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YULEI LUO  
ERIC R. YOUNG

## Long-Run Consumption Risk and Asset Allocation under Recursive Utility and Rational Inattention

We study the portfolio decision of a household with limited information-processing capacity (rational inattention [RI]) in a setting with recursive utility. We find that RI combined with a preference for early resolution of uncertainty could lead to a significant drop in the share of portfolios held in risky assets, even when the departure from the standard expected utility setting with full-information rational expectations is small. In addition, we show that the equilibrium equity premium increases with the degree of inattention because inattentive investors with recursive utility face greater long-run risk and thus require higher compensation in equilibrium.

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THE CANONICAL OPTIMAL CONSUMPTION-PORTFOLIO choice models implicitly assume that consumers and investors have *unlimited* information-processing capacity and thus can observe the state variable(s) without errors; consequently, they can adjust their optimal plans instantaneously and completely to innovations to equity returns. However, plenty of evidence exists that ordinary people only have limited information-processing capacity and face many competing demands for their attention. As a result, agents react to the innovations slowly and incompletely because the channel along which information flows—the Shannon

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YULEI LUO is an Associate Professor of Economics in the Faculty of Business and Economics, University of Hong Kong, Hong Kong (*E-mail:* yulei.luo@gmail.com). ERIC R. YOUNG is an Associate Professor of Economics in the Department of Economics, University of Virginia (*E-mail:* ey2d@virginia.edu).

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channel—cannot carry an infinite amount of information. In Sims (2003), this type of information-processing limitation is termed as “rational inattention”(RI). In the RI framework, entropy is used to measure the uncertainty of a random variable, and the reduction in the entropy is used to measure information flow.<sup>1</sup> For finite Shannon channel capacity, the reduction in entropy is bounded above; as capacity becomes infinitely large, the RI model converges to the standard full-information rational expectations (REs) model.<sup>2</sup>

Luo (2010) applies the RI hypothesis in the intertemporal portfolio choice model with time-separable preferences in the vein of Merton (1969) and shows that RI alters the optimal choice of portfolio as well as the joint behavior of aggregate consumption and asset returns. In particular, limited information-processing capacity leads to smaller shares of risky assets. However, to generate the observed share and realistic joint dynamics of aggregate consumption and asset returns, the degree of attention must be as low as 10% (the corresponding Shannon capacity is 0.08 bits of information); this number means that only 10% of the uncertainty is removed in each period upon receiving a new signal about the aggregate shock to the equity return. Since we cannot estimate the degree of average inattention directly (i.e., without a model), it is difficult to determine whether this limit is empirically reasonable. Indirect measurements of capacity uncover significantly higher channel capacity; we discuss them explicitly later in the paper.<sup>3</sup>

The preferences used in Luo (2010) are known to entangle two distinct aspects of preferences. Risk aversion measures the distaste for marginal utility variation across states of the world, whereas the elasticity of intertemporal substitution measures the distaste for deterministic variation of consumption across time; with expected utility, these two attitudes are controlled by a single parameter such that if risk aversion increases, the elasticity of intertemporal substitution must fall. The result in Luo (2010) shows that RI interacts with this parameter in a way that raises the apparent risk aversion (lowers the apparent intertemporal substitution elasticity) of the investor; however, it is unclear which aspect of preferences is actually being altered. As a result, interpretation of the results is ambiguous. Here, we develop an RI-portfolio choice model within the recursive utility (RU) framework and use it to examine the effects of RI and RU on long-run consumption risk and optimal asset allocation. Specifically, we adopt preferences from the class studied by Kreps and Porteus (1978) and Epstein and Zin (1989), where risk aversion and intertemporal

1. Entropy of a random variable  $X$  with density  $p(X)$  is defined as  $E[\log(p(X))]$ . Cover and Thomas (1991) is a standard introduction to information theory and the notion of entropy.

2. There are a number of papers that study decisions within the linear quadratic (LQ)-RI framework: Sims (2003, 2006), Adam (2005), Luo (2008, 2010), Maćkowiak and Wiederholt (2009), and Luo and Young (2010a, b).

3. The effect of RI on consumption growth and asset prices in the standard expected utility framework has been examined in Luo and Young (2010a). That paper showed that an agent with incomplete information-processing ability will require a higher return to hold a risky asset because RI introduces (i) higher volatility into consumption and (ii) positive autocorrelation into consumption growth. In addition, Luo and Young (2010b) examine how risk-sensitive preferences, a special case of Epstein–Zin RU, affect consumption, precautionary savings, and the welfare of inattentive agents.

substitution are disentangled. These preferences also break indifference to the timing of the resolution of uncertainty, an aspect of preferences that plays an important role in determining the demand for risky assets (see Backus, Routledge, and Zin 2007). Indeed, it turns out that this aspect of preferences is key.

For tractability reasons, we are confined to small deviations away from the standard class of preferences. However, we find that even a small deviation from unlimited information-processing capacity will lead to large changes in portfolio allocation if investors prefer early resolution of uncertainty. The intuition for this result lies in the long-term risk that equities pose: with RI, uncertainty about the value of the equity return (and therefore the marginal utility of consumption) is not resolved for (infinitely) many periods. This postponement of information is distasteful to agents who prefer early resolution of uncertainty, causing them to prefer an asset with an even and certain intertemporal payoff (the risk-free asset); in the standard time-separable expected utility framework, agents must be indifferent to the timing of the resolution of uncertainty, preventing the model in Luo (2010) from producing significant effects without very low channel capacity. Due to the nature of the accumulation of uncertainty, even small deviations from indifference (again, in the direction of preference for early resolution) combined with small deviations from complete information processing lead to large declines in optimal risky asset shares. Thus, we provide a theory for why agents hold such a small share of risky assets without requiring extreme values for preference parameters.

This result is based on the fact that RI introduces positive autocorrelation into consumption growth, that is, consumption under RI reacts gradually to the wealth shock.<sup>4</sup> Here, we show that this effect is amplified by a preference for early resolution of uncertainty and can become quite large, even when the deviation from indifference is arbitrarily small. Around the expected utility setting with unitary intertemporal elasticity of substitution and relative risk aversion, what matters for the size of this effect is the relative size of the deviation in intertemporal elasticity of substitution (IES) from 1 as compared to the size of the deviation from relative risk aversion of 1; the absolute size of either deviation is not important, so they can be arbitrarily small.

To explore the equilibrium asset pricing implications of RU and RI, we consider a simple exchange economy in the vein of Lucas (1978) using the optimal consumption and portfolio rules. Specifically, we assume that in equilibrium the representative agent receives an endowment, which equals optimal consumption obtained in the consumption-portfolio choice model, and can trade two assets: a risky asset entitling the consumer to the endowment and a riskless asset with zero net supply. Using the optimal consumption and portfolio rules and the market-clearing condition, we find that how the interaction of RU and RI significantly increase the equilibrium equity

4. Reis (2006) showed that inattentiveness due to costly planning could lead to slow adjustment of aggregate consumption to income shocks. The main difference between the implications of RI and Reis' inattentiveness for consumption behavior is that in the inattentiveness economy, individuals adjust consumption *infrequently but completely* once they choose to adjust and aggregate consumption stickiness comes from aggregating across all individuals, whereas individuals under RI adjust their optimal consumption plans *frequently but incompletely* and aggregate consumption stickiness comes from individuals' incomplete consumption adjustments.

premium and also improve the joint behavior of aggregate consumption and the equity return.

Finally, we consider two extensions. First, we permit correlation between the equity return and the RI-induced noise.<sup>5</sup> We find that the sign of the correlation affects the long-run consumption and optimal asset allocation. Specifically, a negative correlation will further reduce the optimal share invested in the risky asset. We then present the results of adding nontradable labor income into the model, generating a hedging demand for risky equities. We find that our results survive essentially unchanged—RI combined with a preference of early resolution of uncertainty still decreases the share of risky assets in the portfolio for small deviations around standard log preferences. In addition, we find that the importance of the hedging demand for equities is increasing in the degree of RI. As agents become more constrained, they suffer more from uncertainty about consumption; thus, they are more interested in holding equities if they negatively covary with the labor income shock and less interested if they positively covary. Given that the data support a small correlation between individual wage income and aggregate stock returns (Heaton and Lucas 2000), our results survive this extension intact.

Our model is closely related to van Nieuwerburgh and Veldkamp (2010) and Mondria (2010). van Nieuwerburgh and Veldkamp (2010) discuss the relationship between information acquisition, the preference for early resolution of uncertainty, and portfolio choice in a static model broken into three periods. Specifically, they find that information acquisition help resolves the uncertainty surrounding asset payoffs; consequently, an investor may prefer early resolution of uncertainty either because he has Epstein–Zin preferences or because he can use the early information to adjust his portfolio. In other words, van Nieuwerburgh and Veldkamp (2010) focus on the static portfolio underdiversification problem with information acquisition, while we focus on the dynamic aspect of the interaction between incomplete information and recursive preferences. Mondria (2010) also considers two-period portfolio choice model with correlated risky assets in which investors choose the composition of their attention subject to an information flow constraint. He shows that there is an equilibrium in which all investors choose to observe a linear combination of these asset payoffs as a private signal. In contrast, the mechanism of our model is based on the effects of the interplay of the preference for early resolution of uncertainty and finite capacity on the dynamic response of consumption to the shock to the equity return that determines the long-run consumption risk; in our model, the preference for early resolution of uncertainty amplifies the role of finite information-processing capacity in generating greater long-run risk.

This paper is organized as follows. Section 1 presents an otherwise standard two-asset portfolio choice model with RU and RI. Section 2 solves this RI version of the RU model and examines the implications of the interactions of RI, the separation of risk aversion and intertemporal substitution, and the discount factor for the optimal portfolio rule, consumption dynamics, and the equilibrium equity premium. Section 3

5. This assumption generalizes the i.i.d. noise assumption used in Sims (2003) and Luo (2010).

discusses two extensions: the presence of the correlation between the equity return and the noise and the introduction of nontradable labor income. Section 4 concludes and discusses the extension of the results to non-LQ environments. Appendices contain the proofs and derivations that are omitted from the main text.

## 1. AN INTERTEMPORAL PORTFOLIO CHOICE MODEL WITH RATIONAL INATTENTION AND RECURSIVE UTILITY

In this section, we present and discuss a standard intertemporal portfolio choice model within an RU framework. Following the log-linear approximation method proposed by Campbell (1993), Viceira (2001), and Campbell and Viceira (1999, 2002), we incorporate RI into the standard model and solve it explicitly after considering the long-run consumption risk facing the investors.<sup>6</sup> We then discuss the interplay between RI, risk aversion, and intertemporal substitution for portfolio choice and asset pricing.

### 1.1 Specification of the Portfolio Choice Model with Recursive Utility

Before setting up and solving the portfolio choice model with RI, it is helpful to present the standard portfolio choice model first and then discuss how to introduce RI in this framework. Here, we consider a simple intertemporal model of portfolio choice with a continuum of identical investors. Following Epstein and Zin (1989), Giovannini and Weil (1989), and Campbell and Viceira (1999) suppose that investors maximize an RU function  $U_t$  by choosing consumption and asset holdings:

$$U_t = \left\{ (1 - \beta) C_t^{1-1/\sigma} + \beta \left( E_t \left[ U_{t+1}^{1-\gamma} \right] \right)^{(1-1/\sigma)/(1-\gamma)} \right\}^{\frac{1}{1-1/\sigma}}, \quad (1)$$

where  $C_t$  represents individual's consumption at time  $t$ ,  $\beta$  is the discount factor,  $\gamma$  is the coefficient of relative risk aversion (CRRA) over wealth gambles, and  $\sigma$  is the elasticity of intertemporal substitution.<sup>7</sup> Let  $\rho = (1 - \gamma)/(1 - 1/\sigma)$ ; if  $\rho > 1$ , the household has a preference for early resolution of uncertainty.

We assume that the investment opportunity set is constant and contains only two assets: asset  $e$  is risky, with one-period log (continuously compounded) return  $r_{e,t+1}$ , while the other asset  $f$  is riskless with constant log return given by  $r_f$ . We refer to asset  $e$  as the market portfolio of equities, and to asset  $f$  as the riskless bond.

6. Another major advantage of the log-linearization approach is that we can obtain a quadratic expected loss function by approximating the original value function from the nonlinear problem when relative risk aversion is close to 1 and thus can justify Gaussian posterior uncertainty under RI.

7. When  $\gamma = \sigma^{-1}$ ,  $\rho = 1$  and the RU reduces to the standard time-separable power utility with RRA  $\gamma$  and intertemporal elasticity  $\gamma^{-1}$ . When  $\gamma = \sigma = 1$ , the objective function is the time-separable log utility function.

