

Monetary Policy & Anchored Expectations

An Endogenous Gain Learning Model

By LAURA GÁTI*

This paper analyzes monetary policy in a model that accounts for the unanchoring of inflation expectations. The extent of anchoring is determined by an adaptive learning mechanism in which the public's learning gain varies endogenously. Within an otherwise standard macro model with nominal rigidities, I find that optimal policy involves an aggressive interest rate response to expectations unanchoring. This stabilizes both inflation expectations and inflation. Furthermore, I estimate the model-implied relationship that determines the extent of unanchoring. The data suggest that the expectation process is nonlinear: expectations exhibit a higher sensitivity to large forecast errors than to smaller ones.

Inflation that runs below its desired level can lead to an unwelcome fall in *longer-term inflation expectations*, which, in turn, can pull actual inflation even lower, resulting in an adverse cycle of ever-lower inflation and inflation expectations. [...] *Well-anchored inflation expectations* are critical[.]

Jerome Powell, Chairman of the Federal Reserve¹
(*Emphases added.*)

There is broad consensus among policymakers that anchoring inflation expectations is central to the modern conduct of monetary policy. As Powell emphasizes, policymakers think of expectations as anchored when long-run expectations do not fluctuate systematically with short-run inflation surprises. If long-run expectations did respond to short-term inflation surprises, policymakers fear this would result in an adverse cycle of self-enforcing movements in expectations.

This paper studies the conduct of monetary policy in a New Keynesian model where the degree of expectations anchoring responds endogenously to economic conditions. The main contribution is providing a new theory of monetary policy in which expectations exhibit endogenously varying degrees of unanchoring. The key innovation in my model is the introduction of a continuously variable endogenous gain function, which allows my model to capture the time-varying sensitivity of long-run expectations to short-run conditions. I take the model to the data to quantify my novel anchoring mechanism, and use it to characterize optimal policy analytically and numerically.

* Boston College, 140 Commonwealth Avenue, Chestnut Hill, MA 02467, gati@bc.edu.

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Fig. 1 provides some motivating evidence for continuously time-varying levels of unanchoring. It shows the regression coefficient of a rolling window regression of long-run inflation expectations on short-run forecast errors. Letting $\bar{\pi}_t^i$ denote the 10-year inflation expectation of forecaster i from the Survey of Professional Forecasters (SPF), and $f_{t|t-1}^i \equiv \pi_t - \mathbb{E}_{t-1}^i \pi_t$ denote forecaster i 's one-year ahead forecast error, I run

$$(1) \quad \Delta \bar{\pi}_t^i = \beta_0^w + \beta_1^w f_{t|t-1}^i + \epsilon_t^i,$$

where w indexes windows of 20 quarters. Fig. 1 plots the time series of the estimated coefficient $\hat{\beta}_1^w$, along with 90% and 95% confidence intervals.²

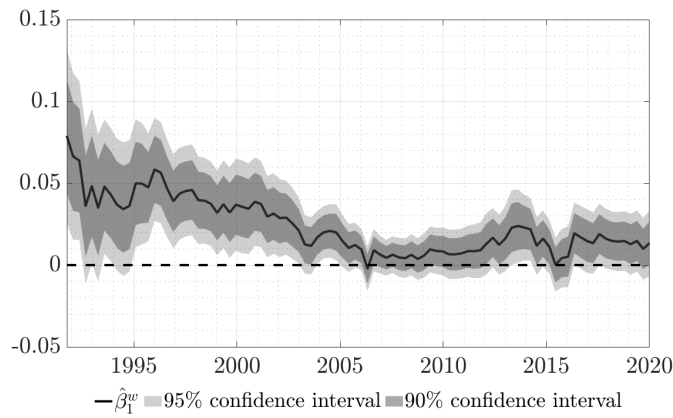


FIGURE 1. TIME SERIES OF RESPONSIVENESS OF LONG-RUN INFLATION EXPECTATIONS TO INFLATION SURPRISES

As seen on Fig. 1, the relationship between 10-year inflation expectations and one-year surprises, $\hat{\beta}_1^w$, is time-varying. Up to about 2005, $\hat{\beta}_1^w$ is positive and significant, with varying magnitude. Between 2005 and 2010, by contrast, it is not significantly different from zero. In this period, then, long-run expectations were unresponsive to short-run conditions. Around 2010, this changed once more. A significantly positive $\hat{\beta}_1^w$ since 2010 indicates that on several occasions in the last ten years, short-run inflation surprises were passed through to long-run expectations.

In order to provide a convincing analysis of optimal policy in an environment with time-varying unanchoring, I need a qualitatively and quantitatively realistic model of expectation formation. To this end, I build on new work by Carvalho et al. (2019), who model the anchoring of expectations as a discrete gain function that determines whether agents learn about long-run inflation using a small or

²Appendix A presents robustness checks. Appendix B discusses alternative measures of long-run inflation expectations.

large weight on past expectations errors. My methodological contribution is to extend this work along two dimensions. First, I embed an anchoring model of expectation formation in a general equilibrium New Keynesian model, allowing me to formally consider the monetary policy problem. Second, I use a continuous gain function, capturing the time-varying degrees of unanchoring in the data.

As an empirical contribution, I bring my smooth gain function to the data to explore the functional form describing the anchoring of expectations. Calibrating the parameters of the New Keynesian core of my model, I employ a simulated method of moments estimation strategy (Duffie and Singleton (1990), Lee and Ingram (1991), Smith (1993)) to back out a piecewise linear approximation to the true functional form in the data. The estimation results show that my novel gain function has several reasonable properties. First, I estimate an implied gain time series with a median of 0.098, very close to the values obtained by Milani (2014) and Carvalho et al. (2019) (0.082 and 0.145 respectively). This number means that, on average, agents in the model put the bulk of weight on the 10 most recent quarters of data when updating their long-run expectations. Most importantly, the expectations process is nonlinear: larger forecast errors in absolute value lead to a higher sensitivity of long-run expectations. In line with other studies, like Hebden et al. (2020), I also find that a forecast error of a particular size leads to higher gains if its sign is negative than if it is positive. In other words, negative inflation surprises unanchor expectations more than same-sized positive mistakes.

Having calibrated the model to the data, and establishing that it provides a realistic description of expectations, I perform my analysis of policy in the model in three stages. First, I present an analytical characterization of the Ramsey problem of the monetary authority. I demonstrate that the first-order condition of the Ramsey problem delivers a target criterion for the policymaker. The target criterion prescribes that the central bank should smooth out the effects of shocks by taking advantage of the current and future expected degree of unanchoring.

