and capital services, respectively.*

We compute the first-order and envelope conditions for households in Appendix B.2. After taking the ratio of the first-order conditions with respect to labor and consumption, we get the marginal rate of substitution between labor supply and consumption

$$\frac{1 - o A_{t-1}^{1-\frac{1}{\xi_l}} (1 - n_{it})^{-\frac{1}{\xi_l}}}{o C_{it}^{-\frac{1}{\xi_l}}} = w_t. \quad (40)$$

The optimal choice of stock holdings is determined by the familiar asset pricing equation,

$$E_{it}[M_{it+1}R_{t+1}] = 1, \quad (41)$$

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<sup>8</sup>To save space we directly use the equilibrium result that households will perfectly share the risk associated with the noise in their private signal.  $H_{it}$  is thus the equilibrium net payoff received by household  $i$  from its contingent claims trading.

where the stochastic discount factor,  $M_{it+1}$ , is given by

$$M_{it+1} = \delta \left( \frac{C_{it+1}}{C_{it}} \right)^{-\frac{1}{\xi_i}} \left( \frac{\tilde{C}_{it+1}}{\tilde{C}_{it}} \right)^{\frac{1}{\xi_i} - \frac{1}{\Psi}} \left( \frac{U_{it+1}}{E_{it} [U_{it+1}^{1-\gamma}]^{\frac{1}{1-\gamma}}} \right)^{\frac{1}{\Psi} - \gamma}, \quad (42)$$

and returns  $R_{t+1}$  are defined in (33). Given these conditions of optimality, consumption follows from the household's budget constraint (32).

For convenience, we write the average of stock holdings across households as

$$\int k_{it+1} di = \bar{K}_{t+1}, \quad (43)$$

such that we can rewrite the market-clearing condition for capital (34) as  $K_{t+1} = \bar{K}_{t+1} + T^k(S_t) + T_{t+1}^\tau$ .

The labor market clears when condition (35) holds. Again for convenience, we write aggregate consumption and labor supply as

$$X_t = \int X_{it} di, \quad X = C, N. \quad (44)$$

Note that noise trader demand shocks affect this system of equations via the resource constraint (36), which determines the amount of aggregate investment. Investment, in turn, influences the price of capital  $Q$  via equation (27).

### 3.3 Solving the Model

In this section, we generalize the three solution steps for the linear model in section 2 to solve the DSGE model with dispersed information. The main trick is again to define a statistic  $\hat{q}$  that aggregates all relevant information about  $\eta_{t+1}$ . We conjecture that this statistic takes analogous form to the linear model,

$$\hat{q}_t \equiv \bar{E}_t + \frac{V_1[\eta]}{\sigma_\eta^2} \tau_t, \quad (45)$$

where  $\bar{E}_t = \int E_{it}[\eta_{t+1}] di$  denotes the average expectation of  $\eta_{t+1}$  across households. We guess that the equilibrium stock price is a function of known state variables of the economy and  $\hat{q}$ , where the mapping from  $\hat{q}$  into  $Q$  can now be non-linear. Using this guess, we show how households form expectations in the non-linear model. We then show that the signal extraction problem remains linear and Gaussian and can thus be solved in closed form. As an immediate consequence, the three main theoretical results from the linear setting carry over to the dynamic economy. In a third step, we confirm our initial guess and show that we find a recursive equilibrium. To complete each of these steps, we need three assumptions, which generalize each of the assumptions L1-L3



in the linear model of section 2.

**Assumption Q1** Contingent stock purchases by noise traders are a function of known state variables,

$$T_t^k = T^k(S_t),$$

where

$$S_t = \{K_t, T_t, \omega_{t-1}, \eta_t, \varphi_t\}.$$

**Assumption Q2** The stochastic component of noise trader demand  $T^\tau$ , is a function of a normally distributed shock to noise trader demand  $\tau \sim N(0, \mu)$  and follows a state-dependent distribution such that the following property holds

$$\hat{I}(S_t, \bar{E}_t, \hat{q}_t) + Q_t T^\tau(S_t, \hat{q}_t, \bar{E}_t, \tau_t) = I(S_t, \hat{q}_t), \quad (46)$$

where  $T^\tau(S_t, \hat{q}_t, \bar{E}_t, \tau_t) = 0$  iff  $\tau_t = 0$  and  $\hat{I}_t = Y_t - Q_{t-1} R_t T_t^\tau - C_t$  is the “fundamental” component of aggregate investment.

Just like we needed stochastic noise trader demand to be a linear function of a normally distributed shock in section 2, we now need it to be a particular (non-linear) function of a normally distributed shock. This function adds noise to the second argument of  $\hat{I}$  such that aggregate investment (and thus the equilibrium stock price) is a function of only  $\hat{q}$  and  $S_t$ . We show below that this assumption uniquely determines  $T^\tau$  as a particular multivariate power series in  $\tau$ .

**Assumption Q3** When forming expectations about future productivity, households condition their expectations on their private information, the equilibrium stock price, and the commonly known state variables of the economy  $S_t$ , but not on other quantities or prices.<sup>9</sup>

$$E_{it}[\eta_{t+1}] = E[\eta_{t+1} | S_t, s_{it}, Q_t]. \quad (47)$$

As L3 in the linear model, this assumption rules out that households condition their expectation on the “fundamental” demand for stocks or any quantity that reflects this information. In the context of this general equilibrium model, it also implies that households cannot condition their expectation of  $\eta$  on the wage rate or other prices. Households in our model thus act as “Lucas households” where the member of the household charged with forecasting  $\eta_{t+1}$  observes  $S_t$ ,  $s_{it}$ , and  $Q$ , forms her expectation based on this information, and then communicates it to another household member who decides on the household’s labor supply.

We make this assumption mainly for convenience. In the more general case in which households can condition their expectation on two prices, the model simply requires an additional

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<sup>9</sup>Agents also know the history of shocks which does not add any predictive power to expectations due to the equilibrium being recursive and choices being determined by the state space.

source of non-fundamental noise.

In addition to assumptions Q1-Q3, we require the following condition.

**Condition 1.** *The equilibrium stock price,  $Q$ , is a strictly monotonic function of  $\hat{q}$ .*

This condition typically holds in a wide range of models. It states that, other things equal, the stock price either strictly increases or strictly decreases when households expect higher productivity in the future. While we cannot solve for the mapping of  $\hat{q}$  into  $Q$  in closed form, we verify this condition ex-post using the numerical solution of the model.

### 3.3.1 Step 1: Guess for state space

Analogously to the linear case, we start by guessing the form of equilibrium variables. The solution of the model is a set of equilibrium quantities and prices that are functions of the underlying state variables. We split these state variables into the commonly known set,  $S_t$ , and a set that depends on expectations about  $\eta$ .

**Lemma 1.** *There exists a recursive equilibrium satisfying the system of equations defined in section 3.2 with the following properties:*

1. *The equilibrium stock price,  $Q_t$ , is a function of the current (commonly known) state of the economy,  $S_t$ , and  $\hat{q}_t$ .*
2. *All other prices and aggregate quantities depend on  $S_t$ , the average expectation,  $\bar{E}_t$ , and  $\hat{q}_t$*

$$X_t = X(\bar{S}_t), X = C, N, \bar{K}', w, d, R, \quad (48)$$

where we abbreviate  $\bar{S}_t = \{S_t, \hat{q}_t, \bar{E}_t\}$ .

3. *A household's optimal behavior is a function of  $S_t$ , the household's conditional expectation of next period's innovation to long-run productivity  $E_{it}[\eta_{t+1}]$ , the average expectation,  $\bar{E}_t$ , and the statistic  $\hat{q}_t$ . The conditional expectation, in turn, depends on the private signal  $s_{it}$  as well as the demand statistic  $\hat{q}_t$ ,*

$$x_{it} = x(S_{it}), x = c, n, k, \quad (49)$$

where, for convenience, we write  $S_{it} = \{\bar{S}_t, E_{it}\}$ . In a slight abuse of notation,  $E_{it} = E_{it}[\eta_{t+1}]$ .

In the remainder of the section, we verify the validity of the lemma.

## Step 2: Bayesian Expectation Formation

Given Lemma 1, we invoke condition 1 (which ensures the stock price is a strictly monotonic function of  $\hat{q}$ ) and assumption Q3 to arrive at the main insight of our solution method: learning from the stock price  $Q$  is just as informative as learning from its monotonic transformation,  $\hat{q}$ . Since there is a one-to-one mapping between the stock price and  $\hat{q}$  conditional on all commonly known state variables,  $S_t$ , households can infer the only unknown quantity  $\hat{q}$  from observing the stock price. In other words, conditioning on  $Q$  and  $\hat{q}$  spans the same  $\sigma$ -algebra.

$$E_{it}[\eta_{t+1}] = E[\eta_{t+1}|S_t, s_{it}, Q_t] = E[\eta_{t+1}|S_t, s_{it}, \hat{q}_t]. \quad (50)$$

The signal extraction problem is thus isomorphic to the one in section 2, despite the non-linear nature of the quantitative model. As a result, we can solve for equilibrium expectations independently of the aggregate dynamics of the model.

**Lemma 2.** *Households' equilibrium expectations of  $\eta_{t+1}$  are independent of the aggregate dynamics of the model. Conditioning on the (normally-distributed) demand statistic  $\hat{q}$  results in expectations of the form*

$$E_{it}[\eta_{t+1}] = \frac{\sigma_\nu^{-2} (\eta_{t+1} + \nu_{it}) + \frac{\sigma_\eta^4}{\sigma_\nu^4 \sigma_\tau^2} \left( \eta_{t+1} + \frac{\sigma_\nu^2}{\sigma_\eta^2} \tau_t \right)}{V_t[\eta_{t+1}]^{-1}}. \quad (51)$$

Moreover, the conditional expectation of  $\eta_{t+1}$  is

$$V_t[\eta_{t+1}] = \left( \sigma_\eta^{-2} + \sigma_\nu^{-2} + \frac{\sigma_\eta^4}{\sigma_\nu^4} \sigma_\tau^{-2} \right)^{-1}. \quad (52)$$

The coefficient on the private signal is given by

$$\alpha_1 = \frac{V_t[\eta_{t+1}]}{\sigma_\nu^2} \quad (53)$$

and the coefficient on  $\hat{q}$  is given by

$$\alpha_2 = \frac{1}{\sigma_\eta^{-4} \sigma_\nu^2 \sigma_\tau^2 + 1}. \quad (54)$$

**Proof:** See Appendix B.4.

As an immediate consequence, we get the following corollary.

**Corollary 1.** *Given condition 1 and assumptions Q1-Q3, results 1-3 hold in the dynamic economy.*

Corollary 1 shows that the main insights from the linear setting survive in the non-linear economy. First, without stochastic shocks to noise trader demand, the economy becomes perfectly revealing. In the context of a dynamic economy, this result means households know innovations to the long-run component of productivity one period in advance. The expectations held by households then act as they would in a “news shocks” model.

The second result states that stochastic shocks to noise trader demand increase the conditional variance of  $\eta_{t+1}$ . As a result, stock prices and all economic aggregates reflect both information about the future and noise. Moreover, when information aggregation is less than perfect, households put weight on their private signal and thus hold heterogeneous expectations in equilibrium. Heterogeneity in equilibrium expectations in turn generates cross-sectional variation in consumption, investment, and labor supply decisions.

Third, noise trading will only have an impact on expectations and information aggregation insofar as it adds noise to the price process. Noise trades based on observable variables will not affect equilibrium expectations.