$r_{e,t+1}$  has expected return  $\mu$ ,  $\mu - r_f$  is the equity premium, and  $r_{e,t+1}$  has an i.i.d. unexpected component  $u_{t+1}$  with  $\text{var}[u_{t+1}] = \omega^2$ .<sup>8</sup>

The intertemporal budget constraint for the investor is

$$A_{t+1} = R_{p,t+1} (A_t - C_t), \quad (2)$$

where  $A_{t+1}$  is the individual's financial wealth (the value of financial assets carried over from period  $t$  at the beginning of period  $t + 1$ ),  $A_t - C_t$  is current period savings, and  $R_{p,t+1}$  is the one-period gross return on savings given by

$$R_{p,t+1} = \alpha_t (R_{e,t+1} - R_f) + R_f, \quad (3)$$

where  $R_{e,t+1} = \exp(r_{e,t+1})$ ,  $R_f = \exp(r_f)$ , and  $\alpha_t = \alpha$  is the proportion of savings invested in the risky asset.<sup>9</sup> As in Campbell (1993), we can derive an approximate expression for the log return on wealth:

$$r_{p,t+1} = \alpha (r_{e,t+1} - r_f) + r_f + \frac{1}{2} \alpha (1 - \alpha) \omega^2. \quad (4)$$

Given the above model specification, it is well known that this simple discrete-time model cannot be solved analytically. We therefore follow the log-linearization method proposed in Campbell (1993), Viceira (2001), and Campbell and Viceira (2002) to obtain a closed-form solution to an approximation of this problem.<sup>10</sup> Specifically, the original intertemporal budget constraint, (2), can be approximated around the unconditional mean of the log consumption-wealth ratio ( $c - a = E[c_t - a_t]$ ):

$$\Delta a_{t+1} = \left(1 - \frac{1}{\phi}\right) (c_t - a_t) + \psi + r_{t+1}^p, \quad (5)$$

where  $\phi = 1 - \exp(c - a)$ ,  $\psi = \log(\phi) - (1 - 1/\phi) \log(1 - \phi)$ , and lowercase letters denote logs. Note that the approximation, (5), holds exactly in our model because the consumption-wealth ratio in the model with i.i.d. returns is constant.<sup>11</sup> As shown in Viceira (2001), the assumptions on the preference and the investment opportunity

8. Under unlimited information-processing capacity, two-fund separation theorems imply that this investment opportunity set is sufficient. All agents would choose the same portfolio of multiple risky assets; differences in preferences would manifest themselves only in terms of the share allocated to this risky portfolio versus the riskless asset. We believe, but have not proven, that this result would go through under RI as well.

9. Given i.i.d. equity returns and an RU function,  $\alpha_t$  will be constant over time. See Giovannini and Weil (1989) for a proof.

10. This method proceeds as follows. First, the flow budget constraint and the consumption Euler equations are log approximated around the steady state. The Euler equations are log approximated by a second-order Taylor expansion so that the second moment is included; these terms are constant and thus the resulting equation is log linear. Second, the optimal consumption and portfolio choices that satisfy these log-linearized equations are chosen as log-linear functions of the state. Finally, the coefficients of these optimal decision rules are pinned down using the method of undetermined coefficients.

11. Campbell (1993) and Campbell and Viceira (1999) have shown that the approximation is exact when the consumption-wealth ratio is constant over time and becomes less accurate when the ratio becomes more volatile.

set ensure that along the optimal path, financial wealth ( $A_t$ ), savings ( $A_t - C_t$ ), and consumption ( $C_t$ ) are strictly positive. Because the marginal utility of consumption approaches  $\infty$  as consumption approaches zero, the investor chooses consumption-savings and portfolio rules that ensure strictly positive consumption next period. Thus, we must have  $A_{t+1} > 0$  and  $A_t - C_t > 0$ , so that the log of these objects is well defined (note that the intertemporal budget constraint implies that  $A_t - C_t > 0$  is a necessary condition for next period's financial wealth to be positive). As shown in Campbell and Viceira (2002), the optimal consumption and portfolio rules under full-information RE are then

$$c_t = b_0 + a_t, \quad (6)$$

$$\alpha = \frac{\mu - r_f + 0.5\omega^2}{\gamma\omega^2}, \quad (7)$$

where  $b_0 = \log(1 - \beta^\sigma(E_t[R_{p,t+1}^{1-\gamma}]^{\frac{\sigma-1}{1-\gamma}}))$  and  $\gamma$  can be written as  $\rho/\sigma + 1 - \rho$ .<sup>12</sup> Note that  $\phi = \beta$  and  $b_0 = \log(1 - \phi)$  when  $\sigma$  is close 1. Consequently, the value function corresponding to (1) is  $V_t = (1 - \beta)A_t$ .

## 1.2 Introducing RI

Following Sims (2003), we introduce RI into the otherwise standard intertemporal portfolio choice model by assuming consumers/investors face information-processing constraints and have only finite Shannon channel capacity to observe the state of the world. Specifically, we use the concept of entropy from information theory to characterize the uncertainty about a random variable; the reduction in entropy is thus a natural measure of information flow. Formally, entropy is defined as the expectation of the negative of the log of the density function,  $-E[\log(f(X))]$ .<sup>13</sup>

With finite capacity  $\kappa \in (0, \infty)$ , the true state  $a$  (a continuous variable) cannot be observed without error; thus, the information set at time  $t + 1$ ,  $\mathcal{I}_{t+1}$ , is generated by the entire history of noisy signals  $\{a_j^*\}_{j=0}^{t+1}$ . Following the RI literature, we assume that the noisy signal takes the additive form:  $a_{t+1}^* = a_{t+1} + \xi_{t+1}$ , where  $\xi_{t+1}$  is the endogenous noise caused by finite capacity. We further assume that  $\xi_{t+1}$  is an i.i.d. idiosyncratic Gaussian shock and is independent of the fundamental shock.<sup>14</sup> Formally, this idea can be described by the information constraint

$$\mathcal{H}(a_{t+1}|\mathcal{I}_t) - \mathcal{H}(a_{t+1}|\mathcal{I}_{t+1}) = \kappa, \quad (8)$$

12. Note that a unitary marginal propensity to consume and a constant optimal fraction invested in the risky asset are valid not only for CRRA expected utility but also for Epstein-Zin RU when the return to equity is i.i.d. See Appendices in Giovannini and Weil (1989) and Campbell and Viceira (1999) for detailed deviations.

13. For the detailed discussions on entropy and its applications in economics, see Sims (2003, 2010).

14. Note that the reason that the RI-induced noise is idiosyncratic is that the endogenous noise arises from the consumer's own internal information-processing constraint.

where  $\kappa$  is the investor's information channel capacity,  $\mathcal{H}(a_{t+1}|\mathcal{I}_t)$  denotes the entropy of the state *prior to* observing the new signal at  $t+1$ , and  $\mathcal{H}(a_{t+1}|\mathcal{I}_{t+1})$  is the entropy *after* observing the new signal.  $\kappa$  imposes an upper bound on the amount of information that can be transmitted in any given period. Furthermore, following the literature, we suppose that the *ex ante*  $a_{t+1}$  is a Gaussian random variable. As shown in Sims (2003), the optimal posterior distribution for  $a_{t+1}$  will also be Gaussian given a quadratic loss function. (Please see Appendix A.1 for a discussion on how to obtain an approximately quadratic loss function in our model.) Finally, we assume that all individuals in the model economy have the same channel capacity; hence, the average capacity in the economy is equal to individual capacity.<sup>15</sup>

As noted earlier, *ex post* Gaussian uncertainty is optimal:

$$a_{t+1}|\mathcal{I}_{t+1} \sim N(\hat{a}_{t+1}, \Sigma_{t+1}), \quad (9)$$

where  $\hat{a}_{t+1} = E[a_{t+1}|\mathcal{I}_{t+1}]$  and  $\Sigma_{t+1} = \text{var}[a_{t+1}|\mathcal{I}_{t+1}]$  are the conditional mean and variance of  $a_{t+1}$ , respectively. The information constraint (8) can thus be reduced to

$$\frac{1}{2} (\log(\Psi_t) - \log(\Sigma_{t+1})) = \kappa, \quad (10)$$

where  $\Sigma_{t+1} = \text{var}[a_{t+1}|\mathcal{I}_{t+1}]$  and  $\Psi_t = \text{var}[a_{t+1}|\mathcal{I}_t]$  are the posterior and prior variance, respectively. Given a finite transmission capacity of  $\kappa$  bits per time unit, the optimizing consumer chooses a signal that reduces the conditional variance by  $(\log(\Psi_t) - \log(\Sigma_{t+1}))/2$ .<sup>16</sup> In the univariate state case, this information constraint completes the characterization of the optimization problem and everything can be solved analytically.<sup>17</sup>

The intertemporal budget constraint (5) then implies that

$$E_t [a_{t+1}] = E_t [r_{p,t+1}] + \psi + \hat{a}_t, \quad (11)$$

$$\text{var}_t [a_{t+1}] = \text{var}_t [r_{p,t+1}] + \left( \frac{1}{\phi} \right)^2 \Sigma_t, \quad (12)$$

15. Assuming that channel capacity follows some distribution in the cross section complicates the problem when aggregating, but would not change the main findings.

16. Note that given  $\Sigma_t$ , choosing  $\Sigma_{t+1}$  is equivalent to choosing the noise  $\text{var}[\xi_t]$ , because the usual updating formula for the variance of a Gaussian distribution is

$$\Sigma_{t+1} = \Psi_t - \Psi_t (\Psi_t + \text{var}[\xi_t])^{-1} \Psi_t,$$

where  $\Psi_t$  is the *ex ante* variance of the state and is a function of  $\Sigma_t$ .

17. With more than one state variable, there is an additional constraint that requires the difference between the prior and the posterior variance–covariance matrices be positive semidefinite; the resulting optimal posterior cannot be characterized analytically and generally poses significant numerical challenges as well. See Sims (2003) for some examples.

where  $E_t[\cdot] \equiv E[\cdot|I_t]$  and  $\text{var}_t[\cdot] \equiv \text{var}[\cdot|I_t]$ , and  $I_t$  is the information set that includes all of the processed information. Note that  $I_t$  are different under RI and FI-RE. Substituting (11) into (10) yields

$$\kappa = \frac{1}{2} \left[ \log \left( \text{var}_t(r_{p,t+1}) + \left( \frac{1}{\phi} \right)^2 \Sigma_t \right) - \log(\Sigma_{t+1}) \right], \quad (13)$$

which has a unique steady state  $\Sigma = \text{var}_t[r_{p,t+1}] / [\exp(2\kappa) - (1/\phi)^2]$  with  $\text{var}_t[r_{p,t+1}] = \alpha^2 \omega^2$ . Note that here  $\phi$  is close to  $\beta$  as  $\sigma$  is close to 1. Using the intertemporal budget constraint (5), we can obtain the corresponding Kalman filtering equation governing the evolution of the perceived state:

**PROPOSITION 1.** *Under RI, the perceived state  $\hat{a}_t$  evolves according to the following equation:*

$$\hat{a}_{t+1} = \frac{1}{\phi} \hat{a}_t + \left( 1 - \frac{1}{\phi} \right) c_t + \psi + \eta_{t+1}, \quad (14)$$

where  $\eta_{t+1}$  is the innovation to the perceived state:

$$\eta_{t+1} = \theta (r_{p,t+1} + \xi_{t+1}) + \frac{\theta}{\phi} (a_t - \hat{a}_t), \quad (15)$$

$a_t - \hat{a}_t$  is the estimation error:

$$a_t - \hat{a}_t = \frac{(1-\theta)r_{p,t+1}}{1 - ((1-\theta)/\phi) \cdot L} - \frac{\theta \xi_t}{1 - ((1-\theta)/\phi) \cdot L}, \quad (16)$$

$\theta = 1 - 1/\exp(2\kappa)$  is the optimal weight on a new observation,  $\xi_{t+1}$  is the i.i.d. Gaussian noise with  $E[\xi_{t+1}] = 0$  and  $\text{var}[\xi_{t+1}] = \Sigma/\theta$ , and  $a_{t+1}^* = a_{t+1} + \xi_{t+1}$  is the observed signal.

**PROOF.** See Appendix 1.2. ■

In the next step, we assume that the share invested in the risky asset ( $\alpha$ ) is constant and derive the expression for consumption dynamics.<sup>18</sup> As we noted before, equations (5) and (14) are homeomorphic because (14) can be obtained by (i) replacing  $a_t$  with  $\hat{a}_t$  and (ii) replacing  $r_{p,t+1}$  with  $\eta_{t+1}$ , in (5). Note that  $r_{p,t+1}$  and  $\eta_{t+1}$  are i.i.d. log-normally distributed innovations with mean 0 and  $\alpha$  is constant. Given this equivalence, we can follow the same procedure used in the literature to show that the consumption function under RI is

$$c_t = b_0 + \hat{a}_t, \quad (17)$$

18. Later, we will verify that our guess that  $\alpha$  is constant under RI is correct.

where  $b_0 = \log(1 - \beta^\sigma(E_t[R_{\eta,t+1}^{1-\gamma}]^{\frac{\sigma-1}{1-\gamma}}))$  and  $R_{\eta,t+1} = \exp(\eta_{t+1})$  follows a log-normal distribution.<sup>19</sup> It is straightforward to show that  $b_0$  is approximately  $\log(1 - \phi)$  and  $\phi = \beta$  when  $\sigma$  is close to 1. That is, in this case, the values of  $\phi$  and  $b_0$  are independent of the impact of RI. Note that here (17) is not the final expression for the consumption function because the optimal share invested in stock market  $\alpha$  has yet to be determined.