Second, I solve the optimality conditions of the Ramsey problem numerically. Because the endogenous gain function renders the model nonlinear, I rely on global methods to obtain the optimal policy function. Like the degree of unanchoring, the optimal interest-rate setting is time-varying. Since the interest rate responds to movements in long-run expectations, the monetary authority acts aggressively when expectations unanchor. When expectations are well-anchored, by contrast, the central bank accommodates fluctuations in inflation.

Third, I consider the class of simple, time-invariant Taylor rules that constitute the most common specification of monetary policy in practice. I solve for the optimal response coefficient of the interest rate to inflation numerically in the case of both the anchoring and the rational expectations versions of my model. It turns out that the central bank finds it optimal to respond less to inflation under anchoring than under rational expectations. The reason is that under the anchoring expectation formation, there is positive feedback between expectations and observables. Therefore aggressive interest rate movements lead to a high

volatility of expectations, which feeds back into inflation and output. Moreover, although the Taylor rule is not fully optimal in the model, an optimally chosen inflation coefficient does a good job in eliminating most of the volatility coming from unanchored expectations.

The paper is related to two main strands of literature. The model I use to study the interaction between monetary policy and anchoring is a behavioral version of the standard New Keynesian (NK) model of the type widely used for monetary policy analysis. Monetary policy in the rational expectations (RE) version of this model has been studied extensively, for example in Clarida, Gali and Gertler (1999) or Woodford (2003). The formulation of a target criterion to implement optimal policy is in the tradition of Svensson (1999).

The behavioral part of the model is the departure from rational expectations on the part of the private sector. Instead, I allow the private sector to form expectations via an adaptive learning scheme, where the learning gain - the parameter governing the extent to which forecasting rules are updated - is endogenous. The learning framework represents an extension to the adaptive learning literature advocated by Evans and Honkapohja (2001). This literature replaces the rational expectations assumption by postulating an ad-hoc forecasting rule, the perceived law of motion (PLM), as the expectation-formation process. Agents use the PLM to form expectations and update it in every period using recursive estimation techniques. My contribution to this literature is to study optimal monetary policy in a learning model with an endogenous gain.

Adaptive learning is an attractive alternative to rational expectations for several reasons. First, many studies document the ability of adaptive learning models to match empirical properties of both expectations and macro aggregates. Adaptive learning models imply that forecast errors are correlated with forecast revisions, a feature of expectations documented by Coibion and Gorodnichenko (2015). In fact, the prediction of adaptive learning models concerning the response of expectations to shocks exactly aligns with new evidence by Angeletos, Huo and Sastry (2020), suggesting that in response to shocks, expectations initially underreact, and then overshoot. As for the macro evidence, Milani (2007) demonstrates that estimated constant gain learning models match the persistence of inflation without recourse to backward-looking elements in the Phillips curve. Eusepi and Preston (2011) show that a calibrated adaptive learning version of the real business cycle (RBC) model outperforms the rational expectations version. In particular, even with a small gain, the learning model leads to persistent and hump-shaped responses to iid shocks, resolving the long-standing critique of RBC models of Cogley and Nason (1993).

Secondly, having an endogenous gain improves the empirical properties of adaptive learning models further. Milani (2014) documents that endogenous gain models can generate endogenous time-varying volatility in models without any time-variation in the exogenous processes. Additionally, Carvalho et al. (2019) estimate the evolution of the endogenous gain for the last fifty years in the US.

Not only does their model display excellent out-of-sample forecasting performance in terms of matching long-run expectations, but the estimated gain time series invites a reinterpretation of the Great Inflation as a period of unanchored expectations.

Thirdly, an extensive experimental literature in the spirit of Anufriev and Hommes (2012) demonstrates that simple adaptive learning rules provide the best fit among competing models to how individuals form expectations in controlled lab settings. In fact, the idea that individuals in the economy do not know the true underlying model and thus rely on simple, estimated heuristics to form expectations is intuitive from an economic perspective. Economists do not know the true model of the economy, so why should firms and households? And just like an econometrician estimates statistical models to form forecasts of relevant variables, it is reasonable to suppose that the private sector does so too.

My work is also related to the literature attempting to explain features of expectations data using departures from the full information rational expectations (FIRE) paradigm. This literature consists of two main lines of attack. The first is relaxing the assumption of full information. In this body of work, information is either not fully or not symmetrically available, or information acquisition is costly (Mankiw and Reis (2002), Sims (2003), Mackowiak and Wiederholt (2009), Angeletos and Pavan (2009)). The second strand of this literature, to which this paper belongs, instead emphasizes that expectation formation departs from rational expectations. One example of this literature is Sargent (1999), who explores the role of adaptive learning on the part of the Federal Reserve for the Great Inflation. A more recent example is Bordalo, Gennaioli and Shleifer (2018). These authors complement the empirical results of Coibion and Gorodnichenko (2015) with new evidence to suggest that the pattern of over- and underreaction to news is consistent with diagnostic expectations instead of dispersed information. My model of anchored expectations is also consistent with these data facts.

The paper is structured as follows. Section I introduces the model. Section II describes the learning framework and spells out the anchoring mechanism. Section III estimates the anchoring function. Section IV presents the results in three parts. First, Section IV.A discusses an analytical characterization of the Ramsey policy. Second, Section IV.B solves for the interest rate sequence that implements the optimal Ramsey allocation using global methods. Third, Section IV.C investigates the optimal choice of response coefficients if monetary policy is restricted to follow a Taylor rule. Section V concludes.