Since the part of noise trading conditioning only on observable variables,  $T^k$ , does not affect equilibrium expectations, we set it to zero for the remainder of the paper.

### 3.3.2 Step 3: Verification of guess

Whereas the previous two steps give us a framework for thinking about the equilibrium, we need to make sure the guess for the equilibrium structure is indeed correct. We proceed in three steps that demonstrate the consistency of each of the three statements in Lemma 2.

The second and third statements in Lemma 1 posit that a household’s consumption, labor supply, and investment decisions can only depend on the variables included in the vector  $S_{it} = \{\bar{S}_t, E_{it}\}$ , whereas  $\bar{S}_t$  determines all aggregate variables and prices. Assuming these statements are correct, we can write any individual choice as a function  $x_i(S_{it})$  and all aggregate variables and prices as functions as  $X(\bar{S}_t)$ . Plugging this structure into the model’s equilibrium conditions and re-arranging terms results in a form

$$g_l(S_{it}) = E_{it} [g_r(S_{it}, S_{it+1})], \quad (55)$$

where  $g_l(\cdot)$  and  $g_r(\cdot)$  are analytic, continuously differentiable functions, and we have used the fact that  $\bar{S}_t \subset S_{it}$ . (See Appendix B.3 for the full list of equilibrium conditions and analytical details.)

Because the functions  $x_i(S_{it})$  are the solution to the system of equations (55), the key to showing the first part of Lemma 1 is to show we can rewrite  $E_{it} [g_r(S_{it}, S_{it+1})]$  as a function of  $S_{it}$ . If all equilibrium conditions depend only on  $S_{it}$ , the same must be true for the the optimal

behavior that is derived from these conditions. The proof follows from Taylor's theorem and the properties of the multivariate normal distribution.

We begin by rewriting  $g_r$  as a function of all elements of  $S_{it}$

$$\begin{aligned} g_r [S_{it}, K_{t+1}, T_{t+1}, \omega_t, \eta_{t+1}, \varphi_{t+1}, \hat{q}_{t+1}, \bar{E}_{t+1}, E_{it+1}] \\ &= \hat{g}_r [S_{it}, K_{t+1}, \tau_{t+1}, \omega_t, \eta_{t+1}, \varphi_{t+1}, \hat{q}_{t+1}, \bar{E}_{t+1}, E_{it+1}] \\ &= \sum_{\mathbf{j}} \frac{c_{\mathbf{j}}(S_{it})}{\mathbf{j}!} (K_{t+1} - K_0)^{j_1} \tau_{t+1}^{j_2} \omega_t^{j_3} \eta_{t+1}^{j_4} \varphi_{t+1}^{j_5} \hat{q}_{t+1}^{j_6} \bar{E}_{t+1}^{j_7} E_{it+1}^{j_8} \end{aligned}$$

The first equality follows from assumptions Q1 and Q3, which implies that we can rewrite  $T_{t+1}$  as a function of state variables known in period  $t$  and the noise shock  $\tau_{t+1}$ . For the second equality, we replace  $g_r$  with its infinite-order Taylor series expansion, where  $K_0$  is the level of capital at the deterministic steady state,  $c_{\mathbf{j}}(S_{it})$  denotes the (state- $t$  dependent) coefficients of the Taylor series, and  $\mathbf{j} = (j_1, j_2, j_3, j_4, j_5, j_6, j_7, j_8)$  is a multi-index for the expansion. (Note that to save space, we have absorbed all the terms depending on  $S_{it}$  into the coefficients of the expansion.)

Now we take the expectation of  $g_r$  conditional on  $S_t$ ,  $s_{it}$ , and  $Q_t$ . The terms depending on  $K_{t+1}$  and  $\omega_t$  are known at time  $t$  and can thus be taken outside the expectations operator. Moreover, we get a series of terms depending on the conditional expectation of  $\varphi_{t+1}$ . Since  $\varphi_{t+1}$  is unpredictable for an investor at time  $t$  and all shocks are uncorrelated with each other, the first-order term is 0, and all the higher-order terms are known moments of the unconditional distribution of  $\varphi$   $E_{it}[\varphi_{t+1}^j] = E[\varphi_{t+1}^j]$  (recall that all higher-order moments of the normal distribution are fully determined by its mean and variance). The same is true for the terms depending on  $E_{it}[\hat{q}_{t+1}^j] = E[\hat{q}_{t+1}^j]$ ,  $E_{it}[\bar{E}_{t+1}^j] = E[\bar{E}_{t+1}^j]$ , and  $E_{it}[E_{it+1}^j] = E[E_{it+1}^j]$ , because all three arguments are normally distributed and have an unconditional mean and variance that follows directly from Lemma 2. The only terms remaining inside the expectations operator are those depending on  $\tau_t$  and  $\eta_{t+1}$ . We can thus write

$$\begin{aligned} E_{it} [\hat{g}_r [S_{it}, S_{it+1}]] &= \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} \frac{\hat{c}_{jk}(S_{it}, K_{t+1}, \rho\omega_{t-1} + \sigma_{\eta}\eta_t)}{j!k!} E_{it} [\tau_t^j \eta_{t+1}^k] \\ &= g_l(K_t, T_t, \omega_{t-1}, \eta_t, \varphi_t, \hat{q}_t, \bar{E}_t, E_{it}), \end{aligned} \tag{56}$$

where the coefficients  $\hat{c}_{jk}(S_{it}, K_{t+1}, \omega_t)$  collect all the terms depending on  $K_{t+1}$ ,  $\omega_t$ , and the higher unconditional moments of  $\eta_{t+1}$ ,  $\bar{E}_{t+1}$ , and  $E_{it+1}$ .

To deal with the remaining conditional term,  $E_{it}[\tau_t^j \eta_{t+1}^k]$ , we use the fact that the two random variables are independent. As a result, their monomials  $\tau_t^j$  and  $\eta_{t+1}^k$  do not co-vary and we can calculate them independently.

$$E_{it}[\tau_t^j \eta_{t+1}^k] = Cov_{it} [\tau_t^j, \eta_{t+1}^k] + E_{it}[\tau_t^j] E_{it} [\eta_{t+1}^k] = E_{it} [\tau_t^j] E_{it} [\eta_{t+1}^k].$$

Now note from Lemma 2 that  $\eta_{t+1}$  is conditionally normal distributed, where its mean and variance are given by (51) and (52), respectively. All higher moments, that is, the conditional expectation of monomials  $\eta_{t+1}^j$  for  $j > 2$  are fully determined by the conditional mean and variance. Since the conditional variance does not vary over time, we merely have to keep track of the conditional mean to recover the entire conditional distribution.

Similarly, the conditional distribution of  $\tau_t$  is normal, as we show in Appendix B.4. The conditional variance is again constant and the conditional mean of  $\tau_t$  is simply a function of  $\hat{q}$  and the conditional mean of  $\eta_{t+1}$ . From (27), we can write

$$E_{it}[\tau_t] = (1 - \alpha_2)\hat{q}_t - \alpha_1 E_{it}[\eta_{t+1}]. \quad (57)$$

Finally, in deriving the set of individual state variables, we notice that contingent claims trading eliminates any meaningful distribution of capital across time, such that any heterogeneity in equilibrium behavior arises exclusively due to cross-sectional variation in  $E_{it}$ . It follows that we can write  $E_{it}[g_r(S_{it}, S_{it+1})]$  as a function of  $S_{it}$ , concluding the proof of the first statement in Lemma 1.

The second part of Lemma 1 states that aggregate quantities and prices depend on  $S_{it}$ ,  $\bar{E}_t$ , and  $\hat{q}$ . To see this result, consider an aggregate variable of the form

$$X(\bar{S}_t) = \int x_i(S_{it})di, \quad (58)$$

where  $X$  can represent aggregate capital (43), labor, or consumption (44). Again, without loss of generality we rewrite the right-hand side of the equation as an infinite-order Taylor series expansion in the elements of  $S_{it}$ ,

$$\int x_i(S_{it})di = \int \sum_{\mathbf{j}} \frac{c_{\mathbf{j}}}{\mathbf{j}!} (K_t - K_0)^{j_1} \omega_{t-1}^{j_2} \eta_t^{j_3} \varphi_t^{j_4} \hat{q}_t^{j_5} \bar{E}_t^{j_6} E_{it}^{j_7} di. \quad (59)$$

Only the last term differs across households and thus all other variables can be taken outside the integral. The integral over  $E_{it}$  can be rewritten as

$$\int E_{it}^j di = \int (E_{it} - \bar{E}_t + \bar{E}_t)^j di = \sum_{k=0}^j \binom{j}{k} \bar{E}_t^{j-k} \int (E_{it} - \bar{E}_t)^k di \quad (60)$$

Now we can use the fact that  $E_{it} - \bar{E}_t = \alpha_1 \nu_i$ , such that we can replace the last remaining term in the integral with the unconditional moments of  $\nu_i$ , which are known. Therefore, all aggregate variables and prices are a function of  $\hat{q}_t$  and  $\bar{E}_t$ , but not a function of  $E_{it}$ , such that equation (58) holds.

Although households' policies are non-linear in  $E_{it} = \bar{E}_t + \alpha_1 \nu_{it}$ , aggregate variables thus

depend only on  $\bar{E}_t$  because the integral of a function of a conditionally normally distributed variable depends only on its conditional mean ( $\bar{E}_t$ ) and its conditional variance which is invariant over time and depends only on the parameters of the model.

The first part of Lemma 1 states that  $Q_t$  depends only on  $S_t$  and  $\hat{q}_t$  but not on the average expectation,  $\bar{E}_t$ . We can see from (27) and (23) that  $Q_t$  is fully determined by  $I_t/K_t$ . Because  $K_t$  is itself a commonly known state variable (a part of  $S_t$ ), it follows that the equilibrium stock price function will depend on the same arguments as aggregate investment. From assumption Q2, we know that the state-dependent distribution of noise trader demand is such that  $I_t = I(S_t, \hat{q}_t)$ , and therefore  $Q_t = Q(S_t, \hat{q}_t)$ , concluding the proof of the Lemma.

$T^\tau$  has a state-dependent distribution such that the noise trading shock  $\tau$  adds linearly to the average expectation. The only remaining question is then what this state-dependent distribution of noise trader demand must look like and how we can compute it. The resource constraint in equation (46) links aggregate variables and noise trading with investment.