Before moving on, we want to comment briefly on the decision rule of an agent with RI. An agent with RI chooses a joint distribution of states and controls, subject to the information-processing constraint and some fixed prior distribution over the state; with  $\kappa = \infty$ , this distribution is degenerate, but with  $\kappa < \infty$ , it is generally nontrivial. The noise terms  $\xi_t$  can be viewed in the following manner: the investor instructs nature to choose consumption in the current period from a certain joint distribution of consumption and current and future permanent income, and then nature selects at random from that distribution (conditioned on the true current permanent income that the agent cannot observe). Thus, an observed signal about future permanent income  $a_{t+1}^*$  is equivalent to making the signal current consumption.

We make the following assumption.

ASSUMPTION 1.

$$2\kappa > \log(1/\phi). \quad (18)$$

Equation (18) ensures that agents have sufficient information-processing ability to “zero out” the unstable root in the Euler equation. It will also ensure that certain infinite sums converge. Note that using the definition of  $\theta$ , we can write this restriction as  $1 - \theta < \phi^2 < \phi$ ; the second inequality arises because  $\phi < 1$ . (Note that  $\phi = \beta$  when  $\sigma$  is close to 1.) Note that along the optimal path, financial wealth ( $A_t$ ), savings ( $A_t - C_t$ ), perceived financial wealth ( $\hat{A}_t = \exp(\hat{a}_t)$ ), and consumption ( $C_t$ ) are strictly positive. Given that  $\lim_{C_t \rightarrow 0} u'(C_t) = \infty$ , the investor chooses optimal consumption savings and portfolio rules to ensure strictly positive consumption next period; that is, we must have  $A_{t+1} > 0$  and  $A_t - C_t > 0$  (i.e.,  $A_t - (1 - \beta)\hat{A}_t > 0$ ), to guarantee that the logarithm of these objects is well defined. The following example is illustrative. An inattentive investor does not have perfect information about his banking account. He knows that he has about \$1,000 in the account, but he does not know the *exact* amount (say \$1,010.00). He has already made a decision to purchase a sofa in a furniture store; when he uses his debit card to check out, he finds that the price of the sofa (say \$1,099.99) exceeds the amount of money in his account. He must then choose a less expensive sofa (say \$999) such that consumption is always less than his wealth. In effect, the consumer constrains nature from choosing points from the joint distribution that imply negative consumption at any future date.

19. Note that as  $\theta$  increases to 1,  $\eta_{t+1}$  and  $R_{\eta,t+1}$  reduce to  $r_{p,t+1}$  and  $R_{p,t+1}$ , respectively.

Combining (5), (14), and (17) gives the expression for individual consumption growth:

$$\Delta c_{t+1} = \theta \left\{ \frac{\alpha u_{t+1}}{1 - ((1 - \theta)/\phi) \cdot L} + \left[ \xi_{t+1} - \frac{(\theta/\phi) \xi_t}{1 - ((1 - \theta)/\phi) \cdot L} \right] \right\}, \quad (19)$$

where  $L$  is the lag operator.<sup>20</sup> Note that all the above dynamics for consumption, perceived state, and the change in consumption are not the final solutions because the optimal share invested in stock market  $\alpha$  has yet to be determined. To determine the optimal allocation in risky assets, we have to use an intertemporal optimality condition. However, the standard Euler equation is not suitable for determining the optimal asset allocation in the RI economy because consumption adjusts slowly and incompletely, making the relevant intertemporal condition one that equates the marginal utility of consumption today to the covariance between marginal utility and the asset return *arbitrarily far* into the future; that is, it is the “long-run Euler equation” that determines optimal consumption/savings plans. We now turn to deriving this equation.

## 2. MAIN FINDINGS

### 2.1 Long-Run Risk under RI

Bansal and Yaron (2004), Hansen, Heaton, and Li (2006), Parker (2001, 2003), and Parker and Julliard (2005) argue that long-term risk is a better measure of the true risk of the stock market if consumption reacts with delay to changes in wealth; the contemporaneous covariance of consumption and wealth understates the risk of equity.<sup>21</sup> Long-term consumption risk is the appropriate measure for the RI model.

Following Parker (2001, 2003), we define the long-term consumption risk as the covariance of asset returns and consumption growth over the period of the return and many subsequent periods. Because the RI model predicts that consumption reacts to the innovations to asset returns gradually and incompletely, it can rationalize the conclusion in Parker (2001, 2003) that consumption risk is long term instead of contemporaneous. Given the above analytical solution for consumption growth, it is straightforward to calculate the ultimate consumption risk in the RI model. Specifically, when agents behave optimally but only have finite channel capacity, we have the following equality for the risky asset  $e$  and the risk-free asset  $f$ :

$$E_t \left[ (U_{2,t+1} \cdots U_{2,t+S}) (R_f)^S U_{1,t+1+S} (R_{e,t+1} - R_f) \right] = 0, \quad (20)$$

20. When  $\theta$  increases to 1,  $\Delta c_{t+1} = \alpha u_{t+1}$ , that is, consumption growth is i.i.d. and is perfectly correlated with the equity return.

21. Bansal and Yaron (2004) also document that consumption and dividend growth rates contain a long-run component. An adverse change in the long-run component will lower asset prices and thus makes holding equity very risky for investors.

where  $U_{i,t}$  for any  $t$  denotes the derivative of the aggregate function with respect to its  $i$ th argument evaluated at  $(C_t, E_t[U_{t+1}])$ .<sup>22</sup> Note that with time-additive expected utility, the discount factor  $U_{2,t+1+j}$  is constant and equal to  $\beta$ . Equation (20) implies that the expected excess return can be written as

$$E_t [R_{e,t+1} - R_f] = -\frac{\text{con}_t \left[ (U_{2,t+1} \cdots U_{2,t+S}) (R_f)^S U_{1,t+1+S}, R_{e,t+1} - R_f \right]}{E_t \left[ (U_{2,t+1} \cdots U_{2,t+S}) (R_f)^S U_{1,t+1+S} \right]},$$

so that

$$\mu - r_f + \frac{1}{2} \omega^2 = \text{con}_t \left[ \frac{\rho}{\sigma} \left( \sum_{j=0}^S \Delta c_{t+1+j} \right) + (1 - \rho) \left( \sum_{j=0}^S r_{p,t+1+j} \right), u_{t+1} \right], \quad (21)$$

where we have used  $\gamma \simeq 1$ ,  $c_{t+1+S} - c_t = \sum_{j=0}^S \Delta c_{t+1+j}$ , and  $\Delta c_{t+1+j}$  as given by (19). Furthermore, because the horizon  $S$  over which consumption responds completely to income shocks under RI is infinite, the right-hand side of (21) can be written as

$$\begin{aligned} & \lim_{S \rightarrow \infty} \left\{ \sum_{j=0}^S \text{con}_t \left[ \frac{\rho}{\sigma} \Delta c_{t+1+j} + (1 - \rho) \left( \sum_{j=0}^S r_{p,t+1+j} \right), u_{t+1} \right] \right\} \\ &= \alpha \left( \frac{\rho}{\sigma} \varsigma + 1 - \rho \right) \omega^2, \end{aligned} \quad (22)$$

where  $\varsigma$  is the ultimate consumption risk measuring the accumulated effect of the equity shock to consumption under RI:

$$\varsigma \equiv \theta \sum_{i=0}^{\infty} \left( \frac{1 - \theta}{\phi} \right)^i = \frac{\theta}{1 - (1 - \theta)/\phi} > 1, \quad (23)$$

when Assumption 1 holds.

22. This long-term Euler equation can be obtained by combining the standard Euler equation for the excess return

$$E_t [U_{1,t+1} (R_{e,t+1} - R_f)] = 0,$$

with the Euler equation for the riskless asset between  $t + 1$  and  $t + 1 + S$ ,

$$U_{1,t+1} = E_{t+1} \left[ (\beta_{t+1} \cdots \beta_{t+S}) (R_f)^S U_{1,t+1+S} \right],$$

where  $\beta_{t+1+j} = U_{2,t+1+j}$ , for  $j = 0, \dots, S$ . In other words, the equality can be obtained by using  $S + 1$  period consumption growth to price a multiperiod return formed by investing in equity for one period and then transforming to the risk-free asset for the next  $S$  periods. See Appendix 1.3 for detailed derivations.

## 2.2 Optimal Consumption and Asset Allocation

Combining Equations (17) and (21) with (22) gives us optimal consumption and portfolio rules under RI. The following proposition gives a complete characterization of the model's solution for optimal consumption and portfolio choice:

**PROPOSITION 2.** *Suppose that  $\gamma$  is close to 1 and Assumption 1 is satisfied. The optimal share invested in the risky asset is*

$$\alpha^* = \left( \frac{\rho}{\sigma} \varsigma + 1 - \rho \right)^{-1} \frac{\mu - r_f + 0.5\omega^2}{\gamma\omega^2}. \quad (24)$$

The consumption function is

$$c_t^* = \log(1 - \phi) + \hat{a}_t, \quad (25)$$

actual wealth evolves according to

$$a_{t+1} = \frac{1}{\phi} a_t + \left(1 - \frac{1}{\phi}\right) c_t^* + \psi + \left[ \alpha^* (r_{e,t+1} - r_f) + r_f + \frac{1}{2} \alpha^* (1 - \alpha^*) \omega^2 \right], \quad (26)$$

and estimated wealth  $\hat{a}_t$  is characterized by the following Kalman filtering equation

$$\hat{a}_{t+1} = \frac{1}{\phi} \hat{a}_t + \left(1 - \frac{1}{\phi}\right) c_t^* + \psi + \eta_{t+1}, \quad (27)$$

where  $\eta_{t+1}$  is defined in (15),  $\psi = \log(\phi) - (1 - 1/\phi) \log(1 - \phi)$ ,  $\phi = \beta^\sigma (E_t[R_{\eta,t+1}^{1-\gamma}])^{\frac{\sigma-1}{1-\gamma}}$ ,  $R_{\eta,t+1} = \exp(\eta_{t+1})$ ,  $\theta = 1 - \exp(-2\kappa)$  is the optimal weight on a new observation,  $\xi_t$  is an i.i.d. idiosyncratic noise shock with  $\omega_\xi^2 = \text{var}[\xi_{t+1}] = \Sigma/\theta$ , and  $\Sigma = \alpha^{*2} \omega^2 / [\exp(2\kappa) - (1/\phi)^2]$  is the steady-state conditional variance. The change in individual consumption is

$$\Delta c_{t+1}^* = \theta \left\{ \frac{\alpha^* u_{t+1}}{1 - ((1 - \theta)/\phi) \cdot L} + \left[ \xi_{t+1} - \frac{(\theta/\phi) \xi_t}{1 - ((1 - \theta)/\phi) \cdot L} \right] \right\}. \quad (28)$$

PROOF. The proof is straightforward. ■

The proposition clearly shows that optimal consumption and portfolio rules are *interdependent* under RI. Expression (24) shows that although the optimal fraction of savings invested in the risky asset is proportional to the risk premium ( $\mu - r_f + 0.5\omega^2$ ), the reciprocal of the CRRA ( $\gamma$ ), and the variance of the unexpected component in the risky asset ( $\omega^2$ ), as predicted by the standard Merton solution, it also depends on the interaction of RI and RU measured by  $(\rho/\sigma)\varsigma + 1 - \rho$ . We now examine how the interplay of RI and the preference for the timing of uncertainty resolution affects the long-term consumption risk and the optimal share invested in the risky asset. Denote  $(\rho/\sigma)\varsigma + 1 - \rho$  in (24) the long-run consumption risk, and rewrite it as

$$\frac{\rho}{\sigma} \varsigma + 1 - \rho = \gamma + \Gamma, \quad (29)$$

where

$$\Gamma \equiv \frac{\gamma - 1}{1 - \sigma} (\varsigma - 1) \quad (30)$$

measures how the interaction of RU  $(\gamma - 1)/(1 - \sigma)$  and the long-run impact of the equity return on consumption under RI  $(\varsigma)$  affect the risk facing the inattentive investors. Expression (29) clearly shows that risk aversion ( $\gamma$ ) and  $\Gamma$  determine the optimal share invested in the risky asset. Specifically, suppose that investors prefer early resolution of uncertainty:  $\gamma > \sigma$ ; even a small deviation from infinite information-processing capacity due to RI will generate large increases in long-run consumption risk and then reduce the demand for the risky asset.<sup>23</sup> From the expression for  $\Gamma$ , it is clear that it is the difference between the magnitudes of CRRA ( $\gamma$ ) and EIS ( $\sigma$ ) that matters, instead of how far away the two parameters are from 1.