I. The model

Apart from expectation formation, the model is a standard New Keynesian (NK) model with nominal frictions à la Calvo (1983). The advantage of having a standard NK backbone to the model is that one can neatly isolate the way the anchoring mechanism alters the behavior of the model. Since the mechanics of the rational expectations version of this model are well understood, I only lay out

the model briefly and pinpoint the places where the assumption of nonrational expectations matters.³

A. Households

The representative household is infinitely-lived and maximizes expected discounted lifetime utility from consumption net of the disutility of supplying labor hours:

$$(2) \quad \hat{\mathbb{E}}_t^i \sum_{T=t}^{\infty} \beta^{T-t} \left[U(C_T^i) - \int_0^1 v(h_T^i(j)) dj \right].$$

In the above, the only non-standard element is the expectations operator, $\hat{\mathbb{E}}^i$. As detailed in Section II, this operator captures non-rational expectations and is assumed to satisfy the law of iteration expectations, so that $\hat{\mathbb{E}}_t^i \hat{\mathbb{E}}_{t+1}^i = \hat{\mathbb{E}}_t^i$. The remaining elements are familiar from the rational expectations version of the NK model. $U(\cdot)$ and $v(\cdot)$ denote the utility of consumption and disutility of labor, respectively, and β is the discount factor of the household. I am using standard CRRA utility of the form $U(c_t) = \frac{c_t^{1-\sigma}}{1-\sigma}$. $h_t^i(j)$ denotes the supply of labor hours of household i at time t to the production of good j , and the household participates in the production of all goods j . Similarly, household i 's consumption bundle at time t , C_t^i , is a Dixit-Stiglitz composite of all goods in the economy:

$$(3) \quad C_t^i = \left[\int_0^1 c_t^i(j)^{\frac{\theta-1}{\theta}} dj \right]^{\frac{\theta}{\theta-1}},$$

where $\theta > 1$ is the elasticity of substitution between the varieties of consumption goods. Denoting by $p_t(j)$ the time- t price of good j , the aggregate price level in the economy can then be written as

$$(4) \quad P_t = \left[\int_0^1 p_t(j)^{1-\theta} dj \right]^{\frac{1}{\theta-1}}.$$

The budget constraint of household i is given by

$$(5) \quad B_t^i \leq (1 + i_{t-1})B_{t-1}^i + \int_0^1 w_t(j)h_t^i(j) + \Pi_t^i(j)dj - T_t - P_t C_t^i,$$

where $\Pi_t^i(j)$ denotes profits from firm j remitted to household i , T_t taxes, and B_t^i the riskless bond purchases at time t .⁴

³For more details on the NK model, see Woodford (2003).

⁴For ease of exposition I have suppressed potential money assets here. This has no bearing on the model implications since it represents the cashless limit of an economy with explicit money balances.

The only difference to the standard New Keynesian model is the expectations operator, $\hat{\mathbb{E}}^i$. This is the subjective expectations operator that differs from its rational expectations counterpart, \mathbb{E} , in that it does not encompass knowledge of the model. In particular, households have no knowledge of the fact that they are identical. By extension, they also do not internalize that they hold identical beliefs about the evolution of the economy. This implies that while the modeler can suppress the index i , understanding that $\hat{\mathbb{E}}^i = \hat{\mathbb{E}}^j = \hat{\mathbb{E}}$, households cannot do so. As we will see in Section I.C, this has implications for their forecasting behavior and will result in decision rules that differ from those of the rational expectations version of the model.

B. Firms

Firms are monopolistically competitive producers of the differentiated varieties $y_t(j)$. The production technology of firm j is $y_t(j) = A_t f(h_t(j))$, whose inverse, $f^{-1}(\cdot)$, signifies the amount of labor input. Noting that A_t is the level of technology and that $w_t(j)$ is the wage per labor hour, firm j profits at time t can be written as

$$(6) \quad \Pi_t^j = p_t(j)y_t(j) - w_t(j)f^{-1}(y_t(j)/A_t).$$

Firm j 's problem then is to set the price of the variety it produces, $p_t(j)$, to maximize the present discounted value of profit streams

$$(7) \quad \hat{\mathbb{E}}_t^j \sum_{T=t}^{\infty} \alpha^{T-t} Q_{t,T} \left[\Pi_t^j(p_t(j)) \right],$$

subject to the downward-sloping demand curve

$$(8) \quad y_t(j) = Y_t \left(\frac{p_t(j)}{P_t} \right)^{-\theta},$$

where

$$(9) \quad Q_{t,T} = \beta^{T-t} \frac{P_t U_c(C_T)}{P_T U_c(C_t)}$$

is the stochastic discount factor from households. Nominal frictions enter the model through the parameter α in Equation (7). This is the Calvo probability that firm j is not able to adjust its price in a given period.

Analogously to households, the setup of the production side of the economy is standard up to the expectation operator. Also here the model-consistent expectations operator \mathbb{E} has been replaced by the subjective expectations operator $\hat{\mathbb{E}}^j$. This implies that firms, like households, do not know the model equations, nor do

they internalize that they are identical. Thus their decision rules, just like those of the households, will be distinct from their rational expectations counterparts.

C. Aggregate laws of motion

The model solution procedure entails deriving first-order conditions, taking a loglinear approximation around the nonstochastic steady state and imposing market clearing conditions to reduce the system to two equations, the New Keynesian Phillips curve and IS curve. The presence of subjective expectations, however, implies that firms and households are not aware of the fact that they are identical. Thus, as Preston (2005) points out, imposing market clearing conditions in the expectations of agents is inconsistent with the assumed information structure.⁵

Instead, I prevent firms and households from internalizing market clearing conditions.⁶ As Preston (2005) demonstrates, this leads to long-horizon forecasts showing up in firms' and households' first-order conditions. As a consequence, instead of the familiar expressions, the IS and Phillips curves take the following form:

$$(10) \quad x_t = -\sigma i_t + \hat{\mathbb{E}}_t \sum_{T=t}^{\infty} \beta^{T-t} ((1-\beta)x_{T+1} - \sigma(\beta i_{T+1} - \pi_{T+1}) + \sigma r_T^n),$$

$$(11) \quad \pi_t = \kappa x_t + \hat{\mathbb{E}}_t \sum_{T=t}^{\infty} (\alpha\beta)^{T-t} (\kappa\alpha\beta x_{T+1} + (1-\alpha)\beta\pi_{T+1} + u_T).$$

Here x_t , π_t and i_t are the log-deviations of the output gap, inflation and the nominal interest rate from their steady state values, and σ is the intertemporal elasticity of substitution. The variables r_t^n and u_t are exogenous disturbances representing a natural rate shock and a cost-push shock respectively.

The laws of motion (10) and (11) are obtained by deriving individual firms' and households' decision rules, which involve long-horizon expectations, and aggregating across the cross-section. Importantly, agents in the economy have no knowledge of these relations since they do not know that they are identical and thus are not able to impose market clearing conditions required to arrive at (10) and (11). Thus, although the evolution of the observables (π, x) is governed by the exogenous state variables (r^n, u) and long-horizon expectations via these two equations, agents in the economy are unaware of this. As I will spell out more formally in Section II, it is indeed the equilibrium mapping between states and jump variables the agents are attempting to learn.