To compute the state-dependent distribution explicitly, we rewrite (46) as

$$\hat{I}(S_t, \bar{E}_t, \hat{q}_t) + \hat{T}^\tau(S_t, \hat{q}_t, \bar{E}_t, \tau_t) = I(S_t, \hat{q}_t), \quad (61)$$

where  $\hat{T}^\tau \equiv T^\tau/Q_t$ . We can then replace the expressions on both sides of the equation with their Taylor series and iteratively match the coefficients of  $\hat{T}^\tau$  such that the equation holds.

$$\hat{T}_0^\tau + \hat{T}_S^\tau \hat{S}_t + \hat{T}_{\bar{E}}^\tau \bar{E} + \hat{T}_{\hat{q}}^\tau \hat{q} + \hat{T}_\tau^\tau \tau_t + \dots + \hat{I}_0 + \hat{I}_S \hat{S}_t + \hat{I}_{\bar{E}} \bar{E} + \hat{I}_{\hat{q}} \hat{q} + \dots = I_0 + I_S \hat{S}_t + I_{\hat{q}} \hat{q} + \dots, \quad (62)$$

where we denote  $F_x$  as the derivative of the function  $F$  with respect to  $x$ . In particular,  $F_S$  is the vector of derivatives of  $F$  with respect to each element of the vector of commonly known state variables  $S_t$  and  $\hat{S}_t$  refers to deviations of the elements of  $S_t$  from their deterministic steady-state values. To a first order, the implied distribution of  $\hat{T}_t^\tau$  only needs to add noise to average expectation,

$$\hat{T}_0^\tau = 0 \quad \hat{T}_S^\tau = 0 \quad \hat{T}_{\bar{E}}^\tau = 0 \quad \hat{T}_{\hat{q}}^\tau = 0 \quad \hat{T}_\tau^\tau = \hat{I}_{\bar{E}} \frac{V_t[\eta_{t+1}]}{\sigma_\eta^2}, \quad (63)$$

which then determines aggregate investment as a function of known state variables and  $\hat{q}$ , such that

$$I_0 = \hat{I}_0 \quad I_S = \hat{T}_S^\tau \quad I_{\hat{q}} = \hat{I}_{\hat{q}} + \hat{T}_{\hat{q}}^\tau + \hat{I}_{\bar{E}} + \hat{T}_\tau^\tau. \quad (64)$$

The matching of higher-order coefficients is analogous.

Using this procedure we can thus solve for  $T^\tau$  as a power series in  $\tau$  and the state variables

of the system. For example, to a second-order we can write

$$\hat{T}^\tau(S_t, \hat{q}_t, \bar{E}_t, \tau_t) = \frac{V_t[\eta_{t+1}]}{\sigma_\eta^2} \tau_t \left( \hat{I}_{\bar{E}} + \hat{I}_{S\bar{E}} \hat{S} + \hat{I}_{\bar{E}\hat{q}} \hat{q}_t + \hat{I}_{\bar{E}\bar{E}} \left( \bar{E}_t + \frac{V_t[\eta_{t+1}]}{\sigma_\eta^2} \frac{1}{2} \tau_t \right) + h.o.t. \right).$$

As in the linear model, there is thus exactly one distribution of noise trader demand shocks which closes the model.

Using these insights, we solve the model using standard perturbation techniques. Perturbation methods approximate equilibrium policy functions by their Taylor series around the deterministic steady-state. To arrive at the coefficients of the Taylor series, we bring all equilibrium conditions into the appropriate form shown in equation (55). Successively differentiating the equation, evaluating at the steady-state, and solving the resulting system of equations for the coefficients in the Taylor series delivers the approximate solutions for the equilibrium policy functions and prices.

## 4 Qualitative Results

Upshot from the analysis above is that given Assumptions Q1-Q3, we can separate the solution of the DSGE model from its information microstructure. Doing so allows us to characterize the the dynamic effects of dispersed information with some generality.

Contrary to a representative agent setting, the model with dispersed information leads to a cross-sectional distribution of choices. A key statistic this distribution is the cross-sectional variance of posterior expectations

$$V_t \left[ E_{it} [\eta_{t+1}] - \int E_{it} [\eta_{t+1}] di \right] = \alpha_1^2 \sigma_\nu^2. \quad (65)$$

Recall from Lemma 1 that households' policy functions can be characterized as a function of the state vector  $\{S_t, \hat{q}_t, \bar{E}_t, E_{it}\}$ . Without loss of generality, we can use equation (45) and the fact that  $E_{it}[\eta_{t+1}] = \alpha_0 + \alpha_1 s_{it} + \alpha_2 \hat{q}_t$  to re-write this state vector as  $\{S_t, \tau, \bar{E}_t, \nu_{it}\}$ . Without using any further information about the information microstructure, we can then use a standard perturbation approach to solve for all endogenous variables of the model as a function of these state variables, as well as the coefficients  $\alpha_1$  and  $\alpha_2$ , and the conditional variance,  $V_t[\eta_{t+1}]$ .



Equation (66) shows the first-order terms of the equilibrium aggregate consumption function,

$$\begin{aligned}
C_t = & \underbrace{c_0 + c'_S \hat{S}_t + \frac{1}{2} c_{\sigma^2}}_{\text{standard RBC}} + \underbrace{c_\tau \tau + \frac{1}{2} c_{\sigma^2}^{NT} \sigma_\tau^2}_{\text{direct effect of noise trading}} + \underbrace{c_{\bar{E}} \eta_{t+1} + \frac{1}{2} c_{\sigma^2}^{ns}}_{\text{News Shock}} \\
& + \underbrace{c_{\bar{E}} \left( - (1 - (\alpha_1 + \alpha_2)) \eta_{t+1} + \alpha_2 \frac{V_t [\eta_{t+1}]}{\sigma_\eta^2} \tau \right)}_{\text{Dispersed Information}} + \frac{1}{2} c_{\sigma^2}^{disp} \alpha_1^2 \sigma_\nu^2 + \text{h.o.t.},
\end{aligned} \tag{66}$$

where the coefficients denoted  $c$  on the right-hand side are numbers that are determined by the usual “macroeconomic” parameters of the model but independent of the parameters relating to information and noise. In other words, any representative agent DSGE model implies such a series of  $c$ 's, where we denote  $c_x$  as the derivative of the equilibrium aggregate consumption function with respect to  $x$ . In particular,  $c_S$  is the vector of derivatives of the aggregate consumption function with respect to each element of the vector of commonly known state variables  $S_t$ , and  $\hat{S}_t$  refers to deviations of the elements of  $S_t$  from their deterministic steady-state values.

The grouping of terms on the right-hand side in (66) isolates the effect of the information microstructure on aggregate consumption. (The effects on all other aggregate variables have the same form, except that the coefficients  $c$  will be different when we consider output, investment, or aggregate labor supply.) The first set of terms on the right-hand side give the solution for aggregate consumption that would obtain in a standard RBC model containing no information about the future,  $\sigma_\nu = \infty$ , and no noise trading,  $\sigma_\tau = 0$ .  $c_0 + c'_S \hat{S}_t$  is the first-order Taylor series in deviations of the commonly known state variables from their deterministic steady-state values, and  $\frac{1}{2} c_{\sigma^2}$  is the effect of risk on the level of consumption in the standard RBC model.

The second set of terms gives the direct effect of noise trading. Even when households learn nothing about the future ( $\sigma_\nu = \infty$ ),  $\tau$  has a direct effect on consumption (and all business-cycle moments) as asset purchases and sales of stocks effectively add and subtract resources from the economy. The second term in the grouping shows that when noise traders are active, they effectively increase the risk faced by households and thus add to the level effect of risk on consumption.

The third grouping shows the effect of information provision in a model in which  $\sigma_\nu = 0$ . If households are perfectly informed about  $\eta_{t+1}$  they fully react to this information in  $t$ , altering the dynamic response of economic aggregates to the long-run productivity shock. In addition, learning about the future reduces the uncertainty households face, and thus may mitigate the effect of risk on the level of economic aggregates (the second term in the grouping).

The fourth grouping gives the dynamic and level effects of dispersed information. When information is dispersed and  $\sigma_\nu > 0$ , households need to rely on  $\hat{q}_t$  when learning about  $\eta_{t+1}$ . When  $\sigma_\tau > 0$ , this inference is not perfect, such that  $(\alpha_1 + \alpha_2) < 1$ . Dispersion in households'

private information then dampens the reaction of economic aggregates to  $\eta_{t+1}$  (see the first term in the round brackets). When  $\alpha_2 > 0$ , households also react to  $\tau$  when making their equilibrium consumption, labor-supply, and investment decisions (the second term in the round brackets).

In addition, when  $\alpha_1 > 0$ , households rely on their (now noisy) private signal when making decisions, such that equilibrium consumption will differ across households. Because households' policy functions are non-linear, this dispersion in equilibrium behavior has itself a level-effect on all economic aggregates. In particular, if individual households' consumption is concave in  $E_{it}[\eta_{t+1}]$ , the dispersion in household expectations lowers the level of aggregate consumption.

## 5 Quantitative Analysis

### 5.1 Calibration and Estimation

As is standard practice in the long-run risk literature, we calibrate our model to a monthly frequency and focus on time-aggregated statistics matching the behavior of annualized moments for the US economy 1929-2008 (Bansal and Yaron, 2004).

Our model depends on 15 parameters, 13 of which are identical to the parameters in the original real business cycle model by Croce (2013). To focus on the incremental effect of dispersed information within this framework, we set all of these 13 parameters to equal the ones in Croce's benchmark calibration.

TABLE 1: CALIBRATION

Parameter	Value	Parameter	Value
$\alpha$	0.34	12 $\delta_k$	0.060
$\beta^{12}$	0.95	$\gamma$	10.
12 $\mu_a$	0.018	$\psi$	2.0
$\rho^{12}$	0.80	$o$	0.20
$\xi$	7.0	$\phi_{lev}$	2.0
$\sqrt{12}\sigma_a$	0.033	$\sqrt{12}\sigma_\eta$	0.0036
$\sqrt{12}\sigma_\tau$	0.0051		

*Notes:* Values of the 13 technology and preference parameters used in all following calibrations and estimations.  $\alpha$ : capital share;  $\delta_k$ : capital depreciation rate;  $\xi$ : elasticity of the adjustment cost function;  $\mu_a$ : average growth of productivity;  $\rho$ : auto-correlation of long-run component in productivity growth;  $\sigma_\eta$ : standard deviation of shock to the long-run component in productivity growth;  $\sigma_\varphi$ : standard deviation of short-run component in productivity;  $\xi_l$ : consumption bundle elasticity;  $o$  consumption share in the consumption bundle;  $\gamma$ : relative risk aversion;  $\psi$ : intertemporal elasticity of substitution;  $\delta$ : subjective discount factor and  $\phi_{lev}$ : leverage of market return.

Table 1 lists the parameter values. On the technology side,  $\alpha$  is set to match the capital income share and  $\delta_k$  is set to match the annualized capital depreciation rate in the US economy

(6%). The elasticity of the adjustment cost function,  $\xi$ , is set to 7, such that investment can be sufficiently volatile. In addition, Croce sets  $\mu_a = 0.0015$  to yield an annual average growth of 1.8%. The long-run component in productivity,  $\omega_t$ , is calibrated so as to be relatively small but persistent, where  $\rho$  is set to yield an annualized persistence of 0.80. To keep the long-run component as small as in the data, he imposes  $\sigma_\eta = 10\% \sigma_\varphi$ , where  $\sigma_\varphi$  is set as 1% to obtain an annual volatility of output growth of 3.34% under the benchmark calibration.

On the preference side, the consumption bundle elasticity is  $\xi_t = 1$  for simplicity. The parameter  $o$  is calibrated so that the labor share is 18% at the steady state. The relative risk aversion and the intertemporal elasticity of substitution are set to values of 10 and 2, respectively. The annualized subjective discount factor  $\delta$  is fixed at 0.95.

We also follow Croce (2013) in calculating excess stock returns as the excess returns on a levered claim to capital

$$R_{ex,t}^{LEV} = \left( R_t - R_{t-1}^f \right)^{\phi_{lev}}. \quad (67)$$

This practice, again, is standard in the finance literature because, in the data, most claims to equity are levered, where we set  $\phi_{lev} = 2$ , consistent with the amount of financial leverage measured by Rauh and Sufi (2012).

