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The Rationality Bias

We analyze differences in consumption and wealth in an estimated New Keynesian model with rational and boundedly rational households. Shocks are shown to cause consumption and wealth heterogeneity due to the “rationality bias” of boundedly rational households. This bias can be decomposed into three components, which, for certain specifications of monetary policy, can exactly offset each other. Moreover, a more hawkish response to inflation leads to more volatility in consumption and wealth heterogeneity, which makes it optimal for the central bank to set lower coefficients in the Taylor rule than would have been the case under homogeneous rational expectations.

JEL codes: C11, C13, E21, E52, E70

Keywords: heterogeneous expectations, monetary policy, bounded rationality

THERE IS A GROWING CONSENSUS that models with homogeneous rational expectations cannot adequately approximate actual human behavior at the microeconomic or macro-economic level. Even when a considerable part of economic actors may be approximately rational, a nonnegligible fraction of the population is not nearly as rational as assumed in theoretical models. For example, Be-

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qiraj, Di Bartolomeo, and Serpieri (2017) estimate a fraction of boundedly rational forecasters in survey data between 5% and 30%. Moreover, D’acunto et al. (2023), using IQ-data of Finnish males, find a strong association between the level of cognitive abilities and biases in the formation of economic beliefs and economic decision making.

Importantly, the presence of agents with different levels of cognitive ability may lead to nontrivial interactions, where economic shocks affect the expectations and, therefore, the economic decisions of different actors differently.¹ On top of the corresponding macro-economic consequences, the interaction of agents with different levels of cognitive ability may have important implications for heterogeneity in consumption and wealth along the business cycle. Whereas different strands of literature that incorporate bounded rationality into macro-economic models have gained popularity (see, e.g., Evans and Honkapohja 2012 and Gabaix 2020), only one of these strands incorporates heterogeneous, possibly nonrational expectations in macromodels (see, e.g., Branch and McGough 2018). Moreover, papers in that tradition have focused on aggregate dynamics, largely ignoring dynamics at the individual level. We want to fill this gap in the literature by explicitly considering how differences in cognitive ability lead to differences in consumption and wealth and what this implies for monetary policy.

For this purpose, we set up a microfounded model where a given fraction of households is *fully rational* in the conventional sense (Muth 1961), while the other fraction is *boundedly rational* as we will explain in detail below. Further, we keep track of the individual bond holdings of both groups. We estimate the model using Bayesian methods, letting the consumption heterogeneity between the two types of agents be informed by a measure taken from Heathcote, Perri, and Violante (2010). As a result, the fraction of boundedly rational agents in our model is estimated to be 12%, which is in line with the estimation of Beqiraj, Di Bartolomeo, and Serpieri (2017) based on survey expectations. We, further, identify the “rationality bias” of boundedly rational households—defined as the deviation from the fully rational benchmark—as the driver of consumption and wealth heterogeneity. Moreover, we find a strong interaction between the size of the rationality bias and monetary policy that implies that the central bank should be relatively less hawkish.

In addition to clearly showing that there is heterogeneity between forecasters, the survey expectations literature also suggests that a sizable fraction of the population seems to follow simple backward-looking heuristics. For instance, Branch (2004) finds evidence of the presence of different expectation types in the Michigan Survey of Consumer Attitudes and Behavior, including both naive expectations, where the last observed value of a variable is used as a best guess for the future, and a more sophisticated VAR (vector autoregression) heuristic. Cornea-Madeira, Hommes, and Massaro (2019) further find that a model with naive agents and agents that use a VAR

1. Rational actors revise their expectations instantly and act in an appropriate manner. However, boundedly rational actors may only observe the effects of the shock with a delay and make mistakes accordingly, and this, in turn, can alter—through anticipation effects—the behavior of the rational agents.

approach to predict inflation based on its forward-looking relation with marginal costs fits actual inflation data well. Moreover, simple backward-looking heuristics are consistent with evidence from laboratory experiments (Pfajfar and Žakelj 2016, Assenza et al. 2021), where a large degree of heterogeneity is found. Also, Fuhrer (2017) identifies slow-moving expectations as a source of macro-economic persistence.

In the analytical parts of the paper, we keep the expectation formation of boundedly rational households as general as possible. For the model estimation and simulation exercises, we will focus on the case where boundedly rational households form their expectations in a naive manner. This assumption is consistent with the evidence of Branch (2004) and Cornea-Madeira, Hommes, and Massaro (2019) and follows earlier literature on heterogeneous expectations such as Branch and McGough (2009,2010), De Grauwe (2011), Gasteiger (2014), and Hommes and Lustenhouwer (2019a). Naive expectations perform well when the variable being forecast is highly persistent and are optimal when the variable follows a random walk.

Our boundedly rational households further base their consumption decision only on the variational intuition of the consumption Euler equation (Euler-equation learning), following Branch and McGough (2009). Boundedly rational households, hence, do not make decisions according to the infinite horizon learning approach of Preston (2005) and Massaro (2013). Infinite horizon learning would require boundedly rational households to form expectations about all variables over an infinite horizon and to make optimal decisions based on these expectations. We believe that this would require too much cognitive ability from boundedly rational households.

The other fraction of households, on the other hand, is fully rational in the conventional sense. These households are fully aware of the presence of boundedly rational households. Further, rational households choose the optimal intertemporal allocation of consumption, labor supply, and bonds based on all their optimality conditions, including their intertemporal budget constraint. Thus, we combine the Euler-equation learning approach of Branch and McGough (2009) and Honkapohja, Mitra, and Evans (2012) for boundedly rational households with full rationality, in the conventional sense, for rational households. To the best of our knowledge, this is the first paper to do so. With this approach, we can contrast boundedly rational households that have considerable limitations in their cognitive ability with fully rational households. The presence of rational households further allows us to construct an intuitive measure of the “rationality bias” of boundedly rational households, as the deviation from the fully rational benchmark.

When fitting our model to U.S. data using Bayesian methods, we find that considerable consumption and wealth heterogeneity arises when the economy is hit by shocks. Moreover, we show analytically and with impulse response functions that the rationality bias of boundedly rational households can be decomposed in three components that may reinforce or counteract each other, depending on the shocks that hit the economy and on monetary policy. In particular, we show that, for a large class of expectation formation processes of boundedly rational households, the three components exactly offset each other when the percentage deviation from steady state of the nominal interest rate and the inflation rate are equal in every period. In this case, the rationality bias completely disappears and new shocks hitting the economy do not

cause any differences in consumption and wealth between rational and boundedly rational households.

Moreover, the more strongly the central bank lets the interest rate respond to inflation, the larger the volatility in the rationality bias. Hence, a more hawkish central bank response increases fluctuations in consumption and wealth differences. As a consequence, when setting its monetary policy parameters, the central bank faces an additional trade-off that is absent in the case of homogeneous expectations. We further show that, because of this trade-off, it is optimal to set lower coefficients in the Taylor rule than in the absence of consumer heterogeneity.

The importance of consumer heterogeneity and its implications for monetary policy has been stressed in the recent literature with heterogeneous agents New Keynesian (HANK) models where households face uninsurable, idiosyncratic income risk and borrowing constraints (Gornemann, Kuester, and Nakajima 2016, McKay, Nakamura, and Steinsson 2016, Kaplan, Moll, and Violante 2018, Auclert 2019). At the same time, two-agent New Keynesian (TANK) models aim to capture important features of consumer heterogeneity in a much simpler setting with two different groups of agents and no within-group heterogeneity. TANK models usually assume limited asset market participation with one group of households being borrowing constrained, whereas the other group is not (Bilbiie 2008, Debortoli and Galí 2017).² This allows for the study of a similar dimension of consumer heterogeneity that is also included in the HANK models. Our paper is related to the TANK literature, in that, we also focus on two different groups of households. However, the dimension of heterogeneity that we study is bounded rationality and expectation formation, which can be seen as orthogonal to the heterogeneity in asset market participation that is central in the HANK/TANK literature. In practice, there are many dimensions along which households differ and our work complements the HANK/TANK literature by analyzing the implications of a different dimension of heterogeneity.

As previously indicated, we are not the first to consider heterogeneity in expectations in a New Keynesian model. Also in that literature, there are different approaches with respect to the degree of heterogeneity. For example, Kurz, Piccillo, and Wu (2013), Pecora and Spelta (2017), and Hommes and Lustenhouwer (2019b) take an approach closer to HANK by having a continuous distribution of beliefs/expectations. At the same time, Branch and McGough (2009), De Grauwe (2011), Gasteiger (2014), Di Bartolomeo, Di Pietro, and Giannini (2016), Hommes and Lustenhouwer (2019a), Jump, Hommes, and Levine (2019), and others consider a model closer to a TANK structure by assuming two different types of expectation formation. We follow a two-agent approach in order to be able to obtain analytical results and intuitions without the need for further restrictive assumptions.

A drawback of the literature on heterogeneous expectations (Branch and McGough 2018) is that, generally, only aggregate dynamics are considered, and that differences in consumption and wealth between households are not explicitly kept track of. Re-

2. A different but related approach is taken by Broer et al. (2020) who assume one group of households to be “capitalists” and the other group to be “workers.”

cent exceptions are Beqiraj, Di Bartolomeo, and Serpieri (2017) and Annicchiarico, Surricchio, and Waldmann (2019). The former calculate a measure of consumption inequality in their economy. The latter present differences in bond holdings that arise between some of their agents. The main interest of these studies, however, remains aggregate dynamics. Moreover, in the above literature, it is not clear to what extent aggregate results are driven by bounded rationality in consumer decisions and to what extent they are driven by bounded rationality in price-setting decisions.³ We, hence, contribute to this literature by isolating the implications of consumer heterogeneity and by explicitly keeping track of both consumption and bond holdings of different groups of households. The latter allows us to study the drivers and dynamic evolution of the differences that arise. Finally, since we estimate the model using Bayesian methods, we are also able to speak to the quantitative implications of heterogeneity in the rationality of households.