⁵The target of Preston (2005)'s critique is the Euler-equation approach as exemplified for example by Bullard and Mitra (2002). This approach involves writing down the loglinearized first-order conditions of the model, and simply replacing the rational expectations operators with subjective ones. In a separate paper, I demonstrate that the Euler-equation approach is not only inconsistent on conceptual grounds as Preston (2005) shows, but also delivers substantially different quantitative dynamics in a simulated New Keynesian model.

⁶There are several ways of doing this. An alternative to Preston (2005)'s long-horizon approach pursued here is the shadow price learning framework advocated by Evans and McGough (2009).

To simplify notation, I gather the exogenous state variables in the vector s_t and observables in the vector z_t as

$$(12) \quad s_t = \begin{bmatrix} r_t^n \\ \bar{i}_t \\ u_t \end{bmatrix} \quad \text{and} \quad z_t = \begin{bmatrix} \pi_t \\ x_t \\ i_t \end{bmatrix},$$

where \bar{i}_t is a shock to the interest rate that only shows up in the model for particular specifications of monetary policy.⁷ This allows me to denote long-horizon expectations by

$$(13) \quad f_{a,t} \equiv \hat{\mathbb{E}}_t \sum_{T=t}^{\infty} (\alpha\beta)^{T-t} z_{T+1} \quad \text{and} \quad f_{b,t} \equiv \hat{\mathbb{E}}_t \sum_{T=t}^{\infty} (\beta)^{T-t} z_{T+1}.$$

As detailed in Appendix D, one can use this notation to reformulate the laws of motion of jump variables (Equations (10), (11) and (41)) compactly as

$$(14) \quad z_t = A_a f_{a,t} + A_b f_{b,t} + A_s s_t,$$

where the matrices A_i , $i = \{a, b, s\}$ gather coefficients and are given in Appendix D. Assuming that exogenous variables evolve according to independent AR(1) processes, I write the state transition matrix equation as

$$(15) \quad s_t = h s_{t-1} + \epsilon_t \quad \text{with} \quad \epsilon_t \sim \mathcal{N}(\mathbf{0}, \Sigma),$$

where h gathers the autoregressive coefficients ρ_j , ϵ_t the Gaussian innovations ε_t^j , and η the standard deviations σ_t^j , for $j = \{r, i, u\}$. $\Sigma = \eta\eta'$ is the variance-covariance matrix of disturbances.⁸

II. Learning with an anchoring mechanism

The informational assumption of the model is that agents do not know the equilibrium mapping between states and jumps in the model. Without knowing the form of the observation equation, then, they are not able to form rational expectations forecasts. Instead, agents postulate an ad-hoc forecasting relationship between states and jumps and seek to refine it in light of incoming data. In other words, they act like an econometrician: they estimate a simple statistical model and constantly attempt to improve their model as new data arrive.

⁷For generality, I treat the exogenous state vector as three-dimensional throughout the paper, even when the monetary policy shock is absent.

⁸For the sake of conciseness, I have suppressed the expressions for these in the main text. See Appendix D.

A. Perceived law of motion

I assume agents consider a forecasting model for the endogenous variables of the form

$$(16) \quad \hat{\mathbb{E}}_t z_{t+1} = a_{t-1} + b_{t-1} s_t,$$

where a and b are estimated coefficients of dimensions 3×1 and 3×3 respectively. This perceived law of motion (PLM) reflects the assumption that agents forecast jumps using a linear function of current states and a constant, with last period's estimated coefficients. Summarizing the estimated coefficients as $\phi_{t-1} \equiv [a_{t-1} \quad b_{t-1}]$, here 3×4 , I can rewrite Equation (16) as

$$(17) \quad \hat{\mathbb{E}}_t z_{t+1} = \phi_{t-1} \begin{bmatrix} 1 \\ s_t \end{bmatrix}.$$

I also assume that

$$(18) \quad \hat{\mathbb{E}}_t \phi_{t+k} = \phi_t \quad \forall k \geq 0.$$

This assumption, known in the learning literature as anticipated utility (Kreps (1998)), means that agents do not internalize that they will update the forecasting rule in the future. Clearly, this poses a higher level of irrationality than not knowing the model and using statistical techniques to attempt to learn it. Nevertheless, because it has been demonstrated not to alter the dynamics of the linearized model (Sargent (1999)), anticipated utility has become a standard assumption in the adaptive learning literature in order to simplify the algebra.

Since the states s_t are exogenous, I assume that agents know Equation (15), the equation governing the evolution of s_t .⁹ Then, the PLM together with anticipated utility implies that k -period ahead forecasts are constructed as

$$(19) \quad \hat{\mathbb{E}}_t z_{t+k} = a_{t-1} + b_{t-1} h^{k-1} s_t \quad \forall k \geq 1.$$

The timing assumptions of the model are as follows. In the beginning of period t , the current state s_t is realized. Agents then form expectations according to (16) using last period's estimate ϕ_{t-1} and the current state s_t . Given exogenous states and expectations, today's jump vector z_t is realized. This allows agents to evaluate the most recent forecast error

$$(20) \quad f_{t|t-1} \equiv z_t - \phi_{t-1} \begin{bmatrix} 1 \\ s_{t-1} \end{bmatrix}$$

⁹This is another common simplifying assumption in the adaptive learning literature. In an extension, I relax this assumption and find that it has similar implications as having agents learn the Taylor rule: initial responses to shocks lack intertemporal expectation effects, but these reemerge as the evolution of state variables is learned.

to update their forecasting rule. The estimate is updated according to the following recursive least-squares algorithm:

$$(21) \quad \phi_t = \left(\phi'_{t-1} + k_t R_t^{-1} \begin{bmatrix} 1 \\ s_{t-1} \end{bmatrix} f'_{t|t-1} \right)',$$

$$(22) \quad R_t = R_{t-1} + k_t \left(\begin{bmatrix} 1 \\ s_{t-1} \end{bmatrix} [1 \quad s_{t-1}] - R_{t-1} \right).$$

Here R_t is the 4×4 variance-covariance matrix of the regressors and k_t is the learning gain, specifying to what extent the updated estimate loads on the forecast error. Clearly, a high gain implies high loadings and thus strong changes in the estimated coefficients ϕ_t . A low gain, by contrast, means that a given forecast error only has a small effect on ϕ_t .