From (29), we can see that two aspects of preferences play a role in determining the portfolio share  $\alpha^*$ : (i) intertemporal substitution, measured by  $\sigma$  and (ii) the preference for the timing of the resolution of uncertainty, measured by  $\rho$ . A household who is highly intolerant of intertemporal variation in consumption will have a high share of risky assets. If  $\sigma < 1$ , a household who prefers earlier resolution of uncertainty (larger  $\rho$ ) will have a lower share of risky assets. Using the identity, this statement is equivalent to noting that larger  $\rho$  means larger  $\gamma$  for fixed  $\sigma$ , so that more risk aversion also implies lower share of risky assets. Thus, as noted in Epstein and Zin (1989), risk aversion and intertemporal substitution, while disentangled from each other, are entwined with the preference for the timing of uncertainty resolution. Here, we choose to focus on the temporal resolution aspect of preferences, rather than risk aversion, for two reasons. First, results in Backus, Routledge, and Zin (2007) show a household with infinite risk aversion and infinite intertemporal elasticity actually holds almost entirely risky assets, and the opposite household (risk neutral with zero intertemporal elasticity) holds almost none (when risks are shared efficiently, at least). The second household prefers early resolution of uncertainty, a preference that cannot be expressed within the expected utility framework, and thus prefers paths of consumption that are smooth, whereas the first household prefers paths of *utility* that are smooth. Holding equities makes consumption risky, but not future utility, and therefore the risk-neutral agent will avoid them. Second, it will turn out that RI will have a strong effect when combined with a preference regarding the timing of the resolution of uncertainty, independent of the values of risk aversion and intertemporal elasticity; specifically, our model will improve upon the standard model by reducing the portfolio share of risky assets if the representative investor has a preference for early resolution.

Figures 1 and 2 illustrate how RI affects the long-run consumption risk  $\Gamma$  when  $\sigma$  equals 0.9999 and 0.99999, respectively, for different values of  $\gamma$ ; following Viceira (2001) and Luo (2010), we set  $\beta = 0.91$ . The figures show that the interaction of RI and RU can significantly increase the long-run consumption risk facing the investors.

23. That is,  $\theta$  is very close to 100%, and therefore  $\varsigma$  is only slightly greater than 1.

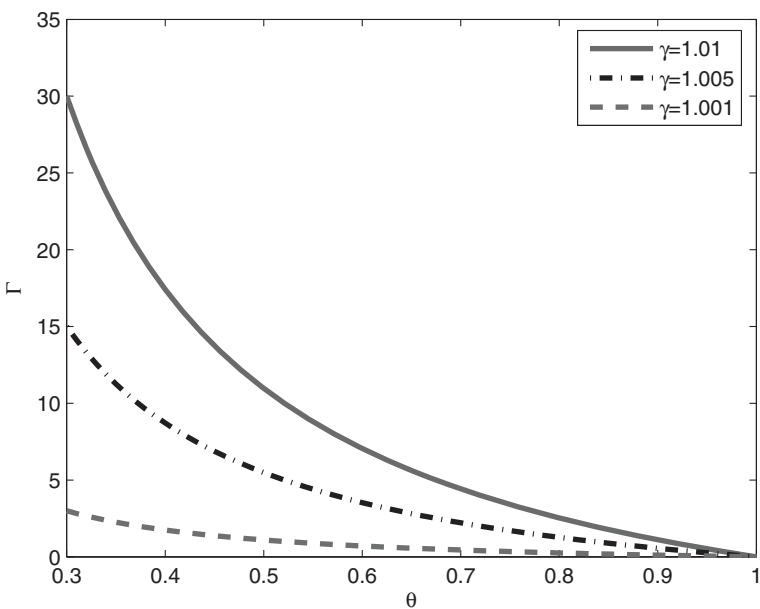


FIG. 1. The Effects of RI and RU on Long-Run Consumption Risk.

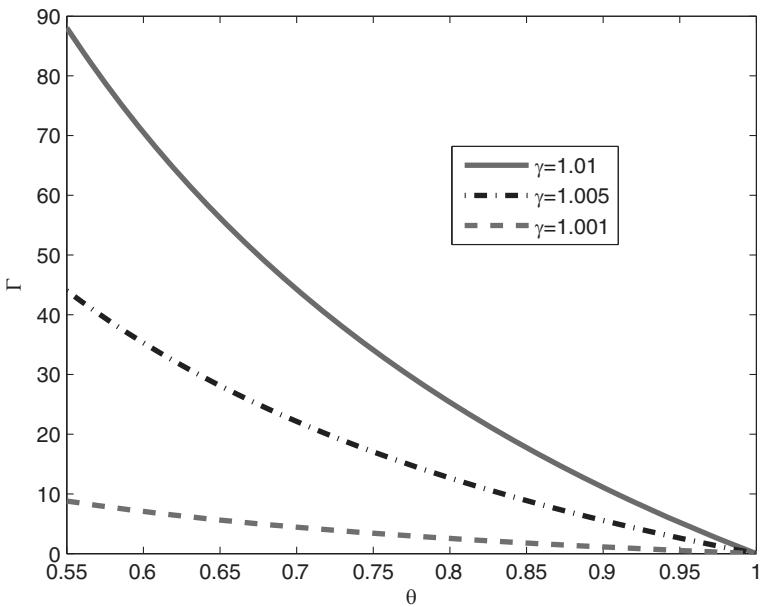


FIG. 2. The Effects of RI and RU on Long-Run Consumption Risk.

In particular, it is obvious that even if  $\theta$  is high (so that investors can process nearly all the information about the equity return), the long-run consumption risk is still nontrivial. For example, when  $\gamma = 1.01$ ,  $\sigma = 0.99999$ , and  $\theta = 0.9$  (i.e., 90% of the uncertainty about the equity return can be removed upon receiving the new signal),  $\Gamma = 11$ ; if  $\theta$  is reduced to 0.8,  $\Gamma = 25$ . That is, a small difference between risk aversion  $\gamma$  and intertemporal substitution  $\sigma$  has a significant impact on optimal portfolio rule.

Note that Equation (24) can be rewritten as

$$\alpha^* = \frac{\mu - r_f + 0.5\omega^2}{\tilde{\gamma}\omega^2}, \quad (31)$$

where  $\tilde{\gamma} = \gamma[(\rho/\sigma)\varsigma + 1 - \rho]$  is the *effective* CRRA.<sup>24</sup> When  $\theta = 1$ ,  $\varsigma = 1$  and optimal portfolio choice (24) under RI reduces to (7) in the standard RU case, which we have discussed previously. Similarly, when  $\rho = 1$  (24) reduces to the optimal solution in the expected utility model discussed in Luo (2010). Later, we will show that  $\tilde{\gamma}$  could be significantly greater than the true CRRA ( $\gamma$ ). In other words, even if the true  $\gamma$  is close to 1 as assumed at the beginning of this section, the effective risk aversion that matters for the optimal asset allocation is  $\gamma + \Gamma$ , which will be greater than 1 if the capacity is low and  $(\gamma - 1)$  is greater than  $(1 - \sigma)$  (indeed, it can be a lot larger even for small deviations from  $\gamma = \sigma = 1$ ). Therefore, the degree of attention ( $\theta$ ) and the discount factor ( $\beta$ ) amount to an increase in the effective CRRA. Holding  $\beta$  constant, the larger the degree of attention, the less the ultimate consumption risk. As a result, investors with low attention will choose to invest less in the risky asset.<sup>25</sup>

As argued in Campbell and Viceira (2002), the effective investment horizon of investors can be measured by the discount factor  $\beta$ . In the standard full-information RE portfolio choice model (such as Merton 1969), the investment horizon measured by  $\beta$  is *irrelevant* for investors who have power utility functions, have only financial wealth, and face constant investment opportunities. In contrast, it is clear from (23) and (24) that the investment horizon measured by  $\beta$  does matter for optimal asset allocations under RU and RI because it affects the valuation of long-term consumption risk. Expression (24) shows that the higher the value of  $\beta$  (the longer the investment horizon), the higher the fraction of financial wealth invested in the risky asset. Figure 3 illustrates how the investment horizon affects the long-run consumption risk  $\Gamma$  when  $\gamma = 1.01$ ,  $\sigma = 0.99999$ ,  $\theta = 0.8$ , and  $\beta = 0.91$ . The figure shows that the investment horizon can significantly affect the long-run consumption risk facing the investors. For example, when  $\beta = 0.91$ ,  $\Gamma = 25$ ; if  $\beta$  is increased to 0.93,  $\Gamma = 19$ .

24. By effective, we mean that if we observed a household's behavior and interpreted it as coming from an individual with unlimited information-processing ability,  $\tilde{\gamma}$  would be our estimate of the risk aversion coefficient.

25. Luo (2010) shows that with heterogeneous channel capacity, the standard RI model would predict that some agents would not participate in the equity market at all. It is clear that the same result would obtain with RU.

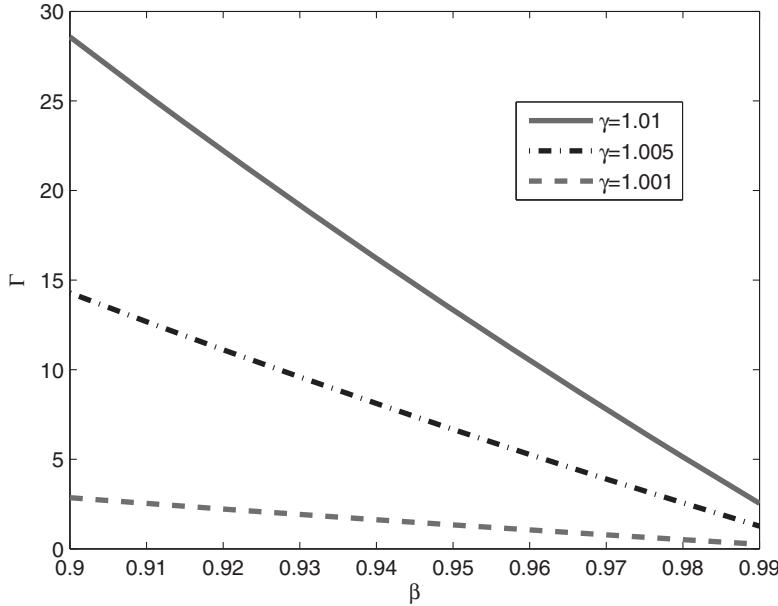


FIG. 3. The Effects of the Investment Horizon on Long-Run Consumption Risk.

That is, a small reduction in the discount factor has a significant effect on long-run consumption risk and the optimal portfolio share when combined with RI.

Given RRA ( $\gamma$ ), IES ( $\sigma$ ), and  $\beta$ , we can calibrate  $\theta$  using the share of wealth held in risky assets. Specifically, we start with the annualized U.S. quarterly data in Campbell (2003) and assume that  $\omega = 0.16$ ,  $\pi = \mu - r_f = 0.06$ ,  $\beta = 0.91$ ,  $\sigma = 0.99999$ , and  $\gamma = 1.001$ . We then calibrate  $\theta$  to match the observed  $\alpha = 0.22$  estimated in section 5.1 of Gabaix and Laibson (1999) to obtain

$$\alpha^* = \left[ \gamma + \frac{\gamma - 1}{1 - \sigma} (\varsigma - 1) \right]^{-1} \frac{\pi + 0.5\omega^2}{\gamma\omega^2} = 0.22, \quad (32)$$

which means that  $\theta = 0.48$ .<sup>26</sup> That is, approximately 48% of the uncertainty is removed upon receiving a new signal about the equity return. Note that if  $\gamma = 1$ , the RE version of the model generates a highly unrealistic share invested in the stock market:  $\alpha = (\pi + 0.5\omega^2)/\omega^2 = 2.84$ . To match the observed fraction in the U.S. economy (0.22),  $\gamma$  must be set to 13.

26. Gabaix and Laibson (2001) assume that all capital is stock market capital and that capital income accounts for 1/3 of total income.

### 2.3 Implications for Consumption Dynamics

Equation (28) shows that individual consumption under RI reacts not only to fundamental shocks ( $u_{t+1}$ ) but also to the endogenous noise ( $\xi_{t+1}$ ) induced by finite capacity. The endogenous noise can be regarded as a type of “consumption shock” or “demand shock.” In the intertemporal consumption literature, some transitory consumption shocks are often used to make the model fit the data better. Under RI, the idiosyncratic noise due to RI provides a theory for these transitory consumption movements. Furthermore, (28) also makes it clear that consumption growth adjusts slowly and incompletely to the innovations to asset returns but reacts quickly to the idiosyncratic noise.