The remainder of the paper is organized as follows. The model is introduced in Section 1 where we put emphasis on the assumptions on bounded rationality. In Section 2, we study in detail the different components that comprise the rationality bias and estimate the model using Bayesian methods. Finally, in Section 3, we show that the rationality bias can be eliminated with certain monetary policy and subsequently study policy trade-offs and implications. Section 4 concludes.

1. MODEL

In this section, we introduce heterogeneous rationality into a standard New Keynesian model. In particular, we assume a unit-mass continuum of households $i \in [0, 1]$ and firms $j \in [0, 1]$ as well as a monetary and fiscal authority. The population of households splits into two groups with a fixed size: rational households, who make up a fraction α of the population, and boundedly rational households, making up the remaining $1 - \alpha$ of the population.

There is an ongoing discussion in the literature (see, e.g., Honkapohja, Mitra, and Evans 2012) whether boundedly rational agents should be assumed to follow Euler-equation learning or rather infinite horizon learning. In the former case, boundedly rational agents base their consumption decision only on the variational intuition of the consumption Euler equation. The latter case assumes boundedly rational agents to make optimal decisions based on their subjective forecasts of the entire future paths of all variables. Since we study differences in consumption and wealth that arise due to heterogeneity in cognitive ability, we let our two types of agents differ considerably in their degrees of rationality. For this reason, we stick with the less cognitive demanding Euler-equation learning approach for our boundedly rational households. Rational households are modeled as being fully rational, instead. Thus, we do not

3. Either because a Yeoman-farmer setting is assumed, or because both firms and households are assumed to feature the same bounded rationality.

follow Branch and McGough (2009) and the related literature on heterogeneous expectations by letting agents with rational expectations also use Euler-equation learning. Instead, we combine the Euler-equation learning of boundedly rational households with fully rational optimization in the conventional sense of rational households. Detailed descriptions of both household types, including their individual expectation formation schemes, are included in Sections 1.2 and 1.3.

Further, we assume perfect consumption insurance within the groups, so that the two types of households can be interpreted as two different representative agents. In order to focus on heterogeneity in households only, we assume that all firms are run by rational managers.

1.1 The Nonlinear Model

First, we introduce the basic model elements in nonlinear form. The log-linearized version, including a specification of each household type and policy rules, is given in a subsequent subsection.

1.1.1 Households. Households of type i with $i \in \{R, B\}$ optimize their expected lifetime utility $E_t^i \sum_{t=0}^{\infty} \beta^t \Upsilon_t U_t^i$ subject to their real flow budget constraint

$$C_t^i + \bar{Y} b_t^i \leq W_t H_t^i + \bar{Y} \frac{I_{t-1}}{\Pi_t} b_{t-1}^i + D_t - T_t, \quad (1)$$

where E_t^i is the type-specific expectations operator, $\beta < 1$ the subjective discount factor, U_t^i period-utility of type i , and Υ_t is a preference shock. C_t^i denotes individual consumption, T_t is a lump-sum tax, and W_t the real wage rate, which are equal across groups.

$b_t^i = B_t^i / (P_t \bar{Y})$ are the real bond holdings of household i as a fraction of steady-state output, where \bar{Y} is the steady state of output, Y_t . B_t^i refer to nominal government bonds, which are the only asset in the economy. Both rational and boundedly rational households can hold positive and negative positions of these bonds and can trade them with each other as well as directly with the government. Note that the price of the nominal government bonds is given by the inverse of the gross nominal interest rate, I_t , which is controlled by the central bank.

Further, H_t^i denotes individual hours, $\Pi_t = P_t / P_{t-1}$ the inflation rate, where P_t is the aggregate price level in period t , and D_t dividends that households obtain as shareholders of the firms.

Period utility is of the CES (constant elasticity of substitution)-form and given by

$$U_t^i = \frac{(C_t^i)^{1-\sigma}}{1-\sigma} - \frac{(H_t^i)^{1+\gamma}}{1+\gamma}, \quad (2)$$

where σ is the coefficient of relative risk aversion and γ the labor supply elasticity.

1.1.2 Firms. We assume that firms are run by rational managers that are appointed by households (who are the shareholders of firms). In the end, this assumption allows us to isolate the effect of *heterogeneous rationality of households* on differences in

consumption and wealth. The assumption that all firm managers are rational can be justified by the fact that rational managers will always perform better than boundedly rational ones. Therefore, if given the chance, all firm owners would prefer to appoint rational managers.

Our further assumptions about the firm side of this model are entirely standard. We assume that production is linear in labor and introduce Calvo pricing so that a firm j is able to reset its price only with a given probability of $1 - \omega$ in each period. We present the derivation of the Phillips curve in Online Appendix D and give the log-linear version in the next section.

Government and market clearing. The government finances its spending via government debt and lump-sum taxes. They further provide a subsidy, $s = 1/\eta$, to firms (as in Galí 2015), which makes the steady state of our model efficient. The real government budget constraint reads

$$b_t = \frac{G_t}{\bar{Y}} - \frac{T_t}{\bar{Y}} + s \frac{H_t}{\bar{Y}} W_t + \frac{l_{t-1}}{\Pi_t} b_{t-1}. \quad (3)$$

Bonds and goods markets clear according to

$$b_t = \alpha b_t^R + (1 - \alpha) b_t^B, \quad (4)$$

$$Y_t = (\alpha C_t^R + (1 - \alpha) C_t^B) + G_t. \quad (5)$$

1.2 Expectations

Rational households are sophisticated enough to compute an optimal linear forecast, that is, they use the expected value $E_t^R z_{t+1} = E_t z_{t+1}$ for any variable z . Boundedly rational households, on the other hand, form expectations in a less sophisticated manner. For the sake of generality, we leave the expectations of boundedly rational households as far as possible unspecified in the analytical derivations and results in the paper. Their expectations operator is, however, always assumed to satisfy assumptions A1–A5 of Branch and McGough (2009).⁴ For estimation and simulations, we consider the case where boundedly rational households use the last observed value (z_{t-1}) of a variable as their best guess for the future with the following naive heuristic: $E_t^B z_{t+1} = z_{t-1}$.

1.3 The Log-Linear Economy

For our policy analysis, we use a log-linear version of the model that is obtained by approximating around a nonstochastic zero-inflation steady state.

4. That is, expectations fix observables while the expectation in steady state of some variable is the steady-state value of that variable itself. Further, usual linearity assumptions apply and the law of iterated expectations needs to hold at the individual level. In section “Individual consumption, labor, and bonds,” we will outline further specific assumptions on bounded optimality.

Individual consumption, labor and bonds. Households' first-order conditions, implied by the optimization problem outlined in section "Households," are given in log-linearized terms by

$$c_t^i = E_t^i c_{t+1}^i - \frac{1}{\sigma} (i_t - E_t^i \pi_{t+1} - v_t + E_t^i v_{t+1}), \quad (6)$$

$$w_t = \gamma h_t^i + \sigma c_t^i, \quad (7)$$

$$\hat{b}_t^i = h_t^i + w_t + \beta^{-1} \hat{b}_{t-1}^i + \bar{b} \beta^{-1} (i_{t-1} - \pi_t) + \eta^{-1} d_t - (1 - \bar{g}) c_t^i - \frac{\bar{T}}{\bar{Y}} \tau_t, \quad (8)$$

where lower case letters indicate log-deviations from steady state (and τ_t indicates log-deviation of taxes from steady state). Further, we denote $\hat{b}_t^i = b_t^i - \bar{b}$ and $\bar{g} = \frac{\bar{G}}{\bar{Y}}$, and we use $\bar{D} = \bar{Y} - (1 - s)\bar{W}\bar{H} = \eta^{-1}\bar{Y}$ where $\bar{W} = 1$. All steady-state values are derived in Online Appendix E.

Equation (6) determines the households' optimal consumption path depending on their subjective real interest rate and preference shock (expectations). The optimal labor supply is pinned down by the optimality condition (7). Equation (8) shows the household's log-linear budget constraint.

For rational households, the budget constraint (8) is given by

$$\hat{b}_t^R = h_t^R + w_t + \beta^{-1} \hat{b}_{t-1}^R + \bar{b} \beta^{-1} (i_{t-1} - \pi_t) + \eta^{-1} d_t - (1 - \bar{g}) c_t^R - \frac{\bar{T}}{\bar{Y}} \tau_t. \quad (9)$$

Rational households are assumed to combine their first-order conditions and intertemporal budget constraint to make fully optimal decisions given their expectations. Moreover, their expectations are fully model consistent and take account of how the presence of boundedly rational households will affect aggregate variables. Here, rational households are assumed to have full knowledge of the fraction of boundedly rational households in the economy and of the expectation formation mechanism and decision rules that these households have. For example, rational households know that, when they consume more now, the resulting increase in output will alter the output expectations of boundedly rational households (depending on their specific forecasting rule). This will affect the consumption decision of these households and hence aggregate demand and other aggregate variables. Rational households fully take this into account. Further, the above assumptions about the knowledge of rational households imply that there is no higher order belief uncertainty as in Angeletos and Lian (2018).