Finally, the parameters  $v_1$  and  $v_2$  in the adjustment cost function are set such that, at the deterministic steady-state,  $G_t = 0$  and  $\partial G_t / \partial (I_t / K_t) = 0$ . This implies  $v_0 = \left( \frac{1}{1-\xi} \right) (\delta + e^\mu - 1)$  and  $v_1 = (\delta + e^\mu - 1)^{\frac{1}{\xi}}$ .

For parsimony, we also assume that noise trader make only random, and no conditional purchases, such that  $T^k(S_t) = 0$ .

Before the introduction of dispersed information, our calibration thus exactly coincides with the one in Croce (2013).<sup>10</sup> The two remaining parameters,  $\sigma_\nu$  and  $\sigma_\tau$  determine the size of noise trader demand shocks, the dispersion in private signals, and therefore the equilibrium expectations of all households. We estimate both parameters to minimize the loss function

$$(m - \theta) W (m - \theta), \quad (68)$$

where  $m$  is a vector of moments generated by the model,  $\theta$  is the vector of data targets for these moments, and  $W$  is a diagonal matrix where each entry is  $\frac{1}{\theta_j^2}$ , and  $\theta_j$  is the  $j$ 'th entry in  $\theta$ . We thus minimize a weighted sum of squared deviations from the target vector.

We first present a set of results for which we calibrate noise trader demand shocks,  $\sigma_\tau$ , to a reasonable ballpark and estimate only  $\sigma_\nu$ . In these specifications, we choose  $\sigma_\tau$  such that the unconditional variance of  $T^\tau$  equals one half of the standard deviation of the growth rate of asset

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<sup>10</sup>The only way in which we deviate from his framework is that we do not introduce exogenous cash-flow shocks to levered returns (67). We omit this detail for clarity, because our objective here is not to argue for or against the ability of the long-run risk model to match the volatility of stock returns in the data.

purchases by the Federal Reserve between 1948 and 2008 (0.43% of GDP). In a second set of results, we freely estimate both  $\sigma_\tau$  and  $\sigma_\nu$  to minimize the deviation from the target moments given in equation (68).

Although we do not explicitly allow households to trade in bonds, we measure the risk-free rate of interest as the shadow rate implied by the stochastic discount factor of the household that holds the average expectation  $E_{it}[\eta_{t+1}] = \bar{E}_t$ .

## 5.2 Results

Table 2 shows our basic results for a range of parameters  $\sigma_\nu$  and  $\sigma_\tau$ . Throughout, lowercase variables denote logs,  $\sigma(\cdot)$  and  $\text{corr}(\cdot)$  denote standard deviations and correlations, respectively, and  $d$  stands for the first difference in the time series (e.g.,  $\sigma(dy)$  stands for the standard deviation of output growth). Column 2 lists the data targets and the remaining columns list the moments generated by the model. All data targets except the one for  $\sigma_{xs}(E[dy])$  are generated using annual data ranging from 1929-2008 following the procedure in Croce (2013) (see appendix C.1 for details).  $\sigma_{xs}(E[dy])$  is our measure of the cross-sectional dispersion of equilibrium expectations. We calculate it as the time-series average of the cross-sectional standard deviation in annualized forecasts of GDP growth in Survey of Professional Forecasters for the period 1969-2008.

The two remaining moments in the second panel have no direct counterpart in the data.  $\sigma(k_{it}/K_{SS})$  is the time-series average of the cross-sectional standard deviation in equity portfolio holdings relative to the deterministic steady state level of capital, which is a simple measure of the dispersion in equilibrium behavior induced by dispersion in equilibrium expectations. In the data, differences in behavior due to differences in expectations are of course conflated with large differences in wealth across households, such that we have no obvious moment in the data to which we can compare our model's prediction. The same applies to our measure of information revelation,  $V_t[\eta]/\sigma_\eta^2$ , calculated as the ratio of the posterior variance of  $\eta$ , divided by its unconditional variance. When this ratio is 1, no information is revealed in equilibrium. When it is zero, households can perfectly infer  $\eta_{t+1}$  one period in advance.

Column 3 ('No Info') shows Croce's original calibration in which households receive no information about the future productivity shock ( $\sigma_\nu = \infty$ ). In this limit, our model coincides with a standard DSGE model in which all shocks are unknown ex-ante. Column 4 ('News Shocks') shows the opposite extreme in which households receive perfectly accurate private signals about the future productivity shock ( $\sigma_\nu = 0$ ). In both specifications all households have identical information sets (no information in the former and full information in the latter). The comparison between these two specifications thus shows the effect of common information about  $\eta$  on the moments generated by the model (the third set of terms in (66)). Comparing the coefficients across rows shows that the provision of common information has only a small effect on conventional business cycle moments such as  $\sigma(dy)$  and  $\sigma(dc)$ . However, it has a larger effect on all moments

TABLE 2: COMMON VS. DISPERSED INFORMATION

	Data	'No Info'	'News Shock'	'Grossman Eq.'	'Dispersed Info'
$\sigma(T^\tau)/Y_{SS}(\%)$		0.	0.	0.	0.43
$\sigma_\nu/\sigma_\eta$		$\infty$	0.	0.	3.2
$V_t[\eta]/\sigma_\eta^2$		1.	0.	0.	0.81
$\sigma(k_i/(K_{SS}))(\%)$		0.	0.	0.	0.04
$\sigma_{xs}(E[dy])(\%)$	0.28	0.	0.	0.	0.05
$\sigma(dy)(\%)$	3.56	3.58	3.57	3.57	3.53
$\sigma(dc)/\sigma(dy)$	0.71	0.61	0.61	0.61	0.61
$\sigma(di)/\sigma(dy)$	4.49	5.27	5.25	5.25	4.97
$E[I/Y](\%)$	20	30.54	30.54	30.54	30.55
$\text{cor}(dc, di)$	0.39	0.29	0.3	0.3	0.41
$\text{cor}(dc, r_{\text{ex}}^{\text{lev}})$	0.25	0.32	0.32	0.32	0.45
$E[r_{\text{ex}}^{\text{lev}}](\%)$	4.71	4.54	4.49	4.49	4.53
$\sigma[r_{\text{ex}}^{\text{lev}}](\%)$	20.89	4.97	4.94	4.94	4.55
$\sigma(q)$	0.29	0.26	0.25	0.25	0.26
$E[\text{rf}](\%)$	0.65	0.89	0.91	0.91	0.89
$\sigma(\text{rf})(\%)$	1.86	1.07	1.07	1.07	1.07

*Notes:* Data are annual (1929-2008). Lowercase letters denote log-units.  $E[\cdot]$ ,  $\sigma(\cdot)$ , and  $\text{corr}(\cdot, \cdot)$  denote the mean, volatility, and correlation respectively.  $\sigma_{xs}(E[dy])$  is the dispersion in GDP forecasts across forecasters, calculated as the time-series average of the cross-sectional standard deviation of one-year ahead forecasts.

that relate to the consumption/savings decision. For example, the equity premium falls from 4.54% in the case without information to 4.49% in the case of perfect information. Similarly, the risk-free interest rate rises from 0.89% to 0.91% between these two scenarios. These effects of information provision make intuitive sense. In our model, households worry about shocks to long-run productivity. When these shocks are revealed one month in advance, the unconditional variance of stock returns fall from 4.97% to 4.94%. In addition, households require a lower risk premium for holding stocks and have less incentive to engage in precautionary savings behavior. As a result, the equity premium falls and the risk-free rate rises.

In column 5 ('Grossman Eq. '), we show results for the case in which  $\sigma_\nu < \infty$ , while  $\sigma_\tau = 0$ . In this case, the stock price becomes perfectly revealing of innovations to productivity  $\eta_{t+1}$ , as predicted by Corollary 1. Although households receive noisy private signals ex-ante, their posterior expectation is perfectly accurate, such that the dispersion of information has no effect on households' equilibrium behavior. The moments given in this column thus are exactly the same as those in column 3.

Although the overall effect of information provision may appear small in this calibration, it is important to keep in mind that we are evaluating the effects of learning about a small shock to the long-run component of productivity. We show below that many moments of the model

are more sensitive to the provision of information about the (much larger) short-run shock to productivity. In addition, all our calculations consider learning about shocks one month, rather than a year or a decade, in advance. While this experiment is a natural starting point because long-run risk models are typically calibrated to monthly data, the model should be interesting at any other frequency as well. In a calibration to annual data, for example, households would learn a year in advance about a larger (annual-sized) shock, such that learning presumably would have a much larger effect on all aspects of the model. Although an in-depth analysis of the effect of information provision at different frequencies is beyond the scope of the present paper, we believe it is an important avenue for future research.

### 5.3 Reasonably Sized Noise Trader Shocks

In column 6, we set the annualized standard deviation of noise trader demand shocks to 0.43% of GDP<sup>11</sup> and estimate  $\sigma_\nu$  to match the cross-sectional standard deviation of expectations of GDP growth from the Survey of Economic Forecasters. The estimation returns  $\sigma_\nu = 3.2 \cdot \sigma_\eta$ , in which case the model is able to generate a cross-sectional dispersion in equilibrium expectations of 0.05% (compared to 0.28% in the data). Similarly, the cross-sectional dispersion of stock holdings is small (0.04%).

Figure 1 plots the comparative statics over  $\sigma_\nu$  for the three variables in the second panel of Table 2. The comparative static for the objective of our estimation,  $\sigma_{xs}(E[dy])$ , is given in the middle of the figure. It shows that no heterogeneity occurs across households in equilibrium expectations when households receive a perfectly revealing private signal ( $\sigma_\nu/\sigma_\eta = 0$ ). For moderate amounts of noise in the private signal, this heterogeneity rapidly increases, peaks at around ( $\sigma_\nu/\sigma_\eta = 5$ ), and then monotonically decreases.

To gain intuition for this result, we can write using equations (65) and (53)

$$V_t[\alpha_1 \nu_{it}] = \left( \frac{V_t[\eta_{t+1}]/\sigma_\eta^2}{\sigma_\nu/\sigma_\eta} \right)^2 \sigma_\eta^2. \quad (69)$$

To the left of the figure,  $V_t[\eta_{t+1}]/\sigma_\eta^2 = 0$  and the dispersion of equilibrium expectations is zero. As we move to the right of the figure, the precision of the private signal decreases, the market's capacity to aggregate information deteriorates, and  $V_t[\eta_{t+1}]/\sigma_\eta^2$  rises, such that households rely more on their private signal when forming expectations. Toward the middle of the graph,  $V_t[\eta_{t+1}]/\sigma_\eta^2$  begins to converge to one and the increase in the denominator,  $\sigma_\nu/\sigma_\eta$ , begins to dominate. As the information content of stock prices and the precision of the private signal continue to deteriorate, households rely more and more on their priors and reduce weight on their private signal. Heterogeneity in equilibrium expectations thus peaks at an intermediate value of  $\sigma_\nu$ . For

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<sup>11</sup>As a rough reference, this corresponds to about one half of the standard deviation of government bond purchases by the Federal Reserve 1970-2013.

a given size of the noise trader demand shock, the information microstructure thus requires that heterogeneity in equilibrium behavior is bounded from above.

The conclusion from our estimation in column 6 of Table 2 is that for a reasonable size of noise trader demand shocks, this upper bound is about an order of magnitude smaller than the dispersion of equilibrium expectations we observe in the data.