Using (28), we can obtain the stochastic properties of the joint dynamics of consumption and the equity return. The following proposition summarizes the major stochastic properties of consumption and the equity return.

**PROPOSITION 3.** *Given finite capacity  $\kappa$  (i.e.,  $\theta$ ) and optimal portfolio choice  $\alpha^*$ , the volatility of consumption growth is*

$$\text{var} [\Delta c_t^*] = \frac{\theta \alpha^{*2}}{1 - (1 - \theta)/\phi^2} \omega^2, \quad (33)$$

the relative volatility of consumption growth to the equity return is

$$\text{rv} = \frac{\text{sd} [\Delta c_t^*]}{\text{sd} [u_t]} = \sqrt{\frac{\theta}{1 - (1 - \theta)/\phi^2}} \alpha^*, \quad (34)$$

the first-order autocorrelation of consumption growth is

$$\rho_{\Delta c} = \text{corr} [\Delta c_t^*, \Delta c_{t+1}^*] = 0, \quad (35)$$

and the contemporaneous correlation between consumption growth and the equity return is

$$\text{corr} [\Delta c_{t+1}^*, u_{t+1}] = \sqrt{\theta (1 - (1 - \theta)/\phi^2)}. \quad (36)$$

PROOF. See online appendix.<sup>27</sup> ■

Expression (34) shows that RI affects the relative volatility of consumption growth to the equity return via two channels: (i)  $\theta/[1 - (1 - \theta)/\phi^2]$  and (ii)  $\alpha^*$ . Holding the optimal share invested in the risky asset  $\alpha^*$  fixed, RI increases the relative volatility of consumption growth via the first channel because  $\partial(\theta \alpha^{*2}/[1 - (1 - \theta)/\phi^2])/\partial\theta < 0$ . Equation (28) indicates that RI has two effects on the volatility of  $\Delta c$ : the gradual response to a fundamental shock and the presence of the RI-induced noise shocks.

27. The online appendix for this paper is available from <http://yluo.weebly.com/uploads/3/2/1/4/3214259/jmcb2015onlineappendix.pdf>

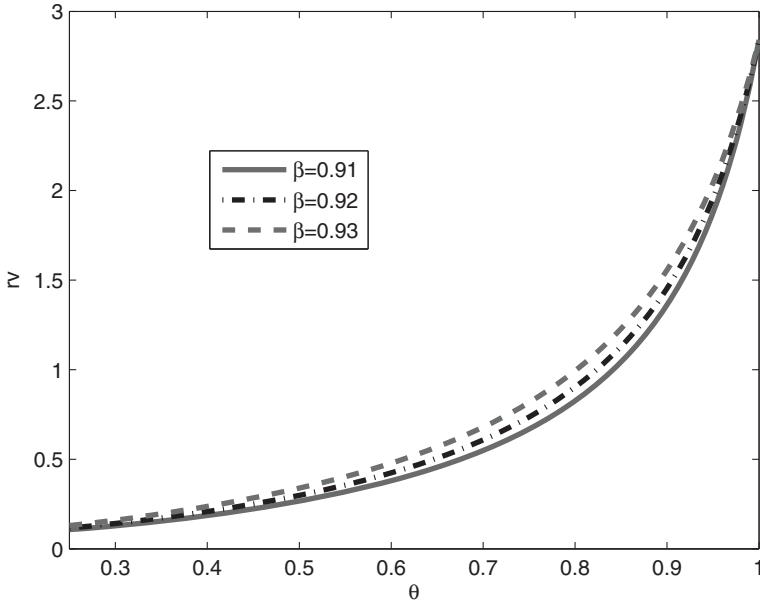


FIG. 4. The Effects of RI on Consumption Volatility.

The former effect reduces consumption volatility, whereas the latter one increases it; the net effect is that RI increases the volatility of consumption growth holding  $\alpha^*$  fixed. Furthermore, as shown above, RI reduces  $\alpha^*$  as it increases the long-run consumption risk via the interaction with the RU preference, which tends to reduce the volatility of consumption growth as households switch to safer portfolios. Figure 4 illustrates how RI affects the relative volatility of consumption to the equity return for different values of  $\beta$  in the RU model; for the parameters selected, RI reduces the volatility of consumption growth in the presence of optimal portfolio choice.

Expression (35) means that there is no persistence in consumption growth under RI. The intuition of this result is as follows. Both  $MA(\infty)$  terms in (28) affect consumption persistence under RI. Specifically, in the absence of the endogenous noises, the gradual response to the shock to the equity return due to RI leads to positive persistence in consumption growth:  $\rho_{\Delta c} = \theta(1 - \theta)/\phi > 0$ . (See online appendix.) The presence of the noise generates negative persistence in consumption growth, exactly offsetting the positive effect of the gradual response to the fundamental shock under RI.

Expression (36) shows that RI reduces the contemporaneous correlation between consumption growth and the equity return because  $\partial \text{corr}(\Delta c_{t+1}^*, u_{t+1})/\partial \theta > 0$ . Figure 5 illustrates the effects of RI on the correlation when  $\beta = 0.91$ . It clearly shows

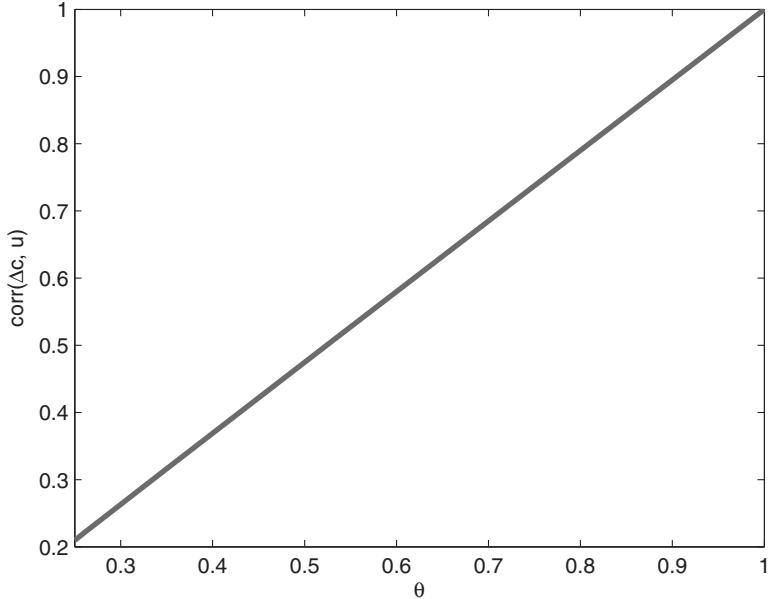


FIG. 5. The Effects of RI on Consumption Correlation.

that the correlation between consumption growth and the equity return is increasing with the degree of attention ( $\theta$ ).

If the model economy consists of a continuum of consumers with identical capacity, we need to consider how to aggregate the decision rules across all consumers facing the idiosyncratic noise shock. Sun (2006) presents an exact law of large numbers (LLN) for this type of economic models and then characterizes the cancellation of individual risk via aggregation. In this model, we adopt this LLN and assume that the initial cross-sectional distribution of the noise shock is its stationary distribution. Provided that we construct the space of agents and the probability space appropriately, all idiosyncratic noises cancel out and aggregate noise is zero. After aggregating over all consumers, we obtain the expression for the change in aggregate consumption:

$$\Delta c_{t+1}^* = \frac{\theta \alpha^* u_{t+1}}{1 - ((1 - \theta)/\phi) \cdot L}, \quad (37)$$

where the i.i.d. idiosyncratic noises in the expressions for individual consumption dynamics have been canceled out. The following proposition summarizes the results of the joint dynamics of aggregate consumption and the equity return.

**PROPOSITION 4.** *Given finite capacity  $\kappa$  (i.e.,  $\theta$ ) and optimal portfolio choice  $\alpha^*$ , the relative volatility of consumption growth to the equity return is*

$$\text{rv} = \frac{\text{sd}[\Delta c_t^*]}{\text{sd}[u_t]} = \sqrt{\frac{\theta^2}{1 - (1 - \theta)/\phi^2}} \alpha^*, \quad (38)$$

*the first-order autocorrelation of consumption growth is*

$$\rho_{\Delta c} = \text{corr}[\Delta c_t^*, \Delta c_{t+1}^*] = \frac{\theta(1 - \theta)}{\phi}, \quad (39)$$

*and the contemporaneous correlation between consumption growth and the equity return is*

$$\text{corr}[\Delta c_{t+1}^*, u_{t+1}] = \sqrt{1 - (1 - \theta)/\phi^2}, \quad (40)$$

*where  $\phi = \beta$  when  $\sigma$  is close to 1.*

PROOF. See online appendix. ■

## 2.4 Channel Capacity

Our required channel capacity ( $\theta = 0.48$  or  $\kappa = 0.33$  nats) may seem low; 1 nat of information transmitted is definitely well below the total information-processing ability of human beings.<sup>28</sup> However, it is not implausible for little capacity to be allocated to the portfolio decision because individuals also face many other competing demands on their attention. For an extreme case, a young worker who accumulates balances in his 401(k) retirement savings account might pay no attention to the behavior of the stock market until he retires. In addition, in our model for simplicity, we only consider an aggregate shock from the equity return, while in reality, consumers/investors face substantial idiosyncratic shocks that we do not model in this paper; Sims (2010) contains a more extensive discussion of low information-processing limits in the context of economic models.

As we noted in the Introduction, there are some existing estimation and calibration results in the literature, albeit of an indirect nature. For example, Adam (2005) found  $\theta = 0.4$  based on the response of aggregate output to monetary policy shocks; Luo (2008) found that if  $\theta = 0.5$ , the otherwise standard permanent income model can generate realistic relative volatility of consumption to labor income; Luo and Young (2009) found that setting  $\theta = 0.57$  allows an otherwise standard real business cycles model to match the postwar U.S. consumption/output volatility. Finally, Melosi (2009) uses a model of firm RI (similar to Maćkowiak and Wiederholt 2009) and estimates it to match the dynamics of output and inflation, obtaining  $\theta = 0.66$ . Thus, it seems that somewhere between 0.4 and 0.7 is a reasonable range, and our number lies right in the middle of this interval, while the one required in Luo (2010) is much lower.

28. See Landauer (1986) for an estimate.

## 2.5 Implications for Equilibrium Asset Pricing

According to the standard consumption-based capital asset pricing theory (CCAPM), the expected excess return on any risky portfolio over the risk-free interest rate is determined by the covariance of the excess return with contemporaneous consumption growth and the CRRA. Given the observed low contemporaneous covariance between equity returns and contemporaneous consumption growth, the standard CCAPM theory predicts that equities are not very risky. Consequently, to generate the observed high equity premium (measured by the difference between the average real stock return and the average short-term real interest rate), the CRRA must be very high. Given that  $\omega = 0.16$ ,  $\pi = \mu - r_f = 0.06$ , and  $\text{con}[\Delta c_{t+1}^*, u_{t+1}] = 6 \times 10^{-4}$  (annualized U.S. quarterly data from Campbell 2003), to generate the observed equity premium, we need a risk aversion coefficient of  $\gamma = 100$ .

To explore the equilibrium asset pricing implications of the optimal consumption and portfolio rules under RU and RI derived in Section 2.2, we now consider a simple exchange economy in the vein of Lucas (1978). Specifically, we assume that the representative agent receives an endowment, which equals consumption in equilibrium and can trade two assets in the economy: a risky asset entitling the consumer to the dividend (i.e., endowment) and a riskless asset (an inside bond, i.e., in equilibrium its net supply is 0). The returns to the assets then adjust to support a no-trade equilibrium. Using the optimal consumption and portfolio rules under RU and RI derived in the above partial equilibrium model, we can then explore how the interaction of RU and RI affects the equilibrium equity premium. The following is the definition of the RU-RI equilibrium in our model economy:

**DEFINITION 5.** *The RU-RI equilibrium consists of (i) the portfolio rule  $\alpha^*$ , (24), (ii) the consumption rule  $c^*$ , (25), and (iii) the perceived state ( $\hat{s}$ ) evolution equation, (27), such that simultaneously,*

- (i) *markets clear in each period:  $c^*$  is just the endowment and  $\alpha^* = 1$ ;*
- (ii) *the consumer solves for  $\alpha^*$  and  $c^*$  using the RU-RI model specified in Sections 1.2–2.2.*

The following proposition summarizes the implications of the interaction of RU and RI for the equity premium in the general equilibrium defined above:

**PROPOSITION 6.** *Given finite capacity  $\kappa$  (i.e.,  $\theta$ ), the equilibrium equity premium,  $\pi$ , is given by:*

$$\pi = (\gamma + \Gamma) \omega^2, \quad (41)$$

where  $\Gamma = [(\gamma - 1)/(1 - \sigma)](\varsigma - 1)$  and  $\varsigma = \theta/[1 - (1 - \theta)/\phi] > 1$ .