In Online Appendix A, we show that the following equation for rational consumption can be derived by iterating (9) until infinity, substituting for all choice variables and plugging in expectations, $E_t^R = E_t$.

$$c_t^R = \zeta \hat{b}_{t-1}^R + \zeta \bar{b} (i_{t-1} - \pi_t) + \zeta \beta E_t \sum_{s=t}^{\infty} \beta^{s-t} [\Gamma_y y_s - \Gamma_g g_s - \Gamma_\tau \tau_s]$$

$$- \frac{(1 - \zeta \bar{b}\sigma)\beta}{\sigma} E_t \sum_{s=t}^{\infty} \beta^{s-t} (i_s - \pi_{s+1}) + \frac{\beta}{\sigma} E_t \sum_{s=t}^{\infty} \beta^{s-t} (v_s - v_{s+1}). \quad (10)$$

Composite parameters ζ , Γ_y , Γ_g , Γ_τ are given in Online Appendix A. Thus, fully rational households base their decisions on predictions over the *entire paths* of output, government spending, taxes, real interest rates, and preference shocks *until infinity*.

For boundedly rational households, we consider such an approach to require too much cognitive load. Therefore, our boundedly rational households follow Euler-equation learning and believe that all other agents will form the same beliefs as they themselves do (higher-order beliefs assumption) as in Branch and McGough (2009). This implies that boundedly rational households will neglect their intertemporal budget constraint as an *optimality condition*. Boundedly rational households are further assumed to know that market clearing holds. Also, we assume that boundedly rational households believe that all other households will satisfy the consumption Euler equation in the same way they themselves do. Finally, we require boundedly rational households to be able to iterate their consumption Euler equation until some period N , where N can be freely chosen by the researcher.

In Online Appendix A, it is shown that under the above assumptions the consumption decision of boundedly rational households is given by

$$c_t^B = \frac{1}{1 - \bar{g}} E_t^B y_{t+1} + E_t^B (c_N^B - c_N) - \frac{1}{\sigma} [i_t - E_t^B \pi_{t+1} - v_t + E_t^B v_{t+1}] \\ - \frac{\bar{g}}{1 - \bar{g}} E_t^B g_{t+1}.$$

It follows that the consumption decision of boundedly rational households depends, among others, on their expectations about their relative consumption level in the period until which they are able to iterate the Euler equation, period N . In Branch and McGough (2009), it is assumed that N goes to infinity. Under the assumption that all agent types follow such a decision rule, an expression for aggregate consumption can then be derived that no longer depends on expectations about period N .⁵ We do not follow this approach for several reasons. First of all, our rational households do not follow (11) but, instead, make consumption decisions based on fully optimal intertemporal utility maximization according to (10). Second, the approach of Branch and McGough (2009) only provides an expression for aggregate consumption, but does not pin down the consumption of boundedly rational households. Third, we do not consider iterating the Euler equation forward to infinity to be fitting to the cognitive abilities of our boundedly rational households and rather prefer a small number for N .

5. In order to achieve this, Branch and McGough (2009) additionally need to assume that all agents agree on expected differences in period- N wealth (Assumption A7) where $N = \infty$ in their case.

Therefore, we take a different approach and let our boundedly rational households be more myopic Euler learners by setting $N = 2$.⁶ These households then only need to come up with expectation about the difference between their consumption and aggregate consumption (i.e., their relative consumption) two periods into the future.

Next, we assume that expectations of boundedly rational households about their relative future consumption depend on their relative wealth. That is, when boundedly rational households have more bonds than the average household, they expect to be able to consume more than the average household. Formally, this implies

$$E_t^B(c_N^B - c_N) = E_t^B(c_2^B - c_2) = \psi(\hat{b}_{t-1}^B - \hat{b}_{t-1}). \quad (12)$$

Plugging this assumption into (11) gives

$$\begin{aligned} c_t^B = & \frac{1}{1 - \bar{g}} E_t^B y_{t+1} + \psi(\hat{b}_{t-1}^B - \hat{b}_{t-1}) - \frac{1}{\sigma} [i_t - E_t^B \pi_{t+1} - v_t + E_t^B v_{t+1}] \\ & - \frac{\bar{g}}{1 - \bar{g}} E_t^B g_{t+1}. \end{aligned} \quad (13)$$

Hence, by expecting that relative wealth is important for relative future consumption, boundedly rational households also partly base their current consumption on their wealth. Without this term in (13), boundedly rational households would have no concern for the development of their assets or debt at all, as they do not iterate their budget constraint forward and do not consider a transversality condition when planning their current consumption.

On the other hand, with the above assumption, we reintroduce concerns for debt and wealth in the consumption decision process of boundedly rational households in a behavioral manner. There is a considerable empirical literature that finds a direct relation between wealth and consumption (a “wealth channel”) in microdata as well as in macrodata (see, e.g., Poterba 2000, Dynan and Maki 2001, Canner, Dynan, and Passmore 2002, Dvornak and Kohler 2007, Bostic, Gabriel, and Painter 2009). We hence assume that boundedly rational households form expectations about their relative future consumption accordingly. Intuitively, the wealth channel should be especially relevant for more myopic agents. This is because myopic agents consider to a lesser extent the infinite sum of their future income and focus more on their current (financial) wealth, instead. For example, in the model of Benjamin, Chinloy, and Jud (2004), which is used to explain their empirical findings regarding the wealth channel, a shorter planning horizon leads to larger wealth effects on consumption. By applying the idea of a dependence of expected relative consumption on relative wealth, the consumption decision of boundedly rational households becomes more in line with this type of myopia and allows for a wealth channel.

6. Note that we could also have set $N = 4$ or $N = 10$ or leave N unspecified. We could then make an analogue assumption to (12) and still end up with (13). We prefer, however, to explicitly set $N = 2$ to highlight the myopia of the boundedly rational households.

Technically, our assumption prevents bond holdings of individual households from being explosive and, thereby, facilitates the existence of an equilibrium that satisfies the intertemporal budget constraint and transversality condition of rational households. Put differently, with our assumption, boundedly rational households will not roll over their debt until infinity. In our framework, there hence is no longer a need to include bonds in the utility function, as in Kurz, Piccillo, and Wu (2013), or to include quadratic adjustment costs of bonds in the budget constraint, as proposed by Schmitt-Grohé and Uribe (2003), in order to guarantee the existence of a stationary equilibrium. To achieve this stationarity, the parameter ψ does not need to be large. However, in this paper, we will let ψ be estimated along with the other model parameters, so that the wealth channel in the decision rule of boundedly rational households can become as large as it needs to be to fit the data. As it will turn out, our estimated value of ψ is quite in line with the size of the wealth affect found in the abovementioned empirical literature, which mostly ranges between 2% and 10%.

Comparing (13) with (10) shows that we impose far less cognitive load on boundedly rational households than on rational households, as discussed above. Boundedly rational households base their decisions on a much smaller set of expectations of variables, and only need to make forecasts for one-period-ahead aggregate variables.

Bond holdings of rational and boundedly rational households are given by (8), where we substitute for hours, wages, and dividends. This gives

$$\hat{b}_t^i = \beta^{-1}\hat{b}_{t-1}^i - \Gamma_c c_t^i + \Gamma_y y_t + \bar{b}\beta^{-1}(i_{t-1} - \pi_t) - \Gamma_g g_t - \Gamma_\tau \tau_t, \quad (14)$$

where the composite parameter Γ_c (as well as the other composite parameters introduced earlier) is given in Online Appendix A.

Aggregate equations. In equilibrium, markets must clear. This implies, in particular, that the following linearized versions of (4) and (5) must hold:

$$\hat{b}_t = \alpha \hat{b}_t^R + (1 - \alpha) \hat{b}_t^B, \quad (15)$$

$$y_t = (1 - \bar{g})(\alpha c_t^R + (1 - \alpha) c_t^B) + \bar{g} g_t. \quad (16)$$

In order to obtain an expressions for aggregate output gap, we first combine the individual decision rules of boundedly rational and rational households, (10) and (13), into (16). That is, given the consumption decisions of boundedly rational and rational households, and given α , we can calculate aggregate consumption and aggregate output. In Online Appendix A, we show that the resulting expression for output can be written recursively and expressed in terms of output gap x_t as follows, where the coefficients Φ_1, \dots, Φ_{20} are defined in Online Appendix A:

$$\begin{aligned} x_t = & -\Phi_1 \pi_t - \Phi_2 i_t - \Phi_3 \tau_t - \Phi_4 \hat{b}_t + \Phi_5 b_t^R + \Phi_6 g_t + \Phi_7 v_t + \Phi_8 E_t x_{t+1} \\ & + \Phi_9 E_t \pi_{t+1} + \Phi_{10} E_t i_{t+1} - \Phi_{11} E_t v_{t+1} - \Phi_{12} E_t g_{t+1} + \Phi_{13} E_t^B x_{t+1} \\ & + \Phi_{14} E_t^B \pi_{t+1} - \Phi_{14} E_t^B v_{t+1} - \Phi_{15} E_t^B g_{t+1} - \Phi_{16} E_t E_{t+1}^B x_{t+2} \end{aligned}$$

$$\begin{aligned}
& -\Phi_{10}E_tE_{t+1}^B\pi_{t+2} + \Phi_{10}E_tE_{t+1}^Bv_{t+2} + \Phi_{17}E_tE_{t+1}^Bg_{t+2} \\
& + \Phi_{18}i_{t-1} + \Phi_{19}\hat{b}_{t-1} - \Phi_{20}\hat{b}_{t-1}^R.
\end{aligned} \tag{17}$$

Note that (17) depends on individual bonds of rational households and on aggregate bonds. This stems from the fact that both the consumption decision of rational households, (10), and the consumption decision of boundedly rational households, (13), depend on their bonds. In the above equation, we have eliminated bond holdings of boundedly rational households using bond market clearing, (15).

Further note that rational expectations of one-period-ahead boundedly rational expectations of two-period-ahead variables show up in equation (17). Since boundedly rational expectations are different from the rational expectations operator, it does *not* simply hold that $E_tE_{t+1}^Bz_{t+2} = E_tz_{t+2}$. However, since we have assumed that rational households have perfect knowledge about the expectation formation mechanism of boundedly rational households, these future expectations of boundedly rational households can simply be replaced using the relevant expectation rule. For example, if boundedly rational households form expectations with the naive heuristic $E_t^Bz_{t+1} = z_{t-1}$, then $E_tE_{t+1}^Bz_{t+2}$ reduces to $E_tz_t = z_t$.