Another interesting result in column 6 of Table 2 is that some moments, such as the equity premium and the risk-free rate, fall into the range established by the “no information” case in column 3 and the “full information” case in column 4. However, most other moments, such as the standard deviation of output (3.53% vs. 3.58% and 3.57%) and the correlation of investment growth with consumption growth (0.41 vs. 0.29 and 0.30) fall well outside of this range.

To further investigate this finding, Figure 2 plots the comparative statics of selected moments in column 6 of Table 2 over  $\sigma_\nu$ . In each panel of the figure, the horizontal dashed line represents the moment generated in the “no information” case (column 3) and the horizontal dotted line represents the same moment in the “full information” case (column 4).

The figure shows that all moments coincide with the moment from the “full information” case when the private signal is fully precise, and appear to converge to the moment from the “no information” case as  $\sigma_\nu$  becomes large. However, for an intermediate range around  $\sigma_\nu/\sigma_\eta = 3.2$ , the standard deviation of output growth, the standard deviation of stock returns, and the ratios of the standard deviations of output and investment growth to output growth are well below that range. Similarly, the correlation of consumption growth and investment growth, as well as the correlation of consumption growth with stock returns, are well above that range.

Comparing these results with Figure 1 suggests the same forces that drive heterogeneity in households’ equilibrium expectations also affect the quantitative results for these moments, because the same value of  $\sigma_\nu$  that maximizes dispersion in equilibrium expectations also maximizes the effect of a given shock to noise trader demand on households’ expectations. To see this, note from (51) that the coefficient on  $\tau_t$  in households’ equilibrium expectation is  $V_t[\eta_{t+1}]\alpha_1/\sigma_\tau^2$ . Substituting (53) yields  $V_t[\eta_{t+1}]^2/(\sigma_\nu^2\sigma_\tau^2)$ , which, for a given  $\sigma_\tau$ , has its maximum at the same  $\sigma_\nu$  as (69). The patterns in Figure 1 can thus be explained by the effect of noise trader demand shocks on the equilibrium expectations held by households (the fourth set of terms in (66)).

Figure 3 shows the effect of a two-standard-deviation (positive) shock to the long-run component of productivity in month 10, where again the dashed line corresponds to the no-information case, the dotted line to the full-information case, and the solid line to the specification in column 6 of Table 2. The graph shows that the no-information and the full-information case look similar in the sense that they show large effects on output growth in the period in which the shock is revealed. By contrast, the solid line shows a partial adjustment in each period, and thus a smoother adjustment to the shock. The reason is that households that see a rise in the stock price are unsure whether this rise is a result of a noise trader demand shock or an productivity

shock. They thus partially adjust to potentially good news in month 9 and adjust fully only when the shock is realized in period 10.

The two panels on the left of Figure 4 show the effect of dispersion in equilibrium behavior on the level of consumption and labor supply that corresponds to the fourth grouping of terms on the right-hand side of (66). It shows that even moderate dispersion in equilibrium expectations may have a surprisingly large effect on the level of both aggregate variables. Because the consumption function is concave in  $E_{it+1}[\eta_{t+1}]$ , the dispersion in consumption choices lowers aggregate consumption by up to 0.015%. Similarly, dispersion in labor-supply decisions may lower aggregate labor supply by up to 0.03% (note that households' labor-supply decisions are convex in  $E_{it+1}[\eta_{t+1}]$ ).

The two panels to the right of Figure 4 compare this level effect of dispersion with the level effect of risk that is present even if the model has a representative agent (the first grouping of terms in (66)). It shows that in both cases, the level effect of dispersion is up to an order of magnitude larger than the level effect of risk in a representative agent framework.

In column 4 of Table 3, we choose  $\sigma_\nu$  to minimize (68) for the full vector of data moments in column 2. Since the “no-information” model in column 3 already gives a reasonably good fit to the data, it is not surprising that we obtain a relatively large estimate  $\sigma_\nu/\sigma_\eta = 6.4$ , such that households learn little about future productivity in equilibrium ( $V_t[\eta]/\sigma_\eta^2 = 0.97$ ). As a result, the macroeconomic and financial moments remain close to those in column 2. The only significant difference between the two specifications is that in column 4, the cross-sectional variance of equilibrium expectations is non-degenerate with  $\sigma_{xs}(E[dy]) = 0.04\%$ .

## 5.4 Large Noise Trader Demand Shocks

In column 5, we repeat the same exercise, but now simultaneously estimate the standard deviation of noise trader demand shocks and the precision of the private signal. Minimization of the distance to target moments in equation (68) returns a standard deviation of noise trader demand shocks of 4.3% of GDP and  $\sigma_\nu/\sigma_\eta = 3.2$ . In equilibrium households again learn little about the future productivity shock ( $V_t[\eta]/\sigma_\eta^2 = 0.95$ ), but the very large noise trader demand shocks significantly improve the overall fit of the model. In particular, large noise trader demand shocks increase the equity premium to 4.66% (relative to 4.54% in column 2), while lowering the risk-free rate to 0.82%.

In column 6, we ask how much heterogeneity in equilibrium behavior the model can produce, by choosing both the size of the noise trader demand shocks and the precision of the private signal to match the cross-sectional standard deviation of equilibrium expectations. This estimation again returns  $\sigma_\tau/\sigma_\eta = 4.3$  (the largest noise trader demand shocks on our grid) and  $\sigma_\nu/\sigma_\eta = 1.6$ . For this extreme set of parameters, the model generates a cross-sectional standard deviation of expected GDP growth of 0.11%, which is about factor four larger than the dispersion we were



TABLE 3: ESTIMATES OF  $\sigma_\nu$  AND  $\sigma_\tau$ 

	Data	'No Info'	'Dispersed Info'	'Dispersed Info'	'Dispersed Info'
Pick $\sigma_\nu$ to match			all	all	$\sigma_{\text{xs}}(\text{E}[\text{dy}])$
$\sigma(T^\tau)/Y^{\text{SS}}(\%)$		0.	0.43	4.3	4.3
$\sigma_\nu/\sigma_\eta$		$\infty$	6.4	3.2	1.6
$V_t[\eta]/\sigma_\eta^2$		1.	0.97	0.95	0.83
$\sigma(k_i/(K_{\text{SS}}))(\%)$		0.	0.03	0.05	0.08
$\sigma_{\text{xs}}(\text{E}[\text{dy}])(\%)$	0.28	0.	0.04	0.07	0.11
$\sigma(\text{dy})(\%)$	3.56	3.58	3.57	3.56	3.53
$\sigma(\text{dc})/\sigma(\text{dy})$	0.71	0.61	0.61	0.61	0.61
$\sigma(\text{di})/\sigma(\text{dy})$	4.49	5.27	5.2	5.16	4.99
$\text{E}[\text{I}/\text{Y}](\%)$	20	30.54	30.54	30.56	30.59
$\text{cor}(\text{dc}, \text{di})$	0.39	0.29	0.32	0.33	0.41
$\text{cor}(\text{dc}, r_{\text{ex}}^{\text{lev}})$	0.25	0.32	0.35	0.36	0.45
$\text{E}[r_{\text{ex}}^{\text{lev}}](\%)$	4.71	4.54	4.54	4.66	4.68
$\sigma[r_{\text{ex}}^{\text{lev}}](\%)$	20.89	4.97	4.86	4.82	4.57
$\sigma(\text{q})$	0.29	0.26	0.26	0.26	0.26
$\text{E}[\text{rf}](\%)$	0.65	0.89	0.88	0.82	0.81
$\sigma(\text{rf})(\%)$	1.86	1.07	1.07	1.07	1.07

Notes: Data are annual (1929-2008). Lowercase letters denote log-units.  $E[\cdot]$ ,  $\sigma(\cdot)$ , and  $\text{corr}(\cdot, \cdot)$  denote the mean, volatility, and correlation, respectively.  $\sigma_{\text{xs}}(\text{E}[\text{dy}])$  is the dispersion in GDP forecasts across forecasters, calculated as the time-series average of the cross-sectional standard deviation of one-year-ahead forecasts (1969-2008).

able to generate in Table 2. Nevertheless, the estimate is still less than half the size of the dispersion observed in the data (0.28%).

## 5.5 Learning about the Short-Run Shock

Figure 5 shows the same comparative static as Figure 2 for the case in which households receive private signals about the short-run shock to productivity,  $\varphi$ , rather than the long-run shock,  $\eta$ . Both models coincide when households have no information about the future (the red dashed line). In all panels the moments estimated for the dispersed information case are now in between the bounds set by the “no information” and the “full information” specifications. In addition, the overall effect of information provision on the standard deviation of output and the other four moments shown on the top of the figure is now smaller than in Figure 2. However, learning about the short-run shock has a much larger effect on the equity premium which now ranges between 4.53 in the “no information” case and 3.65 in the “full information” case. Similarly, the risk-free rate now ranges between 0.89 and 1.32, showing a much larger effect than when households learn about the long-run component of productivity.

The conclusion from this figure is that the effects of dispersed information on the moments generated by the model vary depending on what kind of information households receive. In our example, learning about a persistent shock has relatively larger effects on the dynamics of household behavior, while learning about an *i.i.d.* shock has relatively larger effects on the risk-free rate and the equity premium. Since modern DSGE models often feature a range of different shocks that affect the economy at different frequencies, a more general analysis of these relationships is beyond the scope of the current paper. However, we hope that our work will facilitate future research in this area.

## 6 Conclusion

In this paper, we introduced a solution method that allows us to incorporate the information microstructure of a standard noisy rational expectations model into the framework of a contemporary DSGE model. We showed that under mild assumptions on the distribution of noise trader demand shocks, the main qualitative results of the canonical noisy rational expectations model carry over to the non-linear framework. One of these findings is that any component of noise trader demand that is contingent on variables that are observable by households does not affect equilibrium expectations as long as the equilibrium price function remains monotonic in the productivity shock. An immediate corollary to this result is that any monetary or fiscal policy that conditions only on publicly observable variables does not affect the equilibrium informativeness of stock prices.

Our quantitative exercise yields four main insights. The first main insight is that households' ability to learn about the future affects consumption-savings decisions. A major shortcoming of the present framework is that it does not lend itself to a welfare analysis of these quantitative effects, mainly because noise trading implies large wealth transfers between maximizing households and non-maximizing noise traders, which are hard to judge from a normative perspective. In a related paper (Hassan and Mertens, 2010), we propose to solve this conceptual problem by introducing a single class of near-rational households.

The second main insight is that the differences in opinion about future GDP growth reflected in the Survey of Professional Forecasters are hard to rationalize within a noisy rational expectations model. For a reasonable size of noise trader demand shocks, the dispersion of equilibrium expectations in the model remains an order of magnitude smaller than that in the data.

Third, even when households have moderate differences of opinion in equilibrium, their expectations about the future, and thus their behavior, may load on non-fundamental noise trader demand shocks. As a result, the effect of the demand shocks on household expectations may dramatically change the moments generated by the model. Although these changes did not improve the overall fit of the model to the data in the example we study in this paper, they may do so in

a range of other applications. The main point is that the noisy rational expectations framework predicts that households rationally respond to non-fundamental noise in equilibrium. Our quantitative exercise shows this response is large enough to affect the quantitative predictions of the DSGE model.

Fourth, when noise trader demand shocks are (unreasonably) large, these demand shocks no longer have a large effect on household expectations but nevertheless directly affect the quantitative predictions of the model.