B. Endogenous gain as anchoring mechanism

The vast majority of the learning literature specifies the gain either as a constant, \bar{g} , or decreasing with time, so that $k_t = t^{-1}$, where t indexes time. Instead, to capture the notion of anchoring, I follow Carvalho et al. (2019) in allowing the gain to fluctuate in a time-varying way in response to short-run forecast errors. I use the following endogenous gain specification: I assume the gain evolves as

$$(23) \quad k_t = \mathbf{g}(k_{t-1}, f_{t|t-1}),$$

where $\mathbf{g}(\cdot)$ is a smooth function. I refer to $\mathbf{g}(\cdot)$ as the anchoring function. Notice that this function is an extension to the conventional decreasing or constant gain specifications, as it nests both as special cases. A decreasing gain implies $\mathbf{g}(k_{t-1}, f_{t|t-1}) = t^{-1}$, while a constant gain $\mathbf{g}(k_{t-1}, f_{t|t-1}) = \bar{g}$. Furthermore, in both special cases, $\mathbf{g}_1 = \mathbf{g}_2 = 0$.

By contrast, my novel specification entails the following assumptions on the function $\mathbf{g}(\cdot)$:

$$(24) \quad \mathbf{g}_1 \geq 0,$$

$$(25) \quad \mathbf{g}_{22} \geq 0.$$

Equation (24) says that the current value of the gain depends positively on its past value. In a similar vein, Equation (25) suggests that $\mathbf{g}(\cdot)$ is convex in its second argument. In other words, the gain is increasing in the absolute value of forecast errors.

The novelty of specifying the evolution of the gain using (23) with the properties in (24) and (25) is that it offers a time- and state-dependent model of private sector learning. In both of the standard, exogenous gain schemes the gain is divorced from the current environment. It either decreases deterministically ($k_t = t^{-1}$), or is a constant ($k_t = \bar{g}$). This means that the private sector's learning is static and

not state-dependent in the sense that a volatile environment results in the same learning pattern as a stable one. My specification, instead, allows the private sector to learn in a time-varying and state-dependent way. When high volatility results in large forecast errors in absolute value, the anchoring function outputs a larger gain than when forecast errors are close to zero. Thus the learning coefficients a_t and b_t respond more to forecast errors in volatile states of the world than in stable ones. The time-varying nature of the gain therefore generates periods of well-anchored expectations (low gain) as well as highly unanchored episodes (high gain). The model thus interprets the gain as a metric of the extent of unanchoring.

My anchoring mechanism also displays desirable empirical features. First, as demonstrated by Milani (2014), endogenous gain learning models can match time-varying volatility in the data, a feature that constant gain learning models cannot account for. More importantly, since a_t is my model's expression for long-run expectations, the fact that the gain is a convex function of forecast errors allows the model to match the time-varying sensitivity of long-term inflation expectations documented in Fig. 1.

I am not the first to postulate an endogenous gain. In fact, Milani (2014)'s estimation is based on an endogenous gain scheme introduced by Marcet and Nicolini (2003). Furthermore, Carvalho et al. (2019) are the first to lay out an endogenous gain specification as a model of anchored expectations. The novelty of my endogenous gain model is that, as opposed to Carvalho et al. (2019), the anchoring function $\mathbf{g}(\cdot)$ is a smooth function. In Carvalho et al. (2019)'s specification, discussed in detail in Appendix F, $\mathbf{g}(\cdot)$ is a discrete function of the endogenous component of forecast errors. In their partial equilibrium model, firms use a constant gain if the endogenous component of forecast errors exceeds a given threshold, otherwise they use a decreasing gain.

Assuming instead that $\mathbf{g}(\cdot)$ is a smooth function is useful for two reasons. First, since the derivatives of $\mathbf{g}(\cdot)$ exist, this formulation allows me to consider the Ramsey problem of the monetary authority. This is thus a necessary condition to be able to study optimal monetary policy in the model, which is the main contribution of this paper. Second, the smoothness of $\mathbf{g}(\cdot)$ renders the size of the gain a meaningful metric of the degree of unanchoring. By contrast, in Carvalho et al. (2019)'s model, expectations are either fully anchored or unanchored. My model thus provides more flexibility regarding the extent of unanchoring, in line with the evidence on varying degrees of responsiveness of long-run expectations to short-run mistakes.

My smooth specification of $\mathbf{g}(\cdot)$ also allows me to take the anchoring function to the data. As discussed in Section III, I employ a semi-nonparametric approach to back out the functional form of $\mathbf{g}(\cdot)$ from the data. I then use the estimates to calibrate my model to carry out the numerical analysis of monetary policy.

It is intuitive why the central bank might care whether expectations are anchored or not. When expectations are strongly unanchored at time t , the private

sector believes that the true DGP involves a different mapping between states and jumps than they previously maintained. Private sector forecasts will thus drift in the direction of the update, implying that the observables will also shift in the same direction owing to the law of motion (14). From the perspective of the central bank, stabilization of the observables therefore implies stabilization of expectations. Indeed, the contribution of this paper is to analyze formally the nature of the monetary policy problem when expectations are formed using the anchoring mechanism in Equation (23).

C. Actual law of motion

To complete the model, I now use the specifics of the anchoring expectation formation to characterize the evolution of the jump variables under learning. Using the PLM from Equation (16), I write the long-horizon expectations in (13) as

$$(26) \quad f_{a,t} \equiv \frac{1}{1-\alpha\beta} a_{t-1} + b_{t-1} (I_3 - \alpha\beta h)^{-1} s_t \quad \text{and} \quad f_{b,t} \equiv \frac{1}{1-\beta} a_{t-1} + b_{t-1} (I_3 - \beta h)^{-1} s_t.$$

Substituting these into the law of motion of observables (Equation (14)) yields the actual law of motion (ALM):

$$(27) \quad z_t = g_{t-1}^l \begin{bmatrix} 1 \\ s_t \end{bmatrix},$$

where g^l is a 3×4 matrix given in Appendix E. Thus, instead of the state-space solution of the RE version of the model (Equations (15) and (E1)), the state-space solution for the learning model is characterized by the pair of equations (15) and (27), together with the PLM (19), the learning equations (21) and (22), as well as the anchoring function (23).

D. Simplifying assumptions

To simplify the analytical work in Section IV.A, I make two assumptions that I maintain for the rest of the paper.

ASSUMPTION 1: $e_i' a_t = 0$, $i = 2, 3, \forall t$ and $b_t = g h \forall t$.