Since all firm managers are rational, inflation follows a standard forward-looking Phillips-curve. As shown in Online Appendix D, this implies

$$\pi_t = \beta E_t[\pi_{t+1}] + \delta \left(\gamma + \frac{\sigma}{1 - \bar{g}} \right) x_t + \mu_t, \tag{18}$$

where $\delta = ((1 - \omega\beta)(1 - \omega))/\omega$ and μ_t is a cost-push shock.

The log-linearized government budget constraint is given by

$$\hat{b}_t = \bar{g}g_t - \Gamma_\tau \tau_t + s(w_t + h_t) + \bar{b}\beta^{-1}(i_{t-1} - \pi_t) + \beta^{-1}\hat{b}_{t-1}. \tag{19}$$

The costs of the subsidy, $s(w_t + h_t)$, are assumed to be directly financed by lump-sum taxes. Additionally, taxes are assumed to respond to beginning-of-period debt. The evolution of government debt and lumps sum taxes can therefore be written as⁷

$$\hat{b}_t = \bar{g}g_t + (\beta^{-1} - \Gamma_\tau \phi_{b,\tau})\hat{b}_{t-1} + \bar{b}\beta^{-1}(i_{t-1} - \pi_t), \tag{20}$$

$$\tau_t = \phi_{b,\tau}\hat{b}_{t-1} + \frac{s}{\Gamma_\tau} \left(1 + \gamma + \frac{\sigma}{1 - \bar{g}} \right) x_t + \frac{s}{\Gamma_\tau} \left(\xi \left(1 + \gamma + \frac{\sigma}{1 - \bar{g}} \right) - \frac{\sigma \bar{g}}{1 - \bar{g}} \right) g_t. \tag{21}$$

For central bank policy, we assume a standard Taylor rule, that is,

$$i_t = \phi_\pi \pi_t + \phi_x x_t. \tag{22}$$

7. To obtain (21), we used $h_t = y_t$, $w_t = (\gamma + \sigma/(1 - \bar{g}))y_t - \sigma\bar{g}/(1 - \bar{g})g_t$, and $x_t = y_t - \xi g_t$.

The preference shock, cost push-shock, and government spending shock follow AR(1) processes, with i.i.d. shock innovations $\epsilon_{\mu,t}$, $\epsilon_{v,t}$, and $\epsilon_{g,t}$ that have standard deviations $\sigma_{\epsilon,\mu}$, $\sigma_{\epsilon,v}$, and $\sigma_{\epsilon,g}$.

$$v_t = \rho_v v_{t-1} + \epsilon_{v,t}, \quad (23)$$

$$\mu_t = \rho_\mu \mu_{t-1} + \epsilon_{\mu,t}, \quad (24)$$

$$g_t = \rho_g g_{t-1} + \epsilon_{g,t}. \quad (25)$$

2. THE RATIONALITY BIAS IN THE ESTIMATED MODEL

In this section, we first provide some intuition for the channels that lead to differences in consumption and wealth between rational and boundedly rational households, by means of an analytical decomposition (Section 2.1). Next, we estimate the model using Bayesian methods (Section 2.2). We then use the calibration that results from this estimation to quantify the abovementioned channels and see which channel dominates when it comes to determining whether boundedly rational households consume more or less than rational households in light of shocks (Section 2.3).

For the numerical part, we assume that boundedly rational households form expectations in a naive manner by considering the last observation of each variable ($E_t^B z_{t+1} = z_{t-1}$), as discussed in Section 1.2. We emphasize, however, that the analytical results in Sections 2.1 and 3.1 are derived for a much broader class of expectation rules for boundedly rational households.

2.1 The Components of the Rationality Bias

We first use an analytical decomposition to analyze differences in consumption and wealth that arise due to different degrees of rationality. Differences in wealth between boundedly rational and rational households arise as a consequences of differences in their consumption. We, therefore, focus on the latter.

The difference in individual consumption arises because boundedly rational households make consumption decisions with a decision rule that is not fully optimizing (based on Euler-equation learning) and because they form expectations about aggregate variables in a boundedly rational manner. If a boundedly rational household would not have these two limitations, it would act as a rational household. Hence, the difference $\Delta_i c_t^i = c_t^B - c_t^R$ can be interpreted as the *bias of a boundedly rational household*. We therefore label this difference the *Rationality bias*.

Using the individual consumption Euler equation, (6), of both household types, we can write

$$\Delta_i c_t^i = c_t^B - c_t^R = \underbrace{(E_t^B c_{t+1}^B - E_t c_{t+1}^R)}_{\text{consumption exp. bias}} - \underbrace{\frac{1}{\sigma}(rr_t^B - rr_t)}_{\text{real int. bias}} - \underbrace{\frac{1}{\sigma}(E_t^B v_{t+1} - E_t v_{t+1})}_{\text{preference shock exp. bias}}. \quad (26)$$

Equation (26) shows that we can decompose this consumption difference into three individual sources, and that the rationality bias depends *positively* on the consumption expectation bias, *negatively* on the real interest rate bias, and *negatively* on the preference shock expectation bias.

The preference shock expectation bias arises when boundedly rational households expect the next periods' preference shock to be different from the rational expectations about this shock, whereas the real interest rate bias emerges whenever the subjective (*ex ante*) real interest rate of boundedly rational households, rr_t^B , is different from the objective (*ex ante*) real interest rate. The latter coincides with the subjective real interest rate of rational households.

The consumption expectation bias appears when the expectations of boundedly rational households about their own future consumption deviate from rational expectations about future rational consumption. In Online Appendix A, we show that it implicitly follows from the consumption decision rule and Euler equation of boundedly rational households that their expectations about their own future consumption are given by

$$E_t^B c_{t+1}^B = \frac{1}{1-\bar{g}} \underbrace{(E_t^B y_{t+1} - \bar{g} E_t^B g_{t+1})}_{=E_t^B c_{t+1}} + \psi(\hat{b}_{t-1}^B - \hat{b}_{t-1}). \quad (27)$$

Equation (27) shows that when boundedly rational households expect aggregate consumption in next period to be high, they also expect their own individual consumption to be high in the next period. Additionally, when boundedly rational households own more wealth than the average, they expect to be able to consume more in the future, as discussed in section "Individual consumption, labor and bonds." Hence, the consumption expectation bias is partly driven by expectations and partly by a wealth channel.

Inserting (27) into (26) and plugging in the definitions of the subjective real interest rates yields

$$\begin{aligned} \Delta_i c_t^i = c_t^B - c_t^R = & \underbrace{\left(\frac{1}{1-\bar{g}} (E_t^B y_{t+1} - \bar{g} E_t^B g_{t+1}) + \psi(\hat{b}_{t-1}^B - \hat{b}_{t-1}) - E_t^R c_{t+1}^R \right)}_{\text{consumption exp. bias}} \\ & + \underbrace{\frac{1}{\sigma} (E_t^B \pi_{t+1} - E_t^R \pi_{t+1})}_{\text{neg. real int. bias}} - \underbrace{\frac{1}{\sigma} (E_t^B v_{t+1} - E_t^R v_{t+1})}_{\text{preference shock exp. bias}}. \end{aligned} \quad (28)$$

The first term in the second line of equation (28) reveals that a negative real interest rate bias merely reflects a positive inflation expectation bias. In principle, the individual biases can amplify or counteract each other, as we will discuss in detail in Section 2.3. In Section 3, we will show that these biases exactly off-set each other

when the percentage deviations from steady state of the inflation rate and the nominal interest rate are equal and the economy was initialized without heterogeneity (as in steady state).

2.2 Estimation

In order to meaningfully quantify the above channels, we now turn to an estimation of the model using Bayesian methods. We estimate the model on quarterly U.S. data ranging from 1980Q1 until 2007Q1 (109 observations). We consider four observables, three of which are relatively standard for such estimation exercises. These are consumption growth, CPI inflation, and the 3-month treasury bill rate. As a fourth observable, we use a measure of consumption heterogeneity.⁸ In particular, we use the cross-sectional variance of the logarithm of nondurable consumption. We take this time series from Heathcote, Perri, and Violante (2010) who calculate it from data of the Consumer Expenditure (CEX) Interview Survey.⁹

The advantage of this particular measure of consumption heterogeneity is that it can be linked to the variables in our model even though we only have two types of households. In particular, given that c_t^B and c_t^R already are log-linearized variables, we can calculate the cross-sectional variance of log consumption in our model as $\alpha(1 - \alpha)(c_t^B - c_t^R)^2$. In order to achieve convergence of our estimation, we have to assume the consumption heterogeneity in our model to be imperfectly observable. In particular, the estimation treats it as dynamic latent variable. This assumption is statistically reasonable (see Online Appendix F) as well as economically sensible, since the consumption heterogeneity data will have multiple causes while we focus on differences in cognitive sophistication only.

Since our consumption heterogeneity measure is quadratic, we estimate the model using a particle filter. For the estimation, we use a recent advance on the Metropolis Adjusted Langevin Algorithm (MALA) called fast MALA (fMALA), see Durmus et al. (2017). Further, to integrate out the latent variable, we use a particle Gibbs (PG) sampler (Andrieu, Doucet, and Holenstein 2010). In Online Appendix F, we present our estimation algorithms in detail. In addition to the three shocks introduced in Section 1, we allow for measurement errors for all observables.