The objective of this paper was to merge the most standard information microstructure of a noisy rational expectations model with a standard DSGE model. We view this effort as a first step towards integrating the rich representations of financial markets developed by the noisy rational expectations literature into the standard macroeconomic framework that is conventionally used for quantitative and policy analysis. Interesting avenues for future research include the effect of fiscal and monetary policy on the informativeness of stock prices, the welfare effects of information aggregation in financial markets, and an in-depth analysis of the dynamic effects of private information about fundamental shocks at various frequencies. In addition, future work may consider richer information microstructures that include dynamic learning and higher-order uncertainty.

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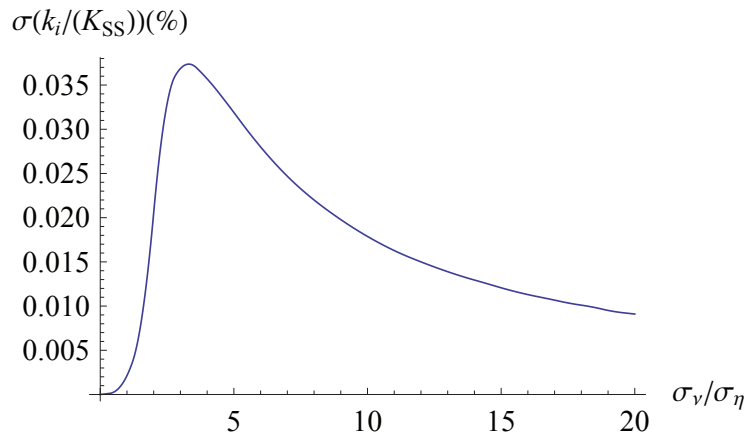
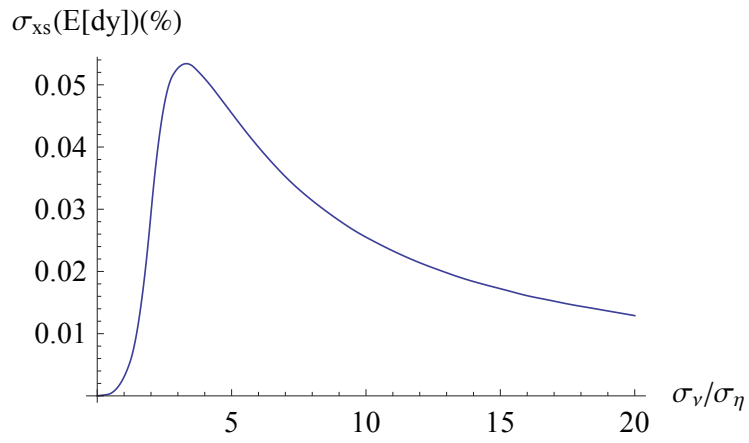
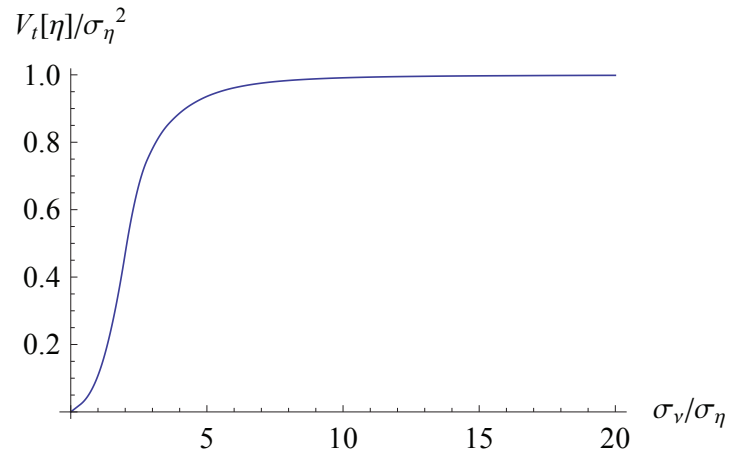


FIGURE 1: CROSS-SECTIONAL VARIATION IN EQUILIBRIUM BEHAVIOR

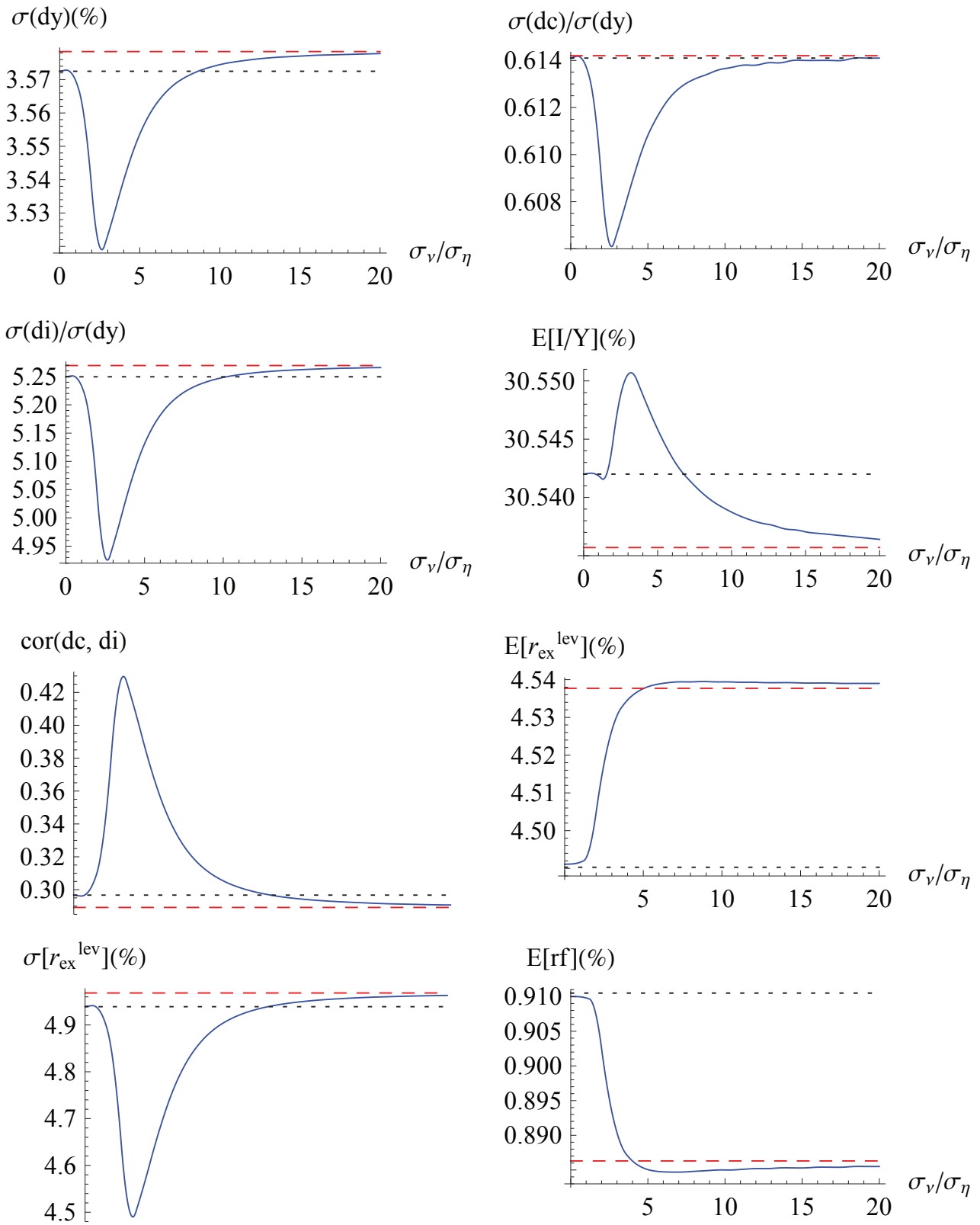


FIGURE 2: COMPARATIVE STATICS FOR SELECTED MOMENTS IN COLUMN 6 OF TABLE 2



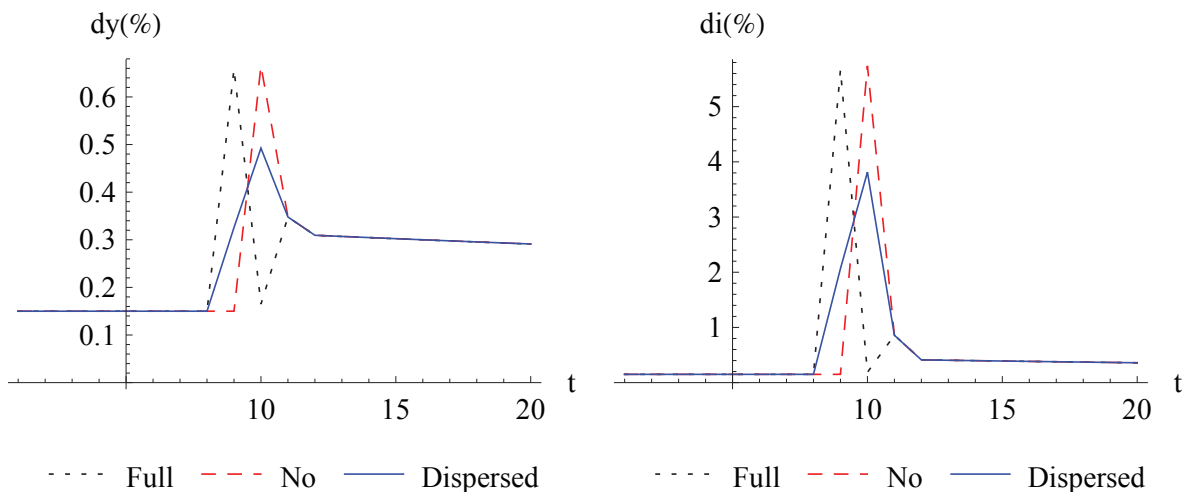


FIGURE 3: RESPONSES OF MACROECONOMIC AGGREGATES TO A 2 STANDARD DEVIATION SHOCK TO  $\eta$  IN MONTH 10. CALCULATIONS BASED ON SPECIFICATION IN COLUMN 6 OF TABLE 2.