**PROOF.** Equation (41) can be obtained by setting  $\alpha^*$  in (24) to be 1. ■

It is clear from (41) that the interaction between RI and RU induces a higher equity premium because risk aversion and intertemporal substitution are disentangled and the accumulated effect of the innovation to the equity on consumption  $\varsigma = \theta/\phi$

TABLE 1

EFFECTS OF RU AND RI ON CONSUMPTION AND THE EQUITY PREMIUM

	U.S. data	Full information	$\theta = 25\%$	$\theta = 35\%$	$\theta = 45\%$	$\theta = 55\%$
$\pi (\sigma = 0.998)$	0.06	0.023	0.073	0.050	0.039	0.034
$\pi (\sigma = 0.9973)$	0.06	0.023	0.060	0.043	0.035	0.031
$\pi (\sigma = 0.996)$	0.06	0.023	0.048	0.036	0.031	0.028
rv	0.07	1	0.441	0.500	0.565	0.633
$\rho_{\Delta c}$	0.22	0	0.226	0.275	0.298	0.298
$\text{corr}(\Delta c_{t+1}^*, u_{t+1})$	0.21	1	0.308	0.464	0.580	0.676

NOTES: The U.S. data are based on Campbell (2003) and we set  $\gamma = 1.01$  and  $\beta = 0.91$ .

$[1 - (1 - \theta)/\phi] > 1$ . The intuition behind this result is that for inattentive investors, the uncertainty about consumption changes induced by changes in the equity return takes many periods to be resolved and this postponement is distasteful for these investors who prefer early uncertainty resolution; consequently, they require higher risk compensation in equilibrium.

Figures 1 and 2 can be used again to illustrate how RI affects the equity premium in equilibrium via increasing the long-run consumption risk  $\Gamma$  when  $\beta = 0.91$  and both  $\gamma$  and  $\sigma$  are close to 1. Using the same example in the portfolio choice problem, when  $\gamma = 1.01$  and  $\theta = 0.9$ ,  $\Gamma = 11$ , which means that the required equity premium would be increased by 11 times; when  $\theta$  is smaller,  $\Gamma$  is larger, as we showed earlier, so the required return must be larger. That is, a small difference between risk aversion  $\gamma$  and intertemporal substitution  $\sigma$  can have a significant impact on the equilibrium equity return if agents have limited attention.

Table 1 reports how RI affects the joint behavior of aggregate consumption and the equity return and the equilibrium equity premium in the RU model. There are two interesting observations in the table. First, inattention governed by low  $\theta$  can significantly increase the equilibrium equity return by interacting with the preference for early uncertainty resolution. For example, when  $\theta = 0.25$ ,  $\gamma = 1.01$ , and  $\sigma = 0.9973$ , the equilibrium equity premium is about 6%, which is just the same as its empirical counterpart. Second, lowering attention can simultaneously improve the joint dynamics of aggregate consumption and the equity premium. Specifically, after matching the equity premium perfectly, we can see that RI can (i) reduce the relative volatility of consumption growth to the equity return (e.g., when  $\theta$  reduces from 0.55 to 0.25, rv can be reduced from 0.633 to 0.441), (ii) generate positive autocorrelation of consumption growth and make the model match the empirical evidence in this aspect perfectly when  $\theta = 0.25$ , and (iii) reduce the contemporaneous correlation between consumption growth and the equity return (e.g., if  $\theta$  is reduced from 0.55 to 0.25, rv falls from 0.676 to 0.308, which matches the empirical counterpart, 0.21, much better). From the table, it is clear that it is difficult to generate the observed relative volatility of consumption growth in the equilibrium model with  $\beta = 0.91$ . The reason is that we are considering a pure exchange economy where the share invested in the risky asset is 100% in equilibrium, which significantly increases

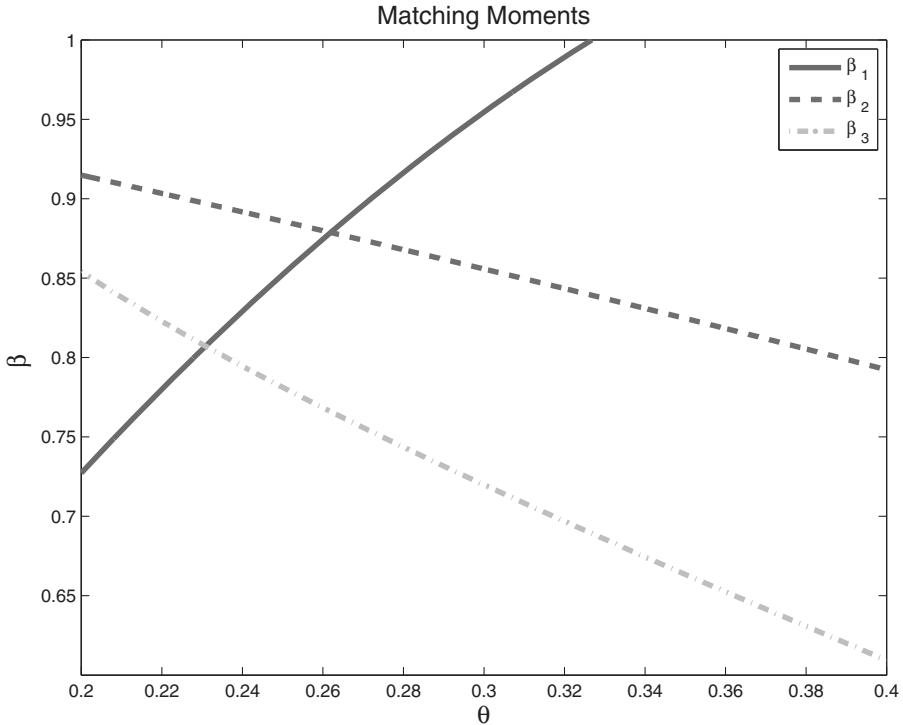


FIG. 6. Matching Consumption/Asset Moments.

consumption volatility. In addition, from (38)–(40) and (41), we can see that the value of EIS only affects the equilibrium equity premium and does not affect the consumption dynamics because  $\phi \cong \beta$ .

We did not conduct a formal Generalized Method of Moments (GMM)-type exercise to fit the four moments in Table 1. However, once we abandon the requirement that  $\beta = 0.91$ , we can reconcile the three moments (38)–(40). We solve each expression for  $\beta(\theta)$ :

$$\begin{aligned}\beta_1 &= \frac{\theta(1-\theta)}{\rho_{\Delta c}}, \\ \beta_2 &= \sqrt{\frac{1-\theta}{1 - \text{corr}[\Delta c_{t+1}^*, u_{t+1}]^2}}, \\ \beta_3 &= \sqrt{\frac{1-\theta}{1 - (\text{rv}/\theta)^2}}.\end{aligned}$$

Figure 6 shows that we cannot choose  $(\beta, \theta)$  to match all three moments exactly, but we can get close; then there exists a value of  $\sigma$  that would match the equity premium

for any given  $\gamma$ . The value of  $\beta$  is a little below what we used in Table 1, and the value of  $\theta$  a little lower (but still substantially above the value from Luo 2010).

## 2.6 Comparison of Portfolio Choice and Asset Pricing Implications under Alternative Hypotheses

*Model uncertainty and robustness.* Robust control and filtering emerged in the engineering literature in the 1970s and was introduced into economics and further developed by Hansen, Sargent, and others. A simple version of robust optimal control considers such a question: How to make decisions when the agent does not know the probability model that generates the data? The agent with the preference for robustness considers a range of models and makes decisions that maximize utility given the worst possible model. The work of Uppal and Wang (2003) and Maenhou (2004) explores how model uncertainty due to a preference for robustness affects optimal portfolio choice. In particular, Maenhou (2004) shows that robustness leads to environment-specific effective risk aversion and thus significantly reduces the demand for the risky asset. In addition, after calibrating the robustness parameter, he finds that robustness increases the equilibrium equity premium.<sup>29</sup> In his model, the optimal portfolio rule is

$$\alpha = \frac{\pi}{(\gamma + \vartheta) \omega^2},$$

where  $\vartheta$  measures the degree of robustness and  $\gamma + \vartheta$  is the effective CRRA. Compared with the portfolio rule derived in our RU-RI model, it is clear that though both of these two specifications, model uncertainty due to robustness and state uncertainty due to inattention, can reduce the optimal share invested in the risky asset, the mechanisms to generate low allocation in the risky asset are distinct: In the former, the aversion to model uncertainty increases the effective degree of risk aversion, and thus reduces the optimal allocation in the equity, whereas in the latter, the interaction of RI and a preference for early resolution of uncertainty strengthens long-run consumption risk and thus reduce the optimal share in the equity.<sup>30</sup>

*Infrequent adjustment.* Another closely related hypothesis about informational frictions is the infrequent adjustment specification (see Lynch 1996, Gabaix and Laibson 1999, Abel, Eberly, and Panageas 2007, and Necho 2014 for discussions of the implications of infrequent adjustment in consumption on portfolio choice or/and asset pricing). Among these models, Gabaix and Laibson (1999)'s 6D bias model is most related to our work. The key difference between Gabaix and Laibson's infrequent adjustment model and our RI model is that in their model, investors adjust their

29. Cecchetti, Lam, and Mark (2000) and Abel (2002) examine how exogenously distorting subjective beliefs can help resolve the equity premium puzzle and the risk-free rate puzzle; robust control distorts beliefs in exactly the right manner.

30. Kasa (2006) derives a formal equivalence between robust control and RI in the filtering problem.

consumption plans infrequently but completely once they choose to adjust, whereas investors with finite capacity adjust their plans frequently but incompletely in every period. In addition, in the 6D model, the optimal fraction of savings invested in the risky asset is assumed to be fixed at the standard Merton solution

$$\alpha = \frac{\pi}{\gamma \omega^2},$$

where  $\pi$  is the equity premium,  $\gamma$  is CRRA, and  $\omega^2$  is the variance of the equity return, whereas optimal portfolio choice under RI reflects the larger long-term consumption risk caused by slow adjustments in consumption, and thus the share invested in the risky asset is less than the standard Merton solution. Abel, Eberly, and Panageas (2007) derived a unique solution for the optimal interval of time between consecutive observations of the value of the portfolio with observation and transaction costs and showed that even a small observation cost can lead to a substantial (eight-month) decision interval. They assume that the investment portfolio of riskless bonds and risky stocks is managed by a portfolio manager who continuously rebalances the portfolio, which is similar to the assumption used in Gabaix and Laibson (1999). In other words, they do not examine how infrequent adjustments affect the optimal asset allocation via the channel of the long-run consumption risk. In all of these infrequent adjustments, aggregate consumption can have low contemporaneous correlation with the equity return because individual investors adjust their consumption plans infrequently and only a fraction of the agents adjust their consumption in each period.

### 3. TWO EXTENSIONS

#### 3.1 Correlated Shock and Noise

In the above analysis, we assumed that the exogenous shock to the equity return ( $u_{t+1}$ ) and RI-induced noise ( $\xi_{t+1}$ ) are uncorrelated. We now discuss how correlated shocks and noises affect the implications of RI for long-run consumption risk and optimal asset allocation. In reality, we do observe correlated shocks and noises. For example, if the system is an airplane and winds are buffeting the plane, the random gusts of wind affect the process (the airplane dynamics) and the measurement (the sensed wind speed) if people use an anemometer to measure wind speed as an input to the Kalman filter. In our model economy, it seems reasonable to assume that given the same level of capacity, when the economy moves into a recession (or financial crisis), the innovation to the equity return and the noise due to finite capacity (the measurement or the perceived/sensed signal) will also be affected by the recession. In the RI problem, the correlation generalizes the assumption in Sims (2003) on the uncorrelated RI-induced noise.

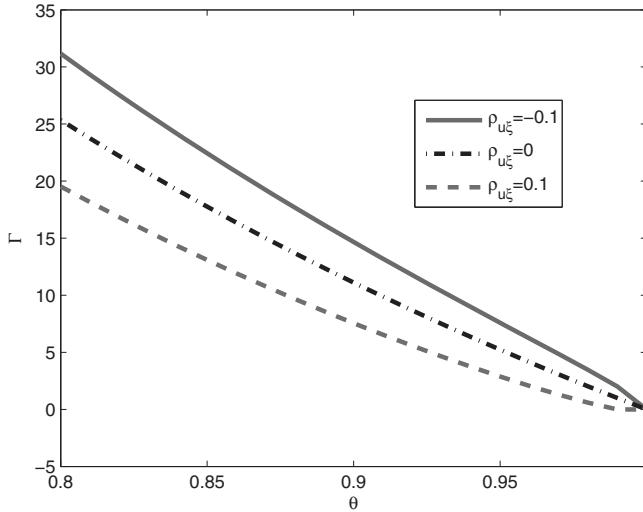


FIG. 7. The Effects of RI and RU on Long-Run Consumption Risk when  $\rho_{u\xi} \neq 0$ .