For the estimation, we fix β , η , ω , and ϕ_b to values from the literature, as our small-scale model cannot identify all model parameters. For the remaining parameters, we set the following priors. For the fraction of boundedly rational households (α) and for the auto-correlation coefficients of shocks (ρ_v , ρ_μ , ρ_g), we set a Beta prior with mean 0.5 and standard deviation 0.2. For the inverse of the elasticity of intertemporal substitution (σ) and for the labor supply elasticity, we set a normal prior with mean 2 and standard deviations 1.5. For the Taylor rule

8. We are grateful to an anonymous referee for suggesting this.

9. We also seasonally adjust this time series using the X-13ARIMA-SEATS program and filter out a linear trend, which renders it stationary.

TABLE 1
PRIORS AND POSTERIOR MODES OF ESTIMATED MODEL

| Parameter | Posterior mode | Prior mean | Prior st. dev. | Prior distr. |
|-------------------------|----------------|------------|----------------|---------------|
| β | 0.99 | | | Fixed |
| α | 0.877 | 0.5 | 0.2 | Beta |
| σ | 3.845 | 2 | 1.5 | Normal |
| γ | 4.481 | 2 | 1.5 | Normal |
| ω | 0.75 | | | Fixed |
| η | 7.84 | | | Fixed |
| ψ | 0.0625 | 0.2 | 0.1 | Gamma |
| ϕ_π | 1.821 | 1.5 | 0.2 | Gamma |
| ϕ_ϵ | 0.2378 | 0.2 | 0.1 | Gamma |
| ϕ_b | 1 | | | Fixed |
| ρ_v | 0.9278 | 0.5 | 0.2 | Beta |
| ρ_μ | 0.8412 | 0.5 | 0.2 | Beta |
| ρ_g | 0.8503 | 0.5 | 0.2 | Beta |
| $\sigma_{\epsilon,v}$ | 0.0187 | 0.1 | 2 | Inverse Gamma |
| $\sigma_{\epsilon,\mu}$ | 0.0164 | 0.1 | 2 | Inverse Gamma |
| $\sigma_{\epsilon,g}$ | 0.0225 | 0.1 | 2 | Inverse Gamma |

parameters, we take Gamma priors with means 1.5 and 0.2 and standard deviations 0.2 and 0.1 for, respectively, inflation and output gap. For the responsiveness of boundedly rational households to differences in wealth (ψ), we also set a Gamma prior with mean 0.2 and standard deviation 0.1. Finally, the standard deviations of the four shocks have Inverse Gamma priors with mean 0.1 and standard deviation 2, while the measurement errors have Inverse Gamma priors with mean 0.01 and standard deviation 0.1.

In Table 1, we present the estimated posterior modes of all parameters used in the model together with the information on the respective priors. Further details on the estimation results and estimation checks are provided in Online Appendix F. The estimation results indicate that the majority of households are rational ($\alpha = 0.877$) and around 12% of households are boundedly rational. This is in line with the findings of Beqiraj, Di Bartolomeo, and Serpieri (2017), who find that between 5% and 30% of forecasters in the U.S. survey of professional forecasters are boundedly rational, with a point estimate of $\alpha = 0.82$. Our estimate is also in line with the experimental finding of Lustenhouwer and Salle (2022) that about 6% to 16% of subjects are not able to learn to respond to forward-looking information or do so only with a delay. Further noteworthy is that the posterior mode of the parameter ψ is approximately 0.06. This indicates that boundedly rational households indeed respond with their consumption decision to their relative wealth, but that the role of the wealth channel for business cycle dynamics is limited.

2.3 Impulse Response Functions

Using the above estimation results, we can now turn to a quantitative analysis of the difference components of the rationality bias and of the resulting differences in

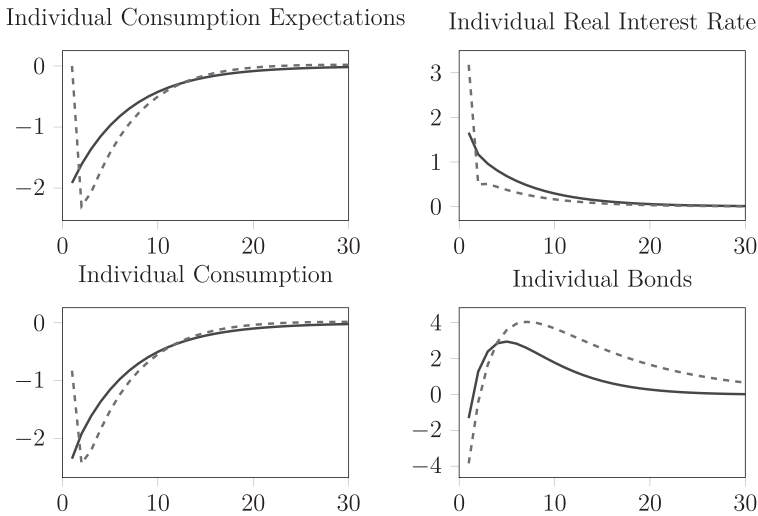


Fig 1. Impulse Responses of Individual Variables to a Persistent, One-Standard-Deviation Cost-Push Shock.
NOTES: The solid curves depict the individual variables of rational households and the dashed curves the individual variables of boundedly rational households.

consumption and wealth between boundedly rational and rational households in a dynamic setting. We will do this by studying the impulse response functions to a cost-push shock and to a preference shock.

Impulse responses to a cost-push shock. Figure 1 plots the impulse responses of a number of individual variables to a persistent, one-standard-deviation cost-push shock. This shock raises the inflation, to which the central bank responds by increasing the nominal interest rate. The bottom-left and bottom-right panels of Figure 1 show the paths of, respectively, consumption and bond holdings of the two household types. The dashed curves depict variables of boundedly rational households, whereas solid curves correspond to rational households.

As discussed in Section 2.1, the dynamics of the differences in these individual variables are driven by the components of the rationality bias. In Figure 1, there is no preference shock. Hence, the preference shock expectation bias is zero. Thus, we need to consider only two different components of the rationality bias: first, the consumption expectation bias and, second, the real interest rate bias. In order to see these biases at work, we need to consider subjective real interest rates of boundedly rational and rational households and their expectations about their own future consumption. These are plotted in the top-right and top-left panels of Figure 1, respectively.

Starting with the top-right panel, it can be seen that the subjective real interest rate of boundedly rational households differs from that of rational households. While the rational households' real interest rate (solid) increases by around 1.7% on impact,

the subjective real interest rate of boundedly rational households (dashed) initially increases by around 3.2%. This is because boundedly rational households base their inflation expectations “naively” on the previous period and have not yet observed the effects of the shock when they form expectations at the beginning of the shock period. Thus, they do not yet anticipate an increase in future inflation. The subjective real interest rate of boundedly rational households, hence, increases as much as the nominal interest rate. Rational households, on the other hand, already anticipate future inflation in the shock period, which implies a lower real interest rate. We can conclude that the real interest rate bias is positive in the first period.

However, from period 2 onward, inflation will gradually fall, as the effects of the shock slowly starts to die out. As a consequence, boundedly rational households—by basing their expectations on past inflation—consistently overestimate future inflation. This results in a subjective real interest rate that is persistently below the real rate of rational households, and hence, a negative real interest rate bias in these periods. Eventually, inflation expectations align when model variables approach the steady state, which also results in an alignment of the subjective real interest rates of both agent types.

These differences in subjective real interest rates can, however, not explain the differences in consumption and bond holdings observed in the bottom two panels of Figure 1. To better explain these dynamics, we need to consider the consumption expectation bias of boundedly rational households.

In the top-left panel of Figure 1, it can be seen that, in the shock period, rational households already expect lower future own consumption. This is because they correctly anticipate positive future real interest rates due to the shock persistence and the response of the central bank. Boundedly rational households, on the other hand, do not expect any deviations from steady state yet and hence expect zero future consumption. Boundedly rational households, hence, have a positive consumption expectation bias in the initial shock period. It turns out that this positive consumption expectation bias outweighs the positive real interest rate bias. As a consequence, boundedly rational households consume more than rational households in the initial shock period (see bottom-left panel).

In subsequent periods, boundedly rational households observe the drop in (aggregate) private consumption caused by the shock and underestimate future consumption. This leads to a negative consumption expectation bias. Again, this bias outweighs the real interest rate bias, so that boundedly rational households now consume less than rational households.

Next, consider the dynamics of individual wealth in the bottom-right panel of Figure 1. In the initial shock period, the higher consumption of boundedly rational households leads them to lose more bonds than rational households.¹⁰ On the other hand, in the medium-run, boundedly rational households are accumulating more

10. Even though households cut consumption, their real bond holdings initially go down due to high inflation.

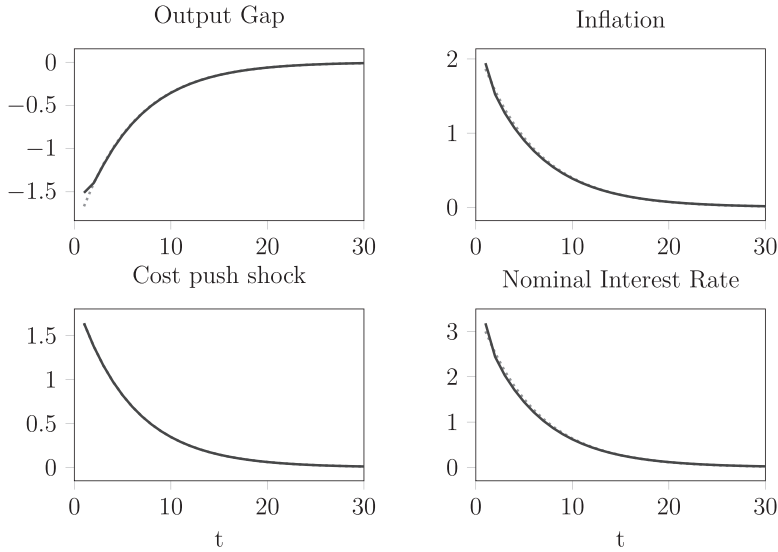


Fig 2. Impulse Responses of Aggregate Variables to a Persistent, One-Standard-Deviation Cost-Push Shock.