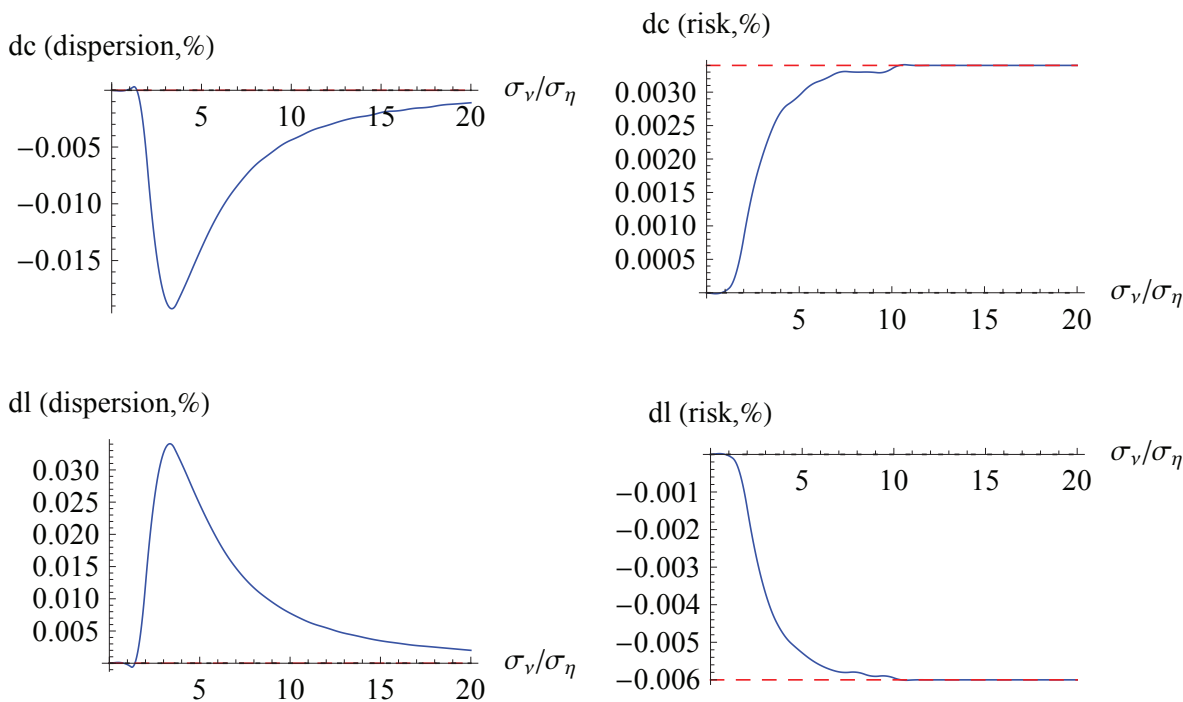


FIGURE 4: THE EFFECT OF DISPERSION ON THE LEVEL OF AGGREGATE CONSUMPTION AND LABOR SUPPLY. CALCULATIONS BASED ON SPECIFICATION IN COLUMN 6 OF TABLE 2.

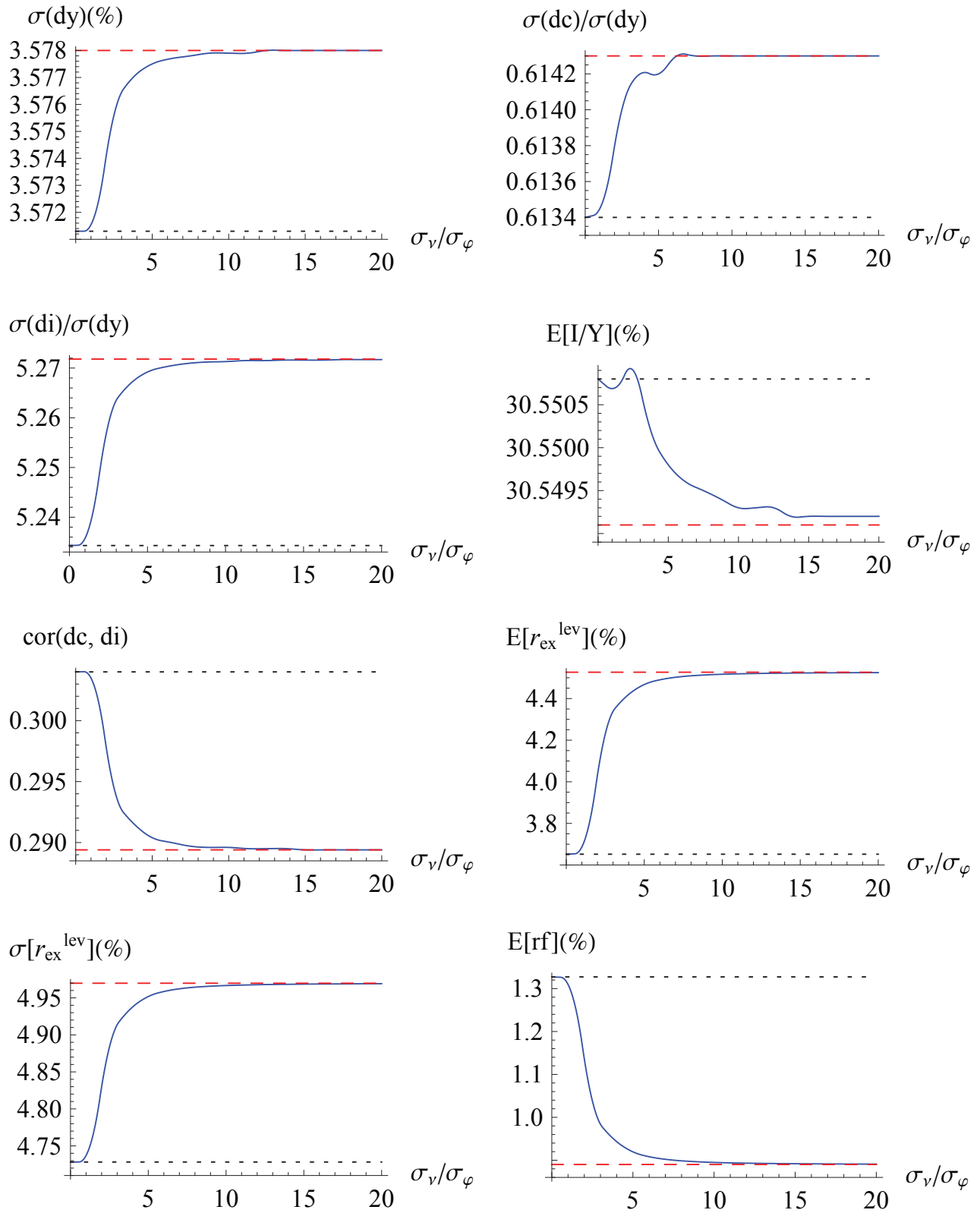


FIGURE 5: COMPARATIVE STATICS IDENTICAL TO THOSE IN FIGURE 2 FOR THE CASE IN WHICH HOUSEHOLDS RECEIVE PRIVATE SIGNALS ABOUT THE SHORT RUN SHOCK TO PRODUCTIVITY ( $\varphi$ ) RATHER THAN  $\eta$ .

# Appendix

## A Appendix to Section 2

### A.1 Deriving (13) and (14)

Using (2) and (9), the vector  $(\eta, s_i, \hat{q})$  has unconditional expectation  $(\bar{\eta}, \bar{\eta}, \frac{\alpha_1}{1-\alpha_2}\bar{\eta})$  and the variance covariance matrix

$$\Sigma = \begin{pmatrix} \sigma_\eta^2 & \sigma_\eta^2 & \frac{\alpha_1}{1-\alpha_2}\sigma_\eta^2 \\ \sigma_\eta^2 & \sigma_\eta^2 + \sigma_\nu^2 & \frac{\alpha_1}{1-\alpha_2}\sigma_\eta^2 \\ \frac{\alpha_1}{1-\alpha_2}\sigma_\eta^2 & \frac{\alpha_1}{1-\alpha_2}\sigma_\eta^2 & (\frac{\alpha_1}{1-\alpha_2})^2\sigma_\eta^2 + (\frac{\rho V_1[\eta]}{1-\alpha_2})^2\sigma_\tau^2 \end{pmatrix}. \quad (70)$$

Thus by the property of the conditional variance of the multi-normal distribution,

$$V[\eta|s_i, \hat{q}] = \sigma_\eta^2 - \begin{pmatrix} \sigma_\eta^2 & \frac{\alpha_1}{1-\alpha_2}\sigma_\eta^2 \end{pmatrix} \begin{pmatrix} \sigma_\eta^2 + \sigma_\nu^2 & \frac{\alpha_1}{1-\alpha_2}\sigma_\eta^2 \\ \frac{\alpha_1}{1-\alpha_2}\sigma_\eta^2 & (\frac{\alpha_1}{1-\alpha_2})^2\sigma_\eta^2 + (\frac{\rho V_1[\eta]}{1-\alpha_2})^2\sigma_\tau^2 \end{pmatrix}^{-1} \begin{pmatrix} \sigma_\eta^2 \\ \frac{\alpha_1}{1-\alpha_2}\sigma_\eta^2 \end{pmatrix}. \quad (71)$$

Simplifying (71) and noting  $V[\eta|s_i, \hat{q}] = V[\eta|s_i, Q]$  gives (13).

Similarly, by the properties of conditional mean of the multi-normal distribution,

$$E[\eta|s_i, \hat{q}] = \bar{\eta} + \begin{pmatrix} \sigma_\eta^2 & \frac{\alpha_1}{1-\alpha_2}\sigma_\eta^2 \end{pmatrix} \begin{pmatrix} \sigma_\eta^2 + \sigma_\nu^2 & \frac{\alpha_1}{1-\alpha_2}\sigma_\eta^2 \\ \frac{\alpha_1}{1-\alpha_2}\sigma_\eta^2 & (\frac{\alpha_1}{1-\alpha_2})^2\sigma_\eta^2 + (\frac{\rho V_1[\eta]}{1-\alpha_2})^2\sigma_\tau^2 \end{pmatrix}^{-1} \begin{pmatrix} s_i - \bar{\eta} \\ \hat{q} - \frac{\alpha_1}{1-\alpha_2}\bar{\eta} \end{pmatrix}. \quad (72)$$

Substituting in  $\hat{q}$  with (12) and  $V[\eta|s_i, \hat{q}]$  with (71) and noting  $E[\eta|s_i, \hat{q}] = E[\eta|s_i, Q]$  gives (14).

## B Appendix to Section 3

### B.1 Equation of Motion for Capital

Plugging (38) into (32) and integrating over individuals on both sides with (34) and (35) gives

$$Q_t (K_{t+1} - T^k [S_t] - T_{t+1}^\tau) = Q_{t-1} R_t (K_t - T^k [S_{t-1}] - T_t^\tau) - C_t + w_t N_t. \quad (73)$$

Plugging in (25), (33), (36), and (37) yields (22).

### B.2 Deriving the Equilibrium Conditions

Agents maximize utility (29) subject to budget constraint (32). State variables in individual optimization are the holdings of capital and bonds, i.e.  $U_{it} = U_{it}(k_{it}, b_{it-1})$ . Thus the first-order

conditions and envelope conditions are as follows:  
 First-order condition with respect to consumption

$$(1 - \delta)\tilde{C}_{it}^{-\frac{1}{\psi}}\tilde{C}_{it}^{\frac{1}{\xi_l}}oC_{it}^{-\frac{1}{\xi_l}} = \delta E_{it} [U_{it+1}^{1-\gamma}]^{\frac{\gamma-\frac{1}{\psi}}{1-\gamma}} E_{it}[U_{it+1}^{-\gamma}U_{ikt+1}\frac{1}{Q_t}]. \quad (74)$$

First-order condition with respect to labor

$$(1 - \delta)\tilde{C}_{it}^{-\frac{1}{\psi}}\tilde{C}_{it}^{\frac{1}{\xi_l}}(1 - o)A_{t-1}^{1-\frac{1}{\xi_l}}(1 - n_{it})^{-\frac{1}{\xi_l}} = \delta E_{it} [U_{it+1}^{1-\gamma}]^{\frac{\gamma-\frac{1}{\psi}}{1-\gamma}} E_{it}[U_{it+1}^{-\gamma}U_{ikt+1}\frac{w_t}{Q_t}]. \quad (75)$$

Envelope condition for capital

$$U_{ikt} = U_{it}^{\frac{1}{\psi}}\delta E_{it} [U_{it+1}^{1-\gamma}]^{\frac{\gamma-\frac{1}{\psi}}{1-\gamma}} E_{it}[U_{it+1}^{-\gamma}U_{ikt+1}\frac{Q_{t-1}}{Q_t}R_t]. \quad (76)$$

Taking the ratio of first-order conditions with respect to labor (75) and to consumption (74) gives (40), where  $w_t$  is given by (25).