Specifically, we consider the case in which the process shock ( $\varepsilon$ ) and the noise ( $\xi$ ) are correlated as follows:

$$\text{corr}(u_{t+1}, \xi_{t+1}) = \rho_{u\xi}, \quad (42)$$

$$\text{con}(u_{t+1}, \xi_{t+1}) = \rho_{u\xi}\omega\omega_\xi, \quad (43)$$

where  $\rho \in [-1, 1]$  is the correlation coefficient between  $u_{t+1}$  and  $\xi_{t+1}$ , and  $\omega_\xi^2 = \text{var}[\xi_{t+1}]$ . Substituting (42) and (43) into the pricing equation (21), we obtain

$$\pi = \lim_{S \rightarrow \infty} \left\{ \sum_{j=0}^S \text{con}_t \left[ \frac{\rho}{\sigma} \Delta c_{t+1+j} + (1-\rho) \left( \sum_{j=0}^S r_{p,t+1+j} \right), u_{t+1} \right] \right\} = (\gamma + \Gamma) \alpha \omega^2,$$

where

$$\Gamma = \frac{\gamma - 1}{1 - \sigma} (\varsigma - 1) + \frac{\rho \rho_{u\xi}}{\sigma} \left( 1 - \frac{1}{\phi} \varsigma \right) \sqrt{\frac{\theta}{1/(1-\theta) - (1/\phi)^2}} \quad (44)$$

measures the long-run consumption risk in the presence of the correlation between the equity return and the noise. (See online appendix.) Figure 7 illustrates how RI affects the long-run consumption risk  $\Gamma$  for different values of the correlation when  $\beta = 0.91$ ,  $\sigma = 0.99999$ , and  $\gamma = 1.01$ . The figure clearly shows that the positive correlation will reduce the long-run consumption risk and thus increase the optimal

share invested in the risky asset. For example, when  $\theta = 0.8$  and  $\rho_{u\xi} = 0.1$ ,  $\Gamma = 20$ ; if  $\rho_{u\xi}$  reduces to  $-0.1$ ,  $\Gamma = 31$ .

What is a reasonable sign for this correlation? If we assume that capacity is fixed when the state of the economy changes, it seems more reasonable that  $\rho_{u\xi}$  is positive because it would be more difficult to observe a more volatile economy given fixed capacity. However, if we relax the assumption that  $\kappa$  is fixed, some capacity from other sources will be reallocated to monitor the state of the economy to increase the economic efficiency because an increase in the underlying uncertainty leads to larger marginal welfare losses due to RI. In this case,  $\rho_{u\xi}$  could be negative as the Kalman gain  $\theta$  will increase with capacity  $\kappa$ .

### 3.2 Nontradable Labor Income

It is known that some of the anomalous predictions of the portfolio model can be reduced, though not eliminated, by the introduction of nontradable labor income. Following Viceira (2001), Campbell and Viceira (2002), and Luo (2015), we assume that labor income  $Y_t$  is uninsurable and nontradable in the sense that investors cannot write claims against future labor income; thus, labor income can be viewed as a dividend on the implicit holdings of human wealth. We will only sketch the results here; formal derivations are a straightforward extension of our existing results and are omitted.

We assume that the process for labor income is

$$Y_{t+1} = Y_t \exp(\nu_{t+1} + g), \quad (45)$$

where  $g$  is a deterministic growth rate and  $\nu_{t+1}$  is an i.i.d. normal random variable with mean zero and variance  $\omega_\nu^2$ . Log labor income therefore follows a random walk with drift; to keep the exposition simpler, we abstract from any transitory income shocks. In order to permit the risky asset to play a hedging role against labor income risk, we suppose that the two shocks are potentially correlated contemporaneously:

$$\text{cov}_t(u_{t+1}, \nu_{t+1}) = \omega_{uv}.$$

If  $\omega_{uv} = 0$ , then labor income can be viewed as purely idiosyncratic. The flow budget constraint then becomes

$$A_{t+1} = R_{p,t+1}(A_t + Y_t - C_t). \quad (46)$$

Log linearizing (46) around the long-run means of the log consumption-income ratio and the log wealth-income ratio,  $c - y = E[c_t - y_t]$  and  $a - y = E[a_t - y_t]$ , and defining a new state variable,  $s_t = a_t + \lambda y_t$ , where  $\lambda = (1 - \rho_a + \rho_c)/(\rho_a - 1)$ , we adopt the same solution method in our benchmark model to solve this model with uninsurable labor income. The following proposition summarizes the results on the optimal consumption and portfolio rules under RI:

**PROPOSITION 7.** Suppose that  $\gamma$  is close to 1 and Assumption 2 is satisfied (see below). The optimal share invested in the risky asset is

$$\alpha^* = \frac{1}{\tilde{\varsigma}} \left[ \frac{1}{b_1} \left( \frac{\mu - r_f + 0.5\omega^2}{\omega^2} \right) + \left( 1 - \frac{1}{b_1} \right) \frac{\tilde{\varsigma}\omega_{uv}}{\omega^2} \right], \quad (47)$$

where  $\tilde{\varsigma} = (\rho/\sigma)\varsigma + 1 - \rho > 1$ ,  $b_1 = (\rho_a - 1)/\rho_c \in (0, 1]$ ,  $\rho_a = \exp(a - y)/(1 + \exp(a - y) - \exp(c - y)) > 0$ , and  $\rho_c = \exp(c - y)/(1 + \exp(a - y) - \exp(c - y)) > 0$ ; the consumption function is

$$c_t^* = b_0 + b_1 \hat{s}_t, \quad (48)$$

where  $b_0 = -[(1/\gamma - b_1)E[r_{p,t+1}] + \frac{1}{\gamma} \log \beta + \frac{1}{2\gamma} \Omega - \rho - (1 - b_1)g]/(\rho_a - 1)$ ,  $\Omega$  is an irrelevant constant term; the true state evolution equation is

$$s_{t+1} = \rho_0 + \rho_a s_t - \rho_c c_t - g + \varepsilon_{t+1} + \frac{1 - \rho_a + \rho_c}{\rho_a - 1} v_{t+1} + r_{p,t+1}, \quad (49)$$

where  $\rho_0 = -(1 - \rho_a + \rho_c) \log(1 - \rho_a + \rho_c) - \rho_a \log(\rho_a) + \rho_c \log(\rho_c)$ ; and the estimated state  $\hat{s}_t$  is characterized by the following Kalman filtering equation

$$\hat{s}_{t+1} = (1 - \theta) \hat{s}_t + \theta (s_{t+1} + \xi_{t+1}) + \Upsilon, \quad (50)$$

where  $\psi = \log(\phi) - (1 - 1/\phi) \log(1 - \phi)$ ,  $\theta = 1 - 1/\exp(2\kappa)$  is the optimal weight on a new observation,  $\xi_t$  is an i.i.d. idiosyncratic noise shock with  $\omega_\xi^2 = \text{var}[\xi_{t+1}] = \Sigma/\theta$ ,  $\Sigma = \alpha^{*2} \omega^2 / [\exp(2\kappa) - (1/\phi)^2]$  is the steady-state conditional variance, and  $\Upsilon$  is an irrelevant constant term. ■

PROOF. See online appendix.

Note that to obtain these results, we require the following assumption.

ASSUMPTION 2.

$$1 - (1 - \theta) \rho_a > 0. \quad (51)$$

Comparing with the assumption used in the benchmark model, here  $\rho_a$  has replaced  $\beta^{-1}$ , but otherwise equation (51) is the same as equation (18). When  $\rho = 1$  (or  $\gamma = 1/\sigma$ ), the RU solution reduces to the expected utility solution:

$$\alpha^* = \frac{1}{\varsigma} \left[ \frac{1}{b_1} \left( \frac{\mu - r_f + 0.5\omega^2}{\omega^2} \right) + \left( 1 - \frac{1}{b_1} \right) \frac{\varsigma\omega_{uv}}{\omega^2} \right], \quad (52)$$

where  $\varsigma = \theta/[1 - (1 - \theta)\rho_a] > 1$ .

$\tilde{\varsigma} > 1$  measures the long-run (accumulated) impacts of financial shocks on consumption. It is clear that our key result—that the presence of RI combined with a preference for early resolution of uncertainty will dramatically reduce the share of

risky assets and increase the required equity premium—survives the introduction of labor income risk. Expression (47) contains two components. The first part is the so-called speculative asset demand, driven by the gap between the return to equity and the risk-free rate. Note that without labor income risk, the optimal asset allocation is solely determined by the speculative demand; that is, the allocation is proportional to the expected excess return of the risky asset and is inversely related to the variance of the equity return and to the elasticity of consumption to perceived wealth,  $b_1$ . The second part is the hedging demand, governed by the correlation between returns and labor income. Given that  $\rho_a > 1$  and  $\theta \in (0, 1)$ , RI affects the optimal allocation in the risky asset via the following two channels:

- (i) Reducing the speculative demand and the income-hedging demand by the long-run consumption risk parameter  $\tilde{\zeta}$ .
- (ii) In addition, as shown in the second term in the bracket of (47), RI increases the income hedging demand by  $\tilde{\zeta}$  because  $u_t$  and  $v_t$  are correlated and consumption reacts to the shock to total wealth  $\zeta_t = \alpha u_t + \lambda v_t$  gradually and indefinitely.

To make these points clear, we rewrite (47) as

$$\alpha^* = \frac{1}{\tilde{\zeta} b_1} \left( \frac{\mu - r_f + 0.5\omega^2}{\omega^2} \right) + \left( 1 - \frac{1}{b_1} \right) \frac{\omega_{uv}}{\omega^2}. \quad (53)$$

This expression clearly shows that RI increases the *relative* importance of the income-hedging demand to the speculative demand via the long-run consumption risk  $\tilde{\zeta}$ ; under RI, the ratio of the income hedging demand to the speculative demand increases by  $\tilde{\zeta}$ . As inattention increases ( $\theta$  declines), the hedging aspect of the demand for risky assets increases in importance, because  $\partial \tilde{\zeta} / \partial \theta < 0$ . To see where this positive relationship derives from, results from Luo (2008) and Luo and Young (2010b) imply that the welfare cost of labor income uncertainty is increasing in the degree of inattention (as  $\theta$  falls, the cost rises). If equity returns are positively correlated with labor income, the agent will decrease demand for the asset as an insurance vehicle; similarly, a negative correlation will increase hedging demand. The data suggest that this correlation is negative but so small as to be quantitatively unimportant.<sup>31</sup> In addition, the second term in (53) also shows that RI has no effect on the absolute value of the income hedging demand. The reason is simple: under RI, the innovation to the equity return affects not only the amount of long-run consumption risk measured by  $1/\zeta$  but also the long-run correlation between the shocks to the equity return and labor income measured by  $\zeta \omega_{uv}$  as both shocks affect consumption growth; consequently, RI does not change the hedging demand of labor income. It is clear from expression (52) that  $\zeta$  in the terms  $1/\zeta$  and  $\zeta \omega_{uv}$  cancels out.

As in Section 2.3, we can examine the asset pricing implications of the twin assumptions of RU and RI in the presence of nontradable labor income. Given that

31. For example, Heaton and Lucas (2000) find that individual labor income is weakly correlated with equity returns, with support for positive and negative correlations. Aggregate wages have a correlation of  $-0.07$  with equity returns.

every investor has the same degree of RI, the following pricing equation linking consumption growth and the equity premium holds when  $\gamma \simeq 1$ :

$$\pi = \alpha^* \tilde{\zeta} b_1 \omega^2 - \tilde{\zeta} (b_1 - 1) \omega_{uv} - 0.5 \omega^2. \quad (54)$$

Under the same assumptions made above (zero net supply of bonds so that  $\alpha^* = 1$ ), (54) becomes

$$\pi = \tilde{\zeta} [b_1 \omega^2 + (1 - b_1) \omega_{uv}] - 0.5 \omega^2, \quad (55)$$

which clearly shows that the positive correlation between the equity return and labor income,  $\omega_{uv} > 0$ , increases the equilibrium equity premium. Specifically, the magnitude of the hedging demand,  $(1 - b_1)\omega_{uv}$ , is increased by  $\zeta$  in the presence of information-processing constraints. In sum, the interaction between RI and positive correlations between the equity return and labor income will increase the equity premium in equilibrium by

$$\varpi = \tilde{\zeta} \left[ 1 + \left( \frac{1}{b_1} - 1 \right) \frac{\rho_{uv} \omega_v}{\omega} \right]. \quad (56)$$

Note that in the case without RI and  $\rho_{uv} = 0$ ,  $\pi + 0.5\omega^2 = b_1\omega^2$ .