NOTES: The dotted curve in each panel shows the homogeneous rational benchmark, that is, $\alpha = 1$. The solid curves show the aggregate dynamics under heterogeneous rationality ($\alpha = 0.877$).

bonds than rational households as they are consuming less. Finally, as the model converges to steady state again, the bonds of both agent types align again. Note, though, that since rational households are fully optimizing using optimal linear forecasts, the consumption utility losses of boundedly rational households over the business cycle are higher than those of rational households by definition.

Finally, we consider the dynamics of aggregate variables. Impulse responses of these variables are depicted by the solid curves in Figure 2. The dotted curves in Figure 2 show a counterfactual simulation where we explore the case of homogeneous rational expectations. Here, we calculate a new set of impulse responses where we keep all parameters fixed but set $\alpha = 1$ so that all households are rational.

In the figure, it can be seen that, even though there is persistent heterogeneity in consumption and wealth after a cost-push shock, the presence of boundedly rational agents does not fundamentally alter the paths of aggregate variables after this shock. It can however be observed that output falls less on impact under heterogeneous rationality. This is driven by the higher initial consumption of boundedly rational agents due to their consumption expectation bias, as discussed above.

Impulse responses to a preference shock. Next, we consider the impulse responses to a persistent, one-standard-deviation preference shock. Before we turn to the responses of individual variables and the components of the rationality bias, we present the impulse responses of aggregate variables in Figure 3. Just as in Figure 2, we show the IRFs (impulse response functions) of the estimated heterogeneous rationality model

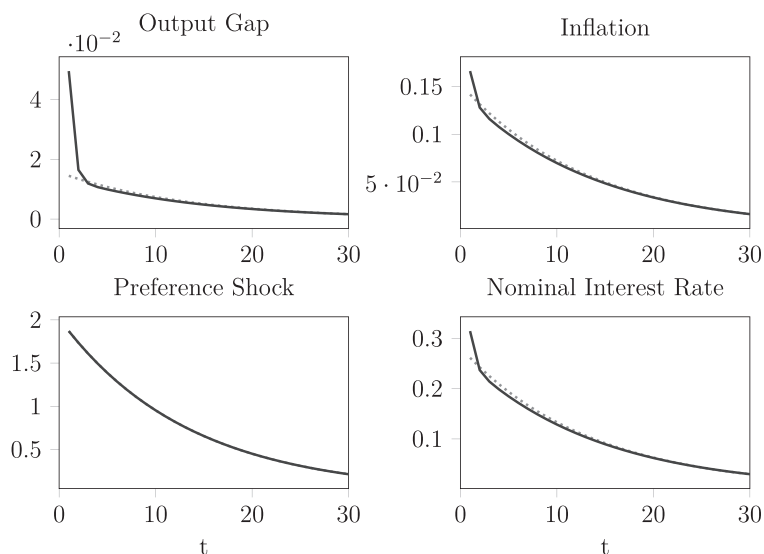


Fig 3. Impulse Responses of Aggregate Variables to a Persistent, One-Standard-Deviation Preference Shock.

NOTES: The dotted curve in each panel shows the homogeneous rational benchmark, that is, $\alpha = 1$. The solid curves show the aggregate dynamics under heterogeneous rationality ($\alpha = 0.877$).

as solid curves and the IRFs of the counterfactual case where α is set to 1 as dotted curves.

The top-left panel of Figure 3 shows that, for the counterfactual case of $\alpha = 1$, the preference shock only marginally increases the output gap. This is due to the high persistence of the shock as well as due to the monetary policy response. For the solid curves in Figure 3, the story is quite different. Here, there is a much larger increase in the output gap on impact. This result is mainly driven by one of the three components of the rationality bias: the preference shock expectation bias.

Unlike for rational households, the expectations of boundedly rational households are not yet affected by the shock in the initial shock period. Thus, boundedly rational households expect a zero future shock realization and have a considerable negative preference shock expectation bias in the shock period. This puts upward pressure on their consumption, as can be observed in the bottom-left panel of Figure 4, which depicts the impulse responses of the same individual variables as above.

From period 2 onward, boundedly rational households consistently overestimate the future shock realization. These households, then, have a negative preference shock expectation bias, which puts downward pressure on their consumption. This explains why boundedly rational consumption is below rational consumption in these periods.

Of course, the other two components of the rationality bias also play a role in explaining the exact difference in consumption between rational and boundedly rational

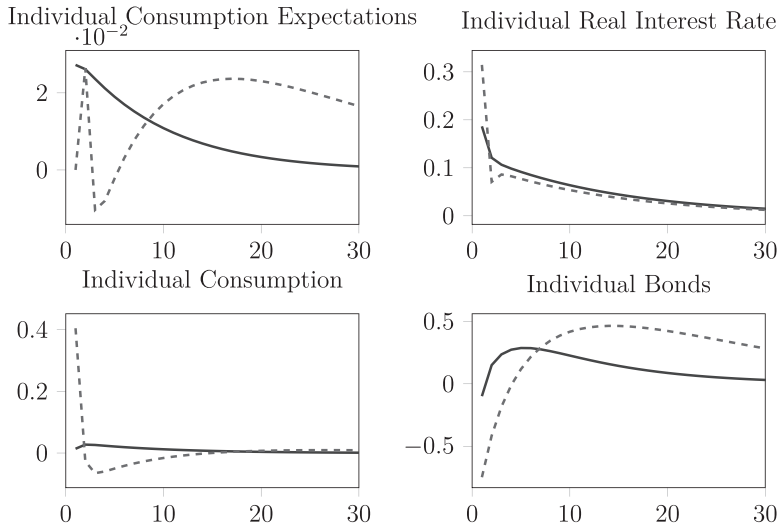


Fig 4. Impulse Responses of Individual Variables to a Persistent, One-Standard-Deviation Preference Shock.

NOTES: The solid curves depict the individual variables of rational households and the dashed curves the individual variables of boundedly rational households.

households. In particular, in the top-right panel of Figure 4, it can be seen that the subjective real interest rate of boundedly rational households initially is higher than that of rational households and then lower, just as in the case of a cost-push shock. The real interest rate bias, hence, works in the opposite direction as the preference shock expectation bias in all periods. The latter bias, however, always dominates the former.

As regards to the consumption expectation bias, boundedly rational households have considerably lower aggregate consumption expectations than rational households in the initial shock period. In the next period, the large observed output gap and consumption realizations lead boundedly rational households to increase their consumption expectations. From period 3 onward, expectations about the output gap and aggregate consumption play a relatively minor role. Instead, the consumption expectation bias is driven by the wealth channel in these periods. This channel first leads boundedly rational households to expect less future own consumption—when they are relatively poorer—and later leads them to expect more future own consumption—when they are relatively richer. As a consequence, the consumption expectation bias reinforces the preference shock expectation bias in some period but partly counteracts it in other periods.

Bounded optimality versus boundedly rational expectations. As mentioned in Section 2.1, boundedly rational households make consumption decisions that are different from that of rational households for two reasons: the bounded rationality of their expectations about aggregate variables and the bounded optimality of their consumption decision rule given their expectations (as described by (13)). In order to

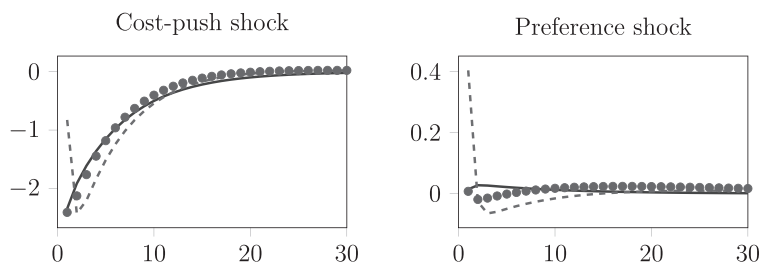


Fig 5. Impulse Responses of Individual Consumption to Different Shocks.

NOTES: The solid curves depict consumption of rational households, the dashed curves the consumption of boundedly rational households, and the dots the consumption of a hypothetical agent with bounded optimality but rational expectations about aggregate variables.

decompose somewhat more finely to what extent consumption differences in the IRF's above are driven by the expectation formation rule and to what extent they are caused by boundedly optimal decision making of boundedly rational households, we can consider the following exercise.

Suppose that, in addition to a fraction α of rational households and a fraction $(1 - \alpha)$ of boundedly rational households, there is—in any period—an individual household with infinitely small mass, that forms its consumption decision according to (13), like boundedly rational households. However, this hypothetical agent forms model-consistent expectations about aggregate variables, so that the expectations entering in (13) for this agent are rational expectations. This infinitely small agent would not affect aggregate dynamics, and hence would not alter the decisions of rational and boundedly rational households. We can therefore, in any period, directly compare the consumption of boundedly rational and rational households with the level of consumption that the hypothetical agent would choose. For each period, we will assume that the hypothetical agent has the same bond holdings as a boundedly rational households in that period, so that we can compare the decision of the hypothetical agent with that of boundedly rational households more directly.¹¹

In Figure 5, we again plot the IRFs of consumption that were also shown in the bottom-left panels of Figures 1 and 4. To these graphs, we now add the dots that correspond to the consumption of the hypothetical agent. For both shocks, it can be seen that the rationality bias is mostly driven by the aggregate expectations of boundedly rational households. If these expectations would have been rational (the dot of the hypothetical agent), consumption of a boundedly rational households would have been quite close to the consumption of rational households (solid).

11. One way to think of this is that we pick a new boundedly rational household to be our hypothetical agent in each period. The evolution of the bond holdings up to the previous period of that agent can then be assumed to have coincided with that of boundedly rational households.