Here e_i is a 3×1 vector of zeros with 1 as its i^{th} element. Assumption 1 amounts to restricting the intercepts in the forecasts of the output gap and the interest rate and the slope coefficients of all forecasts to what they would be under rational expectations. This means that instead of learning the intercept and slope parameters for all three endogenous variables, the private sector only learns the intercept of the inflation process.

The rationale behind this assumption is that it is the smallest possible deviation from rational expectations that at the same time has enough flexibility to

study the unanchoring of inflation expectations. In particular, since the inflation intercept is learned using my novel anchoring mechanism, the formulation is able to capture the time-varying sensitivity of long-run inflation expectations to short-run forecast errors in inflation. In extensions, I relax this assumption and find that it does not change the qualitative or quantitative implications of the model.

With Assumption 1, the updating equations (21) and (22) simplify to a single equation:

$$(28) \quad \bar{\pi}_t = \bar{\pi}_{t-1} + k_t f_{t|t-1},$$

where, using the notation that $b_1 \equiv e_1 b$, the k -period-ahead inflation forecast is given by

$$(29) \quad \hat{\mathbb{E}}_t \pi_{t+k} = \bar{\pi}_{t-1} + b_1^k s_t, \quad \forall k \geq 1.$$

Lastly, the one-period-ahead forecast error in inflation simplifies to

$$(30) \quad f_{t|t-1} = \pi_t - (\bar{\pi}_{t-1} + b_1 s_t).$$

ASSUMPTION 2: $\mathbf{g}_1 = 0$.

The interpretation of this assumption on the anchoring function is that the current gain depends only on forecast errors, not on its own past level. The motivation is to simplify the analytical solution of the Ramsey problem in Section IV.A. Appendix I provides a treatment of the Ramsey problem with the general specification of the anchoring function, relaxing Assumption 2. As seen in the Appendix, this does not change the mechanics nor the intuition behind the solution of the Ramsey problem.

III. Quantification of learning channel

The numerical analysis of monetary policy requires a functional specification for the anchoring function $\mathbf{g}(\cdot)$ of Equation (23). For this reason, I back out the functional form of $\mathbf{g}(\cdot)$ from data. Apart from its usefulness for numerical analysis, the form of the anchoring function is interesting in its own right because it describes empirical properties of the anchoring of expectations. In particular, central bankers may want to know how much forecast errors of a particular sign and magnitude unanchor expectations.

I carry out the estimation in two steps. I first calibrate the parameters of the underlying New Keynesian model. Conditional on these parameter values, I estimate the anchoring function by simulated method of moments à la Lee and Ingram (1991), Duffie and Singleton (1990) and Smith (1993). I target the autocovariance structure of the Baxter-King filtered observables of the model and expectations. The observables are CPI inflation from the Bureau of Labor Statistics (BEA), the output gap and the federal funds rate from the Board of

Governors of the Federal Reserve System.¹⁰ For expectations, I rely on 12-month-ahead CPI inflation forecasts from the Survey of Professional Forecasters (SPF). The dataset is quarterly and ranges from 1981-Q3 to 2020-Q1. Appendix G contains a detailed description of the estimation methodology.

A. Calibration

For the calibration of the NK backbone of the model, I split the parameters into two subsets. The first is calibrated using values from the literature, while the second is calibrated to match the moments outlined above. Tables 1 and 2 show the two subsets of calibrated parameters respectively. As Table 1 depicts, I adopt standard parameters from the literature where possible. In particular, for β , σ and other parameters underlying κ , the slope of the Phillips curve, I rely on the parameterization of Chari, Kehoe and McGrattan (2000), advocated in Woodford (2003).

The composite parameter κ is given by $\kappa = \frac{(1-\alpha)(1-\alpha\beta)}{\alpha}\zeta$, where ζ is a measure of strategic complementarity in price setting. Assuming specific factor markets, constant desired markups with respect to output levels and no intermediate inputs, $\zeta = \frac{\omega+\sigma^{-1}}{1+\omega\theta}$. Here θ is the price elasticity of demand and ω is the elasticity of the marginal cost function with respect to output. Chari, Kehoe and McGrattan (2000)'s calibration involves $\theta = 10$, $\sigma = 1$, $\omega = 1.25$, $\beta = 0.99$, so that together with my choice of α , κ is pinned down. Note that I lower β slightly (0.98 instead of Chari, Kehoe and McGrattan (2000)'s 0.99). This allows the model to better match the autocovariance structure of the output gap because it lowers the pass-through of long-horizon expectations in the IS curve.

The probability of not adjusting prices, α , is set to match an average price duration of two quarters, which is slightly below the numbers found in empirical studies.¹¹ In the literature, the average price duration is a little above 7 months. My number for α corresponds to 6 months. I choose the lower end of this spectrum in order to allow the learning mechanism, and not price stickiness, to drive the bulk of the model's persistence.

To simplify the numerical analysis as well as interpretation, I restrict the shocks to be iid. The volatilities of the disturbances and, where applicable, the output-coefficient of the Taylor rule, are set to match the above-mentioned moments. As shown in Table 2, this implies standard deviations of 0.01 for the natural rate and monetary policy shock and 0.5 for the cost-push shock. In sections of the paper where I assume a Taylor rule, the moment-matching exercise results in a 0.3 coefficient on the output gap. The last parameter of the New Keynesian core

¹⁰The output gap measure is constructed as the difference between real GDP from the Bureau of Economic Analysis (BEA) and the Congressional Budget Office's (CBO) estimate of real potential output.

¹¹On the lower end of the empirical values for α , Bils and Klenow (2004) find a mean duration of 4.3 months and Klenow and Malin (2010) 6.9 months. Klenow and Kryvtsov (2008) and Nakamura and Steinsson (2008) agree on between 7-9 months, while Eichenbaum, Jaimovich and Rebelo (2011)'s number is 10.6 months.

is the inflation coefficient of the Taylor rule, ψ_π . Unless otherwise specified, I set ψ_π to 1.5, the value recommended by Taylor (1993). Note that the asterisks in Tables 1 and 2 demarcate parameters that pertain to the Taylor rule and thus only to sections of the paper which assume that a Taylor rule is in effect.

TABLE 1—PARAMETERS CALIBRATED FROM LITERATURE

β	0.98	stochastic discount factor
σ	1	intertemporal elasticity of substitution
α	0.5	Calvo probability of not adjusting prices
κ	0.0842	slope of the Phillips curve
ψ_π	1.5	coefficient of inflation in Taylor rule*
\bar{g}	0.145	initial value of the gain

Note: Parameters with an asterisk refer to sections of the paper where a Taylor rule is in effect.