Following the same procedure adopted in the benchmark model, we can obtain the expression for aggregate consumption by aggregating over all consumers:

$$\Delta c_{t+1}^* = \theta b_1 \frac{\lambda v_{t+1} + \alpha^* u_{t+1}}{1 - (1 - \theta) \rho_a \cdot L}, \quad (57)$$

where the i.i.d. idiosyncratic noises in the expressions for individual consumption dynamics have been canceled out. The following proposition summarizes the results of the joint dynamics of aggregate consumption and the equity return.

**PROPOSITION 8.** *Given finite capacity  $\kappa$  (i.e.,  $\theta$ ) and optimal portfolio choice  $\alpha^*$ , the relative volatility of consumption growth to the equity return is*

$$\text{rv} = \frac{\text{sd}[\Delta c_t^*]}{\text{sd}[u_t]} = \frac{\theta b_1}{\sqrt{1 - (1 - \theta)^2 \rho_a^2}} \frac{\omega_\zeta}{\omega}, \quad (58)$$

where  $\omega_\zeta = \sqrt{\alpha^{*2} \omega^2 + \lambda^2 \omega_v^2 + 2\alpha^* \lambda \rho_{uv} \omega \omega_v}$ , the first-order autocorrelation of consumption growth is

$$\rho_{\Delta c} = \text{corr}[\Delta c_t^*, \Delta c_{t+1}^*] = \theta (1 - \theta) \rho_a \frac{1 - (1 - \theta) \rho_a^2}{1 - (1 - \theta)^2 \rho_a^2}, \quad (59)$$

TABLE 2

EFFECTS OF RU AND RI ON CONSUMPTION AND THE EQUITY PREMIUM IN THE PRESENCE OF LABOR INCOME

	U.S. data	Full information	$\theta = 25\%$	$\theta = 35\%$	$\theta = 45\%$	$\theta = 55\%$
$\pi (\sigma = 0.9982)$	0.06	0.023	0.060	0.038	0.029	0.025
$r_v$	0.07	1	0.541	0.470	0.475	0.493
$\rho_{\Delta c}$	0.22	0	0.059	0.112	0.146	0.166
$\text{corr}(\Delta c_{t+1}^*, u_{t+1})$	0.21	1	0.356	0.566	0.715	0.836

and the contemporaneous correlation between consumption growth and the equity return is

$$\text{corr}[\Delta c_{t+1}^*, u_{t+1}] = \sqrt{1 - (1 - \theta)^2 \rho_a^2} \left( \alpha^* + \lambda \frac{\rho_{uv} \omega_v}{\omega} \right). \quad (60)$$

PROOF. See online appendix. ■

Table 2 reports how RI affects the joint behavior of aggregate consumption and the equity return and the equity premium in the presence of nondiversified labor income in general equilibrium. When computing the equilibrium equity return and the key moments of the joint dynamics of aggregate consumption and the equity return, we follow Viceira (2001) and Campbell and Viceira (2002) and set  $R_f = 1.02$ ,  $E_t[R_{e,t+1}/R_f] = 1.06$ ,  $\omega = 0.153$ ,  $E_t[Y_{t+1}/Y_t] = 1.03$ ,  $\omega_v = 0.15$ ,  $\rho_{uv} = 0.35$ , and  $W/Y = 15$ . From this table, we can see that in the presence of nondiversified labor income, the interaction of RU and RI has the similar effects on these key moments as in the benchmark model and can significantly improve the model's predictions on these important aspects. For example, if  $\theta$  is reduced from 1 to 0.25, we choose  $\sigma = 0.9982$  to match the equilibrium equity premium perfectly; at the same time, the model generates much lower relative volatility of aggregate consumption (from 1 to 0.541) and contemporaneous correlation between aggregate consumption and the equity return (from 1 to 0.356), and positive autocorrelation of aggregate consumption (from 0 to 0.059).

#### 4. CONCLUSION

In this paper, we have studied the portfolio choice of a household with Kreps–Porteus/Epstein–Zin preferences and limited information-processing capacity (RI). RI interacts with a preference for early resolution of uncertainty to generate significant decreases in the demand for risky assets; small deviations from indifference over timing and infinite channel capacity are magnified over the infinite future to produce empirically reasonable portfolios with actual risk aversion essentially equal to 1, whether the agent has nontradable labor income. This result raises important questions about empirical assessment, such as how to identify risk aversion separately from channel capacity, that we will not pursue here.

We have focused on solutions in which *ex post* uncertainty is Gaussian. Recent results in the RI literature (Matejka and Sims 2010) have noted that there exist *discrete* optimal solutions to the decision problem when the state space is bounded that may dominate the Gaussian one; the intuition for this result is that information costs can be reduced by dividing the state space into regions and only permitting solutions to differ across these regions instead of inside them. With these solutions in mind, Batchuluun, Luo, and Young (2008) show that fully nonlinear portfolio decisions are discrete in a simple two-period economy; these solutions have the property that agents will place positive measure on only a small number of different portfolio shares. For reasonable degrees of risk aversion and low enough channel capacity, one group of these points involves zero equity holdings because agents who want to borrow from future income will do so using the risk-free asset, and there is always a positive probability that wealth is actually such that borrowing would be optimal. A second group of points involves a small amount of risky assets (and generally this set of points has the most mass), whereas a third group has a significant amount of risky assets. Extending these results to study portfolios in long-horizon models has the potential to rationalize why few households hold assets that do not appear very risky (in terms of consumption or utility), why those that hold these assets hold so few of them, and why these assets pay such high rates of return. The mechanism identified here will still be present, if somewhat obscured by the numerical solution.

## APPENDIX A

### A.1 Deriving an Approximate Loss Function

Given the optimal consumption and portfolio rules derived in the FI case, it is straightforward to show that the value function under full information about the state,  $V(A_t)$ , corresponding to the RU model (1), takes the following form:

$$V(A_t) = \Phi A_t,$$

where  $\Phi$  is a coefficient determined by the model parameters and is not relevant to our analysis.<sup>32</sup> Now we assume that the agents cannot observe the true state. In this case, we approximate the value function around the perceived value for the true state variable ( $a_t = \ln A_t$ ),  $\hat{a}_t$ , as follows:

$$\begin{aligned} V_t &= \Phi \exp(a_t) \\ &\cong \hat{V}_t + \Phi \left[ \exp(\hat{a}_t)(a_t - \hat{a}_t) + \frac{1}{2} \exp(\hat{a}_t)(a_t - \hat{a}_t)^2 \right], \end{aligned}$$

where  $\hat{V} = \Phi \exp(\hat{a}_t)$ . Therefore, minimizing the expected welfare loss due to imperfect observations,  $E_t[V_t - \hat{V}_t]$ , is equivalent to minimizing

$$\min_{\hat{a}_t} E_t [(a_t - \hat{a}_t)^2].$$

32. When  $\sigma$  is close to 1,  $\Phi = 1 - \delta$ . Please see Appendix D of Giovannini and Weil (1989) for a detailed derivation.

In other words, when the approximation is accurate, the best estimate of the true state,  $\hat{a}_t$ , should be its conditional mean based on the available information,  $E_t[a_t]$ . In addition, when  $\sigma$  is close to 1,  $\widehat{V}_t \cong (1 - \beta) \exp(\hat{a}_t)$  is just the value function under RI. The key reason for this result is that the original state transition equation and the Kalman filtering equation are homeomorphic, and the values of  $\phi$  and  $b_0$  in the consumption functions under FI-RE and RI are approximately the same when  $\sigma$  is close to 1.<sup>33</sup>

### A.2 Deriving the Perceived State Evolution Equation

Here, we detail the straightforward steps omitted in the main part of the paper that derive the perceived state evolution equation. The Kalman filtering equation can be written as:

$$\hat{a}_{t+1} = (1 - \theta) \left[ \frac{1}{\phi} \hat{a}_t + \left(1 - \frac{1}{\phi}\right) c_t \right] + \theta a_{t+1}^*.$$

Combining this Kalman filtering equation with the true state evolution equation yields:

$$\hat{a}_{t+1} = \frac{1}{\phi} \hat{a}_t + \left(1 - \frac{1}{\phi}\right) c_t^* + \psi + \eta_{t+1},$$

where  $\eta_{t+1}$  is the innovation to the perceived state:

$$\eta_{t+1} = \theta \left[ \alpha^* (r_{e,t+1} - r_f) + r_f + \frac{1}{2} \alpha^* (1 - \alpha^*) \omega^2 + \xi_{t+1} \right] + \frac{\theta}{\phi} (a_t - \hat{a}_t),$$

and  $a_t - \hat{a}_t$  is the estimation error:

$$a_t - \hat{a}_t = \frac{(1 - \theta) [\alpha^* (r_{e,t+1} - r_f) + r_f + \frac{1}{2} \alpha^* (1 - \alpha^*) \omega^2]}{1 - ((1 - \theta)/\phi) \cdot L} - \frac{\theta \xi_t}{1 - ((1 - \theta)/\phi) \cdot L}.$$

### A.3 Deriving Long-Term Euler Equation within the Recursive Utility Framework

Within the RU framework, when wealth is allocated efficiently across assets, the marginal investment in any asset yields the same expected increase in future utility,

$$E_t \left[ \frac{U_{2,t} U_{1,t+1}}{U_{1,t}} (R_{e,t+1} - R_f) \right] = 0,$$

which means that

$$E_t [U_{1,t+1} (R_{e,t+1} - R_f)] = 0, \quad (\text{A1})$$

33. Note that in our key quantitative analysis, we set  $\sigma = 0.99999$ .

where  $U_{i,t}$  for any  $t$  denotes the derivative of the aggregator function with respect to its  $i$ th argument, evaluated at  $(C_t, E_t[U_{t+1}])$ .

Using the Euler equation for the risk-free asset between  $t + 1$  and  $t + 1 + S$ ,

$$\begin{aligned} U_{1,t+1} &= E_{t+1} \left[ (\beta_{t+1} \cdots \beta_{t+S}) (R_f)^S U_{1,t+1+S} \right] \\ &= E_{t+1} \left[ (U_{2,t+1} \cdots U_{2,t+S}) (R_f)^S U_{1,t+1+S} \right], \end{aligned} \quad (\text{A2})$$

where we denote  $\beta_{t+1+j} = U_{2,t+j}$ , for  $j = 0, \dots, S$ . Substituting (A2) into (A1) yields

$$\begin{aligned} &E_t \left[ E_{t+1} \left[ (U_{2,t+1} \cdots U_{2,t+S}) (R_f)^S U_{1,t+1+S} \right] (R_{e,t+1} - R_f) \right] \\ &= E_t \left[ (U_{2,t+1} \cdots U_{2,t+S}) (R_f)^S U_{1,t+1+S} (R_{e,t+1} - R_f) \right] = 0. \end{aligned}$$

Hence, the expected excess return can be written as

$$\begin{aligned} E_t [R_{e,t+1} - R_f] &= -\frac{\text{con}_t \left[ (U_{2,t+1} \cdots U_{2,t+S}) (R_f)^S U_{1,t+1+S}, R_{e,t+1} - R_f \right]}{E_t \left[ (U_{2,t+1} \cdots U_{2,t+S}) (R_f)^S U_{1,t+1+S} \right]} \\ &= -\frac{\text{con}_t \left[ (U_{2,t+1} \cdots U_{2,t+S}) (R_f)^S U_{1,t+1+S}, R_{e,t+1} - R_f \right]}{E_t [U_{1,t+1}]} \\ &= -\frac{\text{con}_t \left[ (U_{2,t+1} \cdots U_{2,t+S}) (R_f)^S U_{1,t+1+S}, R_{e,t+1} - R_f \right]}{U_{1,t} / (U_{2,t} R_f)} \\ &= -\text{con}_t \left[ (U_{2,t} \cdots U_{2,t+S}) (R_f)^{S+1} \frac{U_{1,t+1+S}}{U_{1,t}}, R_{e,t+1} - R_f \right] \\ &= -\text{con}_t \left[ \left( R_f U_{2,t} \frac{U_{1,t+1}}{U_{1,t}} \right) \cdots \left( R_f U_{2,t+S} \frac{U_{1,t+1+S}}{U_{1,t+S}} \right), R_{e,t+1} - R_f \right] \\ &\simeq \text{con}_t \left[ \left( \frac{\theta}{\rho} \Delta c_{t+1} + (1-\theta) r_{p,t+1} \right) + \cdots + \left( \frac{\theta}{\rho} \Delta c_{t+1+S} + (1-\theta) r_{p,t+1+S} \right), u_{t+1} \right] \\ &= \text{con}_t \left[ \frac{\theta}{\rho} \left( \sum_{j=0}^S \Delta c_{t+1+j} \right) + (1-\theta) \left( \sum_{j=0}^S r_{p,t+1+j} \right), u_{t+1} \right]. \end{aligned}$$

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