3. THE RATIONALITY BIAS AND MONETARY POLICY

So far, we have decomposed the rationality bias into three individual components and estimated the model to quantify the effects of these components in light of shocks. In this section, we study how the rationality bias interacts with monetary policy and consider some policy implications.

3.1 Eliminating the Rationality Bias

It turns out that the magnitude of the rationality bias directly depends on monetary policy. In particular, depending on monetary policy, the rationality bias can completely be eliminated. In order to prove this and to provide intuition, we first present the following two lemmas:

LEMMA 1. *If the log-deviations from steady state of the nominal interest rate and the inflation rate are equal in every period, then rational consumption is given by*

$$c_t^R = -\frac{1}{\sigma}(\pi_t - v_t). \quad (29)$$

LEMMA 2. *If the log-deviations from steady state of the nominal interest rate and the inflation rate are equal in every period, then in any period where $c_t^R = c_t^B$ and $b_t^B = b_t$ (i.e., no consumption or wealth heterogeneity), it must hold that*

$$\frac{1}{1 - \bar{g}}(y_t - \bar{g}g_t) + \frac{1}{\sigma}(\pi_t - v_t) = 0. \quad (30)$$

The proofs of these two lemmas as well as the proof of our main proposition, which we state below, are given in Online Appendix B.

PROPOSITION 1. *Let the log-deviations from steady state of the nominal interest rate and the inflation rate be equal in every period. Then*

- (a) *if, in any period, there is no consumption and wealth heterogeneity, there will also be no consumption and wealth heterogeneity in all future periods: (i) when boundedly rational expectations are proportional to the most recent observation of the variable being forecast; or (ii) when boundedly rational expectations are a linear combination of rational expectations and the most recent observation of the variable being forecast.*
- (b) *If the model starts out with a history of no consumption and wealth heterogeneity, there will also be no consumption and wealth heterogeneity in all future periods: (i) when boundedly rational expectations can be written as a linear combination of the past realizations of the variable being forecast; or (ii) when boundedly rational expectations can be written as a linear combination of past realizations of the variable being forecast and current and past rational expectations.*

These results hold independently of (future) shock realizations.

Part a(i) of Proposition 1 implies that, if the model starts out with a period of no heterogeneity in consumption and wealth, shocks to the economy will not cause such heterogeneity as long as inflation and the nominal interest rate coincide. This part of the proposition concerns all expectations of the form $E_t^B z_{t+1} = \theta z_{t-1}$ and thereby a more general class of boundedly rational expectations than the naive expectations rule that we assumed in the model we estimated. Part a(ii) further generalizes this to, among others, a form of “natural expectations” of Fuster, Laibson, and Mendel (2010): $E_t^B z_{t+1} = \theta_n E_t z_{t+1} + (1 - \theta_n) z_{t-1}$.

Part b(i) concerns a larger class of boundedly rational expectations that, among others, also includes adaptive expectations of the form $E_t^B z_{t+1} = (1 - \theta_a) E_{t-1}^B z_t + \theta_a z_{t-1}$ and trend following expectations such as $E_t^B z_{t+1} = z_{t-1} + \theta_{tr}(z_{t-1} - z_{t-2})$. Finally, part b(ii) of the proposition also covers cases such as sticky expectations, $E_t^B z_{t+1} = (1 - \theta_{st}) E_t z_{t+1} + \theta_{st} E_{t-1}^B z_{t+1}$, and forward-looking extrapolative expectations, $E_t^B z_{t+1} = E_t z_{t+1} + \theta_{fw}(z_{t-1} - E_{t-2} z_{t-1})$.¹²

For parts b(i) and b(ii) of the proposition, the model must start in an initial state with a history of no consumption and wealth heterogeneity. If this is the case, then it again holds that shocks will not cause heterogeneity in consumption and wealth and thus that the heterogeneity will remain absent in all future periods.

Note that the assumption that the model is initialized with no consumption and wealth heterogeneity is not as restrictive as it may seem. In particular, when the well-known Taylor principle is satisfied, our model is stable and determinate. Heterogeneity would, in the absence of shocks, then always disappear over time as the model converges to steady state. Moreover, Proposition 1 states that, when its conditions are satisfied, shocks do not lead to a rationality bias. It is, therefore, intuitive that, also in the presence of shocks, consumption and wealth heterogeneity would disappear over time when $i_t = \pi_t$ in every period.

We find that this is indeed the case. When we initialize simulations of the model with wealth and consumption heterogeneity and shock the model in every period, differences in consumption and bond holdings between the two household types quickly go to zero.

To understand the intuition of Proposition 1, recall the different components of the rationality bias depicted in equation (28). From Lemma 1, it follows that the rational expectation of rational consumption is $E_t c_{t+1}^R = -\sigma^{-1}(E_t \pi_{t+1} - E_t v_{t+1})$. Also, from Lemma 2 and the assumed form of boundedly rational expectations, it follows that $(1 - \bar{g})^{-1}(E_t^B y_{t+1} - \bar{g} E_t^B g_{t+1}) = -\sigma^{-1}(E_t^B \pi_{t+1} - E_t^B v_{t+1})$.

12. See, for example, Coibion and Gorodnichenko (2015), Fuhrer (2018), Ma et al. (2018), Hagenhoff and Lustenhouwer (2023) for empirical evidence in favor of these types of expectations.

Equation (28) then reduces to

$$\begin{aligned} \Delta_i c_t^i = c_t^B - c_t^R = & -\frac{1}{\sigma} \underbrace{(E_t^B \pi_{t+1} - E_t^B v_{t+1} - (E_t \pi_{t+1} - E_t v_{t+1}))}_{\text{consumption exp. bias}} \\ & + \underbrace{\frac{1}{\sigma} (E_t^B \pi_{t+1} - E_t \pi_{t+1})}_{\text{neg. real int. bias}} - \underbrace{\frac{1}{\sigma} (E_t^B v_{t+1} - E_t v_{t+1})}_{\text{preference shock exp. bias}} = 0. \end{aligned} \quad (31)$$

In equation (31), it can be seen that the consumption expectation bias, the real interest rate bias, and the preference shock expectation bias *exactly off-set* each other, even though the individual components may very well be different from zero. Hence, Proposition 1 implies that boundedly rational households act *as if* they were rational, so that the difference $\Delta_i c_t^i$ is zero, but that they do so for different reasons than rational households. Finally, note that the proposition holds for any fraction of rational households, α .

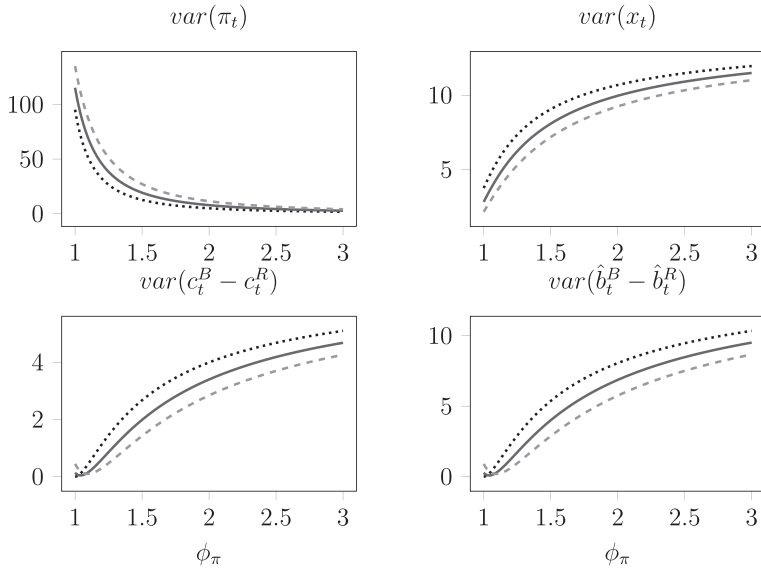
3.2 Monetary Policy Trade-Offs

A possible implementation of Proposition 1 is setting $\phi_\pi = 1$ and $\phi_x = 0$ in the Taylor rule. This would, however, imply that the model is infinitely close to being indeterminate. Indeterminacy issues can be solved by setting ϕ_π slightly bigger than 1 or ϕ_x slightly bigger than 0, which would still approximately implement Proposition 1. Note, though, that such a weak response of monetary policy implies increased aggregate volatility in the economy. It may, therefore, not be desirable for a central bank to implement a policy where the bias is (almost) completely eliminated.

To study further the trade-offs faced by the central bank, we present the theoretical variances of inflation, output gap, and consumption and wealth differences in Figure 6. These theoretical variances are calculated for a range of values of ϕ_π , which is varied along the horizontal axis. The solid curves correspond to the case where ϕ_x is equal to its posterior mode from Table 1 ($\phi_x = 0.24$). The dotted and dashed curves depict the cases where we, instead, respectively set $\phi_x = 0$ and $\phi_x = 0.5$. All other parameters, including standard deviations and autocorrelations of shocks, are set to their posterior modes from Table 1.

The top two panels display the standard monetary policy trade-off that arises when cost-push shocks are present: a stronger response of monetary policy to inflation stabilizes inflation more but output gap less, whereas a stronger response to output gap does the opposite.

In the bottom-left panel, we focus first on the case of $\phi_x = 0$ (dotted). Here it can, first of all, be seen that the theoretical variance of the rationality bias goes to 0 as ϕ_π goes to 1, in line with Proposition 1. Second, the curve is upward sloping, just like the theoretical output gap variance in the top-right panel. That is, a more hawkish response to inflation increases not only output gap volatility but also the volatility of the rationality bias.

Fig 6. Theoretical Variances as a Function of ϕ_π .