TABLE 2—PARAMETERS SET TO MATCH DATA MOMENTS

ψ_x	0.3	coefficient of the output gap in Taylor rule*
σ_r	0.01	standard deviation, natural rate shock
σ_i	0.01	standard deviation, monetary policy shock*
σ_u	0.5	standard deviation, cost-push shock

Note: Parameters with an asterisk refer to sections of the paper where a Taylor rule is in effect.

I initialize the value of the gain at $\bar{g} = 0.145$. This is Carvalho et al. (2019)’s estimate for the case of unanchored expectations in their discrete anchoring function model. In the case of a discrete anchoring function, as in Carvalho et al. (2019), this parameter has important implications for model dynamics because by construction, the gain takes on this value very frequently. However, since my specification for $\mathbf{g}(\cdot)$ is smooth, \bar{g} does not have a strong bearing on model dynamics.

B. Estimation

In inferring the functional form of the anchoring function $\mathbf{g}(\cdot)$, I proceed as follows. First, since the analysis in Section IV relies on Assumptions 1 and 2, I similarly impose these on the estimation. In other words, I seek to back out the functional form of the relationship between the size of the gain and forecast errors in inflation, $k_t = \mathbf{g}(f_{t|t-1})$.

To be as close as possible to a non-parametric estimate of $\mathbf{g}(\cdot)$, while at the same time preserve the shape of the function, I employ a piecewise linear approximation of the form:

$$(31) \quad \mathbf{g}(f_{t|t-1}) = \sum_i \gamma_i b_i(f_{t|t-1}).$$

Here $b_i(\cdot)$ is a piecewise linear basis and γ is a vector of approximating coefficients. The index i refers to the breakpoints of the piecewise linear approximation. As explained above, I estimate γ by simulated method of moments, targeting the autocovariance structure of the observables of the model and expectations.

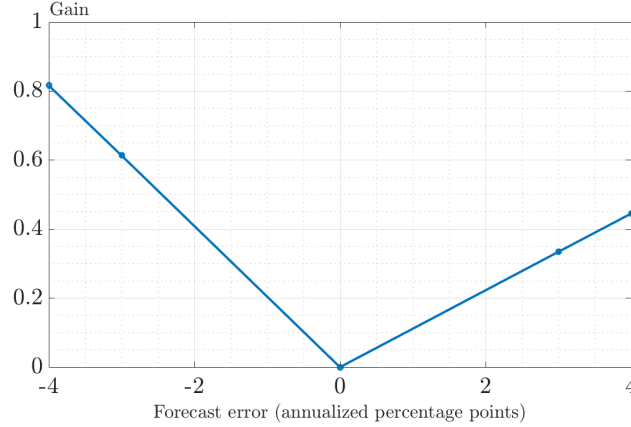


FIGURE 2. ESTIMATED $\hat{\alpha}$: k_t AS A FUNCTION OF $f_{t|t-1}$

Note: Estimates for 5 knots, cross-section of size $N = 1000$.

Fig. 2 presents the estimated coefficients: $\hat{\gamma} = (0.82; 0.61; 0; 0.33; 0.45)$. The circles indicate the nodes of the piecewise linear approximation. The interpretation of the elements of $\hat{\gamma}$ is the value of the gain the private sector chooses when it observes a forecast error of a particular magnitude. For example, a forecast error of -4 pp in inflation is associated with a gain of 0.82.

Before interpreting the estimated anchoring function, it is helpful to work out what amounts to a large gain. In particular, since the gain is the model's metric of the extent of unanchoring, from what size of the gain should one consider expectations to be significantly unanchored? The consensus in the literature on estimating learning gains is that if the true model is one with constant gain learning, then the gain lies between 0.01-0.05. On the higher end of the empirical estimates, Branch and Evans (2006) obtain a constant gain on inflation of 0.062. Milani (2007) finds 0.0183. The estimates of the maximal value for endogenous gains lie somewhat higher, at 0.082 in Milani (2014) and at 0.145 in Carvalho et al. (2019). Calibrated models tend to use the consensus values between 0.01-0.05, with the number 0.05 having attained particular prominence. However, Eusepi

and Preston (2011) find that the value of 0.002 is sufficient to significantly alter the dynamic behavior of a standard RBC model.

An intuitive interpretation of the gain is that its inverse gives the number of past observations the private sector uses to form its current forecasts. Eusepi and Preston (2011)'s number, 0.002, thus implies that firms and households rely on the last 125 years of data. By contrast, the consensus number of 0.05 translates to using five years of data.

Seen from both of these perspectives, a gain of 0.05 corresponds to a sizable amount of unanchoring. With this benchmark number in mind, the message of Fig. 2 seems stark: the estimated coefficients are very large. The highest gain value in my estimation, 0.82, can be interpreted as seeing forecast errors of 4 pp in absolute value prompting the private sector to discount any observations older than about 5 months. That is a very short time.

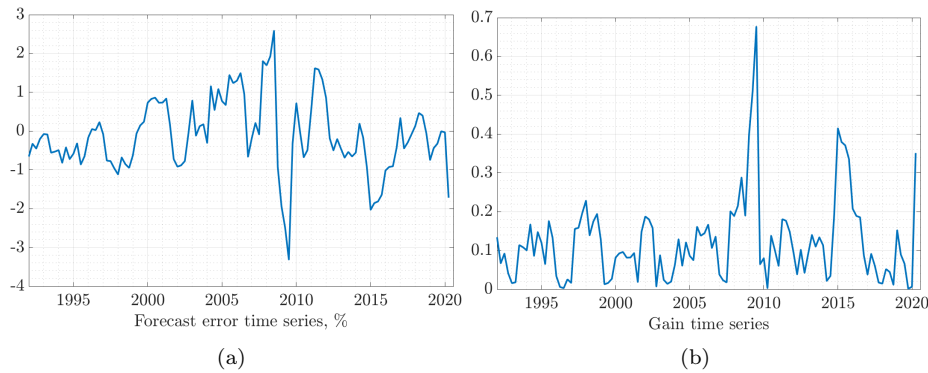


FIGURE 3. FORECAST ERRORS AND IMPLIED GAIN IN THE SPF DATA

Note: Forecast errors are in annualized percentage points.