Plugging the first-order condition with respect to consumption (74) into the right-hand side of the envelope condition for capital (76) gives

$$U_{ikt} = U_{it}^{\frac{1}{\psi}}(1 - \delta)\tilde{C}_{it}^{\frac{1}{\xi_l}-\frac{1}{\psi}}oC_{it}^{-\frac{1}{\xi_l}}Q_{t-1}R_t. \quad (77)$$

Iterating (77) to  $t + 1$ , plugging  $\frac{U_{ikt+1}}{Q_t}$  into the first-order condition with respect to consumption (74), and rearranging yield

$$\tilde{C}_{it}^{-\frac{1}{\psi}}\tilde{C}_{it}^{\frac{1}{\xi_l}}oC_{it}^{-\frac{1}{\xi_l}} = \delta E_t [U_{it+1}^{1-\gamma}]^{\frac{\gamma-\frac{1}{\psi}}{1-\gamma}} E_t[U_{it+1}^{-\gamma}U_{it+1}^{\frac{1}{\psi}}\tilde{C}_{it+1}^{\frac{1}{\xi_l}-\frac{1}{\psi}}oC_{it+1}^{-\frac{1}{\xi_l}}R_{t+1}]. \quad (78)$$

Defining  $M_{it+1} = \delta \left(\frac{C_{it+1}}{C_{it}}\right)^{-\frac{1}{\xi_l}} \left(\frac{\tilde{C}_{it+1}}{\tilde{C}_{it}}\right)^{\frac{1}{\xi_l}-\frac{1}{\psi}} \left(\frac{U_{it+1}}{E_t[U_{it+1}^{1-\gamma}]^{\frac{1}{1-\gamma}}}\right)^{\frac{1}{\psi}-\gamma}$  in (78) gives (41) and (42).

### B.3 Structure of Equilibrium Conditions

Rearranging (40) yields

$$\frac{1 - o A_{t-1}^{1-\frac{1}{\xi_l}}(1 - n_{it})^{-\frac{1}{\xi_l}}}{o C_{it}^{-\frac{1}{\xi_l}}} - w_t = 0. \quad (79)$$

Rearranging (41) yields

$$Q_t C_{it}^{-\frac{1}{\xi_l}} \tilde{C}_{it}^{\frac{1}{\xi_l}-\frac{1}{\psi}} E_{it} [U_{it+1}^{1-\gamma}]^{\frac{\frac{1}{\psi}-\gamma}{1-\gamma}} = E_{it} \left[ \delta C_{it+1}^{-\frac{1}{\xi_l}} \tilde{C}_{it+1}^{\frac{1}{\xi_l}-\frac{1}{\psi}} U_{it+1}^{\frac{1}{\psi}-\gamma} \left( \alpha \frac{Y_{t+1}}{K_{t+1}} + Q_{t+1}(1 - \delta_k + G'_{t+1}) \frac{I_{t+1}}{K_{t+1}} - G_{t+1} \right) \right] \quad (80)$$

Rearranging (32) yields

$$Q_t k_{it+1} - Q_{t-1} R_t k_{it} - T_{it} + c_{it} - w_t n_{it} = 0 \quad (81)$$

## B.4 Proof of Lemma 2

Given Lemma 1, it follows immediately that

$$E_{it} [\eta_{t+1}] = E [\eta_{t+1} | s_{it}, S_t] = E [\eta_{t+1} | s_{it}, \hat{q}_t], \quad (82)$$

We can thus guess that the rational expectation of  $\eta_{t+1}$  to be the linear function

$$E_{it}[\eta_{t+1}] = \alpha_0 + \alpha_1 s_{it} + \alpha_2 \hat{q}_t, \quad (83)$$

where  $\alpha_0$ ,  $\alpha_1$ , and  $\alpha_2$  are the optimal weights on the prior, the private signal and the average expectation, respectively. Substituting in (45), taking the integral across individuals, and solving for  $\int E_{it} [\eta_{t+1}]$  gives

$$\int E_{it}[\eta_{t+1}] di = \frac{\alpha_0}{1 - \alpha_2} + \frac{\alpha_1}{1 - \alpha_2} \eta_{t+1} + \frac{\alpha_2}{1 - \alpha_2} \frac{V_t[\eta]}{\sigma_\eta^2} \tau_t. \quad (84)$$

Adding  $\frac{V_t[\eta]}{\sigma_\eta^2} \tau_t$  on both sides of the equation, substituting (45) and simplifying yields

$$\frac{1 - \alpha_2}{\alpha_1} \hat{q}_t - \frac{\alpha_0}{\alpha_1} = \eta_{t+1} + \frac{1}{\alpha_1} \frac{V_t[\eta]}{\sigma_\eta^2} \tau_t. \quad (85)$$

Thus with the normality of the fundamental shock  $\tau_t$  and the demand statistic  $\hat{q}_t$ , the vector  $(\eta_{t+1}, s_{it}, \hat{q}_t)$  has an unconditional expectation of

$$\mu_t = \left( \bar{\eta} \quad \bar{\eta} \quad \frac{\alpha_0}{1 - \alpha_2} + \frac{\alpha_1}{1 - \alpha_2} \bar{\eta} \right) \quad (86)$$

and an unconditional variance covariance matrix of

$$\Sigma_t = \begin{pmatrix} \sigma_\eta^2 & \sigma_\eta^2 & \frac{\alpha_1 \sigma_\eta^2}{1 - \alpha_2} \\ \sigma_\eta^2 & \sigma_\eta^2 + \sigma_\nu^2 & \frac{\alpha_1 \sigma_\eta^2}{1 - \alpha_2} \\ \frac{\alpha_1 \sigma_\eta^2}{1 - \alpha_2} & \frac{\alpha_1 \sigma_\eta^2}{1 - \alpha_2} & \frac{\alpha_1^2 \sigma_\eta^2}{(1 - \alpha_2)^2} + \frac{V_1^2 \sigma_\tau^2}{(1 - \alpha_2)^2 \sigma_\eta^4} \end{pmatrix}. \quad (87)$$

Thus by the property of the conditional variance of the multi-normal distribution, the condi-

tional variance is

$$V[\eta_{t+1}|s_{it}, \hat{q}_t] = \sigma_\eta^2 - \begin{pmatrix} \sigma_\eta^2 & \frac{\alpha_1}{1-\alpha_2} \sigma_\eta^2 \end{pmatrix} \begin{pmatrix} \sigma_\eta^2 + \sigma_\nu^2 & \frac{V_1 \sigma_\eta^2}{(1-\alpha_2) \sigma_\nu^2} \\ \frac{V_1 \sigma_\eta^2}{(1-\alpha_2) \sigma_\nu^2} & \frac{V_1^2 \sigma_\eta^2}{(1-\alpha_2)^2 \sigma_\nu^4} + \frac{V_1^2 \sigma_\tau^2}{(1-\alpha_2)^2 \sigma_\eta^4} \end{pmatrix}^{-1} \begin{pmatrix} \sigma_\eta^2 \\ \frac{\alpha_1}{1-\alpha_2} \sigma_\eta^2 \end{pmatrix} \quad (88)$$

which simplifies to (52). Similarly, the conditional mean is

$$E[\eta_{t+1}|s_{it}, \hat{q}_t] = \bar{\eta} + \begin{pmatrix} \sigma_\eta^2 & \frac{\alpha_1}{1-\alpha_2} \sigma_\eta^2 \end{pmatrix} \begin{pmatrix} \sigma_\eta^2 + \sigma_\nu^2 & \frac{\alpha_1}{1-\alpha_2} \sigma_\eta^2 \\ \frac{\alpha_1}{1-\alpha_2} \sigma_\eta^2 & (\frac{\alpha_1}{1-\alpha_2})^2 \sigma_\eta^2 + (\frac{\rho V_1[\eta]}{1-\alpha_2})^2 \sigma_\tau^2 \end{pmatrix}^{-1} \begin{pmatrix} s_{it} - \bar{\eta} \\ \hat{q}_t - (\frac{\alpha_0}{1-\alpha_2} + \frac{\alpha_1}{1-\alpha_2} \bar{\eta}) \end{pmatrix}, \quad (89)$$

which simplifies to (51).

Matching coefficients with (83) gives (53) and (54).

Taking conditional expectation on both sides of (85) and solving for  $E_{it}[\tau_t]$  yields

$$E_{it}[\tau_t] = ((1 - \alpha_2) \hat{q}_t - \alpha_0 - \alpha_1 E_{it}[\eta_{t+1}]) \frac{\sigma_\eta^2}{V_t[\eta]}.$$

Similarly, taking conditional variance on both sides of (85) and plugging (53) gives

$$V_{it}[\tau_t] = \frac{\sigma_\eta^4}{\sigma_\nu^4} V_{it}[\eta_{t+1}]$$

## C Appendix to Section 5

### C.1 Data Sources

**Consumption** ( $C_t$ ). Per-capita consumption data are from the National Income and Product Accounts (NIPA) annual data reported by the Bureau of Economic Analysis (BEA). The data are constructed as the sum of consumption expenditures on nondurable goods and services (Table 1.1.5, Lines 5 and 6) deflated by corresponding price deflators (Table 1.1.9, Lines 5 and 6).

**Physical Investment** ( $I_t$ ). Per-capita physical investment data are also from the NIPA tables. We measure physical investment by fixed investment (Table 1.1.5, Line 8) minus information-processing equipment (Table 5.5.5, Line 3) deflated by its price deflator (Table 1.1.9, Line 8). Information-processing equipment is interpreted as investment in intangible capital and is therefore subtracted from fixed investment.

**Output** ( $Y_t$ ). It is the sum of total consumption and investment, that is,  $C_t + I_t$ . We exclude government expenditure and net export because they are not explicitly modeled in our economy.

**Labor** ( $N_t$ ). It is measured as the total number of full-time and part-time employees as reported in the NIPA Table 6.4. Data are annual.

**Stock market returns** ( $R_t$ ) and **Risk-free rate** ( $R_t^f$ ) The stock market return are from the Fama-French dataset available online on K. French's webpage at

[http://mba.tuck.dartmouth.edu/pages/faculty/ken.french/ftp/F-F\\_Research\\_Data\\_Factors.zip](http://mba.tuck.dartmouth.edu/pages/faculty/ken.french/ftp/F-F_Research_Data_Factors.zip).

The nominal risk-free rate is measured by the annual three-month T-bill return. The real stock market returns and risk-free rate are computed by subtracting realized inflation (annual CPI through FRED) from the nominal risk-free rate.

**Price-dividends** ( $pd_t$ ) ratio and **Tobin's Q** ( $Q_t$ ). Data on annual price-dividend ratio, and dividend are obtained from CRSP. Annual dividends are obtained by time-aggregating monthly dividends. Nominal dividends are turned into real dividends using the CPI index. Data on Tobin's Q are from the Flow of Funds (FoF) and are obtained directly from the St. Louis Fed by dividing the variable MVEONWMVBSNNCB (Line 35 of Table B.102 in the FoF report) by TNWMVBSNNCB (Line 32 of table B.102 in the FoF report).

**GDP Forecast** ( $\hat{y}_{it}$  and  $\hat{y}_t$ ). GDP forecast data during 1969-2010 are from the Survey of Professional Forecasters provided by the Philadelphia Federal Reserve at

<http://www.philadelphiafed.org/research-and-data/real-time-center/survey-of-professional-forecasters/>