NOTES: The solid curves correspond to the case where ϕ_x is equal to its posterior mode from Table 1 ($\phi_x = 0.24$). The dotted and dashed curves correspond to $\phi_x = 0$ and $\phi_x = 0.5$, respectively.

Next, consider the solid and dashed curves in the bottom-left panel. Comparing all three curves, it can be seen that a stronger response to output gap reduces volatility in the rationality bias if ϕ_π is large enough. For very small values of ϕ_π , on the other hand, a more aggressive response to the output gap increases the variance of the rationality bias. Interestingly, from the low values attained at the minima of the solid and dashed curves, it appears that, for these values of $\phi_x > 0$, values of $\phi_\pi > 1$ can be found that almost implement Proposition 1 and almost eliminate the rationality bias.

Finally, a quick comparison of the bottom-right and bottom-left panel shows that volatility in wealth difference practically mirrors volatility in the rationality bias. This is intuitive since, in our model, wealth differences arises as a direct consequence of differences in consumption between rational and boundedly rational households.

How the central bank should deal with the trade-offs between stabilizing inflation, output gap, and the rationality bias depends on the relative importance that is attributed to each of these variables. One approach for judging this is to calculate welfare in the model by assuming individual preferences can be aggregated by simply summing up their utilities. In Online Appendix C, we show that, un-

der this assumption, the second-order approximated aggregate utility loss is given by¹³

$$L_t \simeq a_1 \text{var}(x_t) + a_2 \text{var}(\pi_t) + a_3 \text{var}(c_t^B - c_t^R) \quad (32)$$

with

$$a_1 = \left[\gamma + \frac{\sigma}{(1 - \bar{g})} \right], \quad (33)$$

$$a_2 = \frac{\eta}{\delta}, \quad (34)$$

$$a_3 = \alpha(1 - \alpha) \left[(1 - \bar{g})\sigma + \frac{\sigma^2}{\gamma} \right]. \quad (35)$$

Under the calibration of Section 2.2, the weight a_2 on inflation volatility is around 10 times larger than the weight on output gap volatility, a_1 , and more than 20 times as large as the weight on the variance of the rationality bias, a_3 . This reflects a very strong distaste of agents in this economy for inflation volatility and a rather minor distaste for volatility in the rationality bias and in the output gap. Thus, even though the third term in equation (32) disappears when Proposition 1 is implemented, the corresponding increase in inflation volatility will lead to a considerably higher welfare loss.

Note that such a strong dislike for inflation volatility is inherent to this type of New Keynesian model and also arises for different parameterizations of the model; see, for example, Galí (2015), Woodford (2003), Di Bartolomeo, Di Pietro, and Giannini (2016), and Debortoli and Galí (2017) for loss functions in similar models. This stems from the assumption of a constant Calvo parameter, that is, the probability for an individual firm of being able to reset its price in any given period is constant. Therefore, in the absence of an endogenous frequency of price adjustments, inflation would quickly result in very large welfare losses.

Hence, it is not obvious that such a large weight on minimizing inflation volatility is a realistic representation of a real-world social planner's objective function. In order to obtain broader insights, we will, therefore, additionally consider a different loss function that takes the same form as (32), but where we assume equal weights on the three objectives. That is, we set $a_1 = a_2 = a_3 = \frac{1}{3}$.

For both these specifications for the loss function, we calculate the optimal value of ϕ_π , as well as the corresponding loss, for a range of values of ϕ_x . The results are plotted in Figure 7 where the left panels correspond to the welfare function that is derived from the second-order approximation of the sum of household utilities and the right panels correspond to the equally weighted loss function. The solid curves

13. This loss function is somewhat different from the loss function derived in Di Bartolomeo, Di Pietro, and Giannini (2016) because their model also features heterogeneous expectations in price setting decisions, whereas we isolate the effects of heterogeneity in *household* rationality. In particular, price dispersion in their loss function does not only depend on inflation volatility but also on some further variables that appear because of differences in expectations of price setters about future marginal costs.

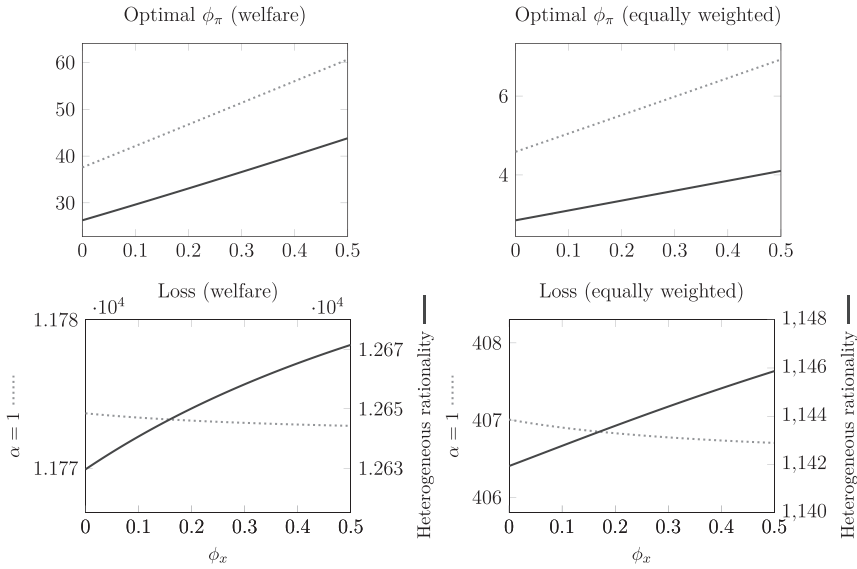


Fig 7. Optimal Coefficient ϕ_π (Top Panels) and Corresponding Value of the Loss Function (Bottom Panels) for Different Values of ϕ_x (Varied Along the X-Axis).

NOTES: The left panels correspond to the case of a loss function that represents welfare whereas the right panels correspond to the case of $a_1 = a_2 = a_3 = \frac{1}{3}$.

depict the results for our calibrated heterogeneous rationality model. We compare this with the counterfactual case where we set $\alpha = 1$ so that all households are rational. This case is plotted as dotted curves.

For both loss functions, it can be seen in the top panels that the solid curves lie below and have a flatter slope than the dotted curves. This means that, for a given value of ϕ_x , the central bank should respond *less strongly* to inflation under heterogeneous rationality than would be optimal under homogeneous rational expectations.

Furthermore, in both bottom panels, the slopes of the solid and dotted curves are qualitatively different from each other. The dotted curves are always downward sloping, at a marginally decreasing rate. This implies that, for the case of homogeneous rational expectations, it is always optimal for the central bank to increase its coefficient on output gap in the Taylor rule (as long as the coefficient on inflation is increased accordingly as well). The marginal gains of such an increase become, however, smaller and smaller.

In our calibrated model with $\alpha = 0.877$, a quite different picture arises. In both bottom panels the, the solid curve is monotonically upward sloping. This means that it is optimal for the central bank to not react to the output gap at all. Combining this finding with the bottom two panels, it turns out that the optimal Taylor rule coefficient under our estimated model of heterogeneous rationality are $\phi_\pi = 26.27$ and $\phi_x = 0$

for the welfare-based loss function and that they are $\phi_\pi = 2.85$ and $\phi_x = 0$ for the equally weighted loss function.

All in all, we can conclude that the presence of boundedly rational households and the rationality bias imply that the central bank should set lower coefficients in the Taylor rule.¹⁴

The intuition for this is that a less aggressive response of the central bank to inflation reduces the rationality bias, as discussed above. Correspondingly, this leads to a reduction in consumption heterogeneity and an improvement in the objective function. For the case of homogeneous rational expectations, the central bank need not be concerned about consumption heterogeneity. Therefore, there is no pressure for the central bank to be less hawkish, and the optimization of the objective function, instead, prescribes a more aggressive response to both inflation and output gap.

4. CONCLUSION

We build a macro-economic model with different degrees of rationality. While rational households are indeed fully rational, boundedly rational households follow the less cognitive demanding Euler-equation learning and use a simpler forecasting heuristic to form expectations such as naive expectations. Using Bayesian methods, we estimate the fraction of rational households to be around 88%. Because both household types make different decisions, substantial consumption and wealth heterogeneity arises when the economy is hit by shocks. We show that the rationality bias of boundedly rational households that drives these different decisions can be decomposed into three components: the consumption expectation bias, the real interest rate bias, and the preference shock expectation bias.

Further, we show that, for a large class of boundedly rational expectation formation rules, certain monetary policy can eliminate the rationality bias, no matter what shocks hit the economy. In this case, the components of the rationality bias exactly offset each other while they are nonzero individually. Moreover, in the estimated model, we find that a more hawkish response to inflation leads to more volatility in consumption and wealth differences. This implies that the central bank faces an additional monetary policy trade-off. As a consequence, it becomes optimal for the central bank to set lower coefficients in the Taylor rule than would have been the case under homogeneous rational expectations.

14. Note that this result appears not to be in line with the experimental findings of, for example, Asensza et al. (2021) and Mauersberger (2021). The reason for this is that we isolate the effects of heterogeneity and bounded rationality of households. In these studies, on the other hand, results are largely driven by the bounded rationality of firms. In particular, inflation expectations of human subjects are also plugged into firm equations, and, because of this, relatively weak monetary policy results in strong positive feedback of subject's inflation expectations. This results in self-fulfilling inflation drifts as well as volatility in all parts of the experimental economies in a way that would not arise if firms were modeled as fully rational.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table 1: Posterior statistics

Figure 1: Trace plots for selected parameters

Figure 2: Autocorrelation functions of selected parameters

Figure 3: L_t and Λ_t

Table 2: Forecast error variance decomposition

Figure 4: Impulse responses of aggregate variables to a persistent, one-standard-deviation government spending shock.

Figure 5: Impulse responses of aggregate variables to a persistent, one-standard-deviation government spending shock.