Presumably, such large forecast errors are rare, however. In fact, Fig. 3 confirms that this is indeed the case in the SPF data since the 1990s. As shown on the left panel, in this time period, forecast errors were always below 4 percentage points in absolute value, the largest being an error of -3.31 pp. The right panel depicts the time series for the gain implied by the model and the estimated $\hat{\gamma}$. The mean and median values of the gain, 0.121 and 0.098 respectively, suggest that there is substantial sensitivity of long-run expectations to forecast errors overall in the data.

Clearly, the main feature of the gain is that it is time-varying. Periods of near-zero values are frequently followed by high values around or above 0.1. The negative inflation surprises brought on by the Great Recession and the Covid-19 crisis unsurprisingly result in very large gains, almost 0.7 and around 0.35 respectively, yielding highly unanchored expectations. More surprising is the fact

that the decade-long boom between 2010 and 2020 also involves a very unanchored episode. In fact, the gain in 2015 is above 0.4, exceeding its 2020 value. Moreover, following 2015, the gain remained elevated for almost five years. By contrast, after the Great Recession, expectations recovered fast and by 2010 looked very well-anchored.

On the one hand, this suggests that exogenous shocks such, for example shocks to credit or to oil prices, have similar effects as the Fed missing its inflation target. On the other hand, a potentially more alarming implication is that failing to get inflation back up to target seems to go hand-in-hand with persistently unanchored expectations. Thus central bank misses may result in unanchoring that is more difficult to combat than that following exogenous shocks.

The three sizable unanchoring episodes since 2008 may also stem from a change in the pattern of forecast errors. Up to 2008, most forecast errors were positive and small in magnitude. This reversed in 2008. Not only were most post-2008 forecast errors negative, but they were also larger than the positive surprises. This connects with the finding that unanchoring is asymmetric. Notice that, as seen on Fig. 2, negative inflation surprises raise the gain about twice as much as positive ones do. Consistent with the findings of Hebden et al. (2020), this indicates that long-run expectations are more sensitive to negative than to positive surprises. This implies, then, that not only is the magnitude of forecast errors after 2008 responsible for the spikes in the gain, but also that inflation consistently turned out to be lower than what the public had expected.

IV. Monetary policy and anchoring

This section sets up and solves the optimal monetary policy problem in the model with the anchoring expectation formation. In Section IV.A, I begin by analyzing the Ramsey problem of determining optimal paths for the endogenous variables that policy seeks to bring about. While the anchoring mechanism introduces substantial nonlinearity into the model, it is possible to derive analytically an optimal target criterion for the policymaker to follow. As we shall see, the optimal rule prescribes for monetary policy to act conditionally on the stance of expectations, and will thus be time-varying and state-dependent. In particular, whether expectations are anchored or not matters for the extent to which there is a tradeoff between inflation and output gap stabilization, and also for the volatility cost of getting expectations anchored.

I then turn to the question of how to implement optimal policy. Section IV.B uses global methods to solve for the interest rate sequence that implements the target criterion. I then discuss the properties of the optimal interest rate policy and why it is successful in stabilizing both inflation expectations and inflation.

The optimal interest rate policy will thus be a nonlinear function of all the states in the model - a complicated object to compute. In practice, however, monetary policy is most commonly modeled using time-invariant rules like the Taylor rule that are simple to compute and to communicate to the public. In

Section IV.C, I therefore restrict attention to Taylor-type feedback rules for the interest rate. I solve for the optimal Taylor-rule coefficient on inflation numerically and investigate how this choice affects the anchoring mechanism. As I expand upon further in Section IV.C, a Taylor rule with given coefficients involves higher fluctuations in the anchoring model than under rational expectations because it does not allow the central bank to respond to long-run expectations. At the same time, it involves responding to inflation even in periods when expectations are anchored, causing excess volatility. For this reason, the optimal Taylor-rule inflation-coefficient is lower than under rational expectations.

A. The Ramsey policy under anchoring

I assume the monetary authority seeks to maximize welfare of the representative household under commitment. As shown in Woodford (2003), a second-order Taylor approximation of household utility delivers a central bank loss function of the form

$$(32) \quad L^{CB} = \mathbb{E}_t \sum_{T=t}^{\infty} \{(\pi_T - \pi^*)^2 + \lambda_x (x_T - x^*)^2\},$$

where λ_x is the weight the central bank assigns to stabilizing the output gap. In the rational expectations New Keynesian model, λ_x is a function of deep parameters: $\lambda_x = \frac{\kappa}{\theta}$. Just as under rational expectations, one can show that it is optimal to set the central bank's targets, π^* and x^* , to zero. The central bank's problem, then, is to determine paths for inflation, the output gap and the interest rate that minimize the loss in Equation (32), subject to the model equations (10) and (11), as well as the PLM (19), the learning equations (21) and (22), and the anchoring function (23). The full statement of the Ramsey problem under Assumptions 1 and 2 is as follows:

$$(33) \quad \begin{aligned} & \min_{\{\pi_t, x_t, i_t, \bar{\pi}_{t-1}, k_t\}_{t=t_0}^{\infty}} \mathbb{E}_{t_0} \sum_{t=t_0}^{\infty} \beta^{t-t_0} (\pi_t^2 + \lambda_x x_t^2) \quad \text{s.t.} \\ & x_t = -\sigma i_t + \hat{\mathbb{E}}_t \sum_{T=t}^{\infty} \beta^{T-t} ((1-\beta)x_{T+1} - \sigma(\beta i_{T+1} - \pi_{T+1}) + \sigma r_T^n), \\ & \pi_t = \kappa x_t + \hat{\mathbb{E}}_t \sum_{T=t}^{\infty} (\alpha\beta)^{T-t} (\kappa\alpha\beta x_{T+1} + (1-\alpha)\beta\pi_{T+1} + u_T), \\ & \hat{\mathbb{E}}_t \pi_{t+k} = \bar{\pi}_{t-1} + b_1^k s_t \quad \forall k \geq 1, \\ & \bar{\pi}_t = \bar{\pi}_{t-1} + k_t f_{t|t-1}, \\ & k_t = \mathbf{g}(f_{t|t-1}). \end{aligned}$$

OPTIMAL RAMSEY POLICY AS A TARGET CRITERION

As foreshadowed above, the nonlinearity of the model due to the anchoring function prevents a full analytical solution to the Ramsey problem. Therefore I now characterize the first-order conditions of the problem analytically, and proceed in Section IV.B to solve the full problem numerically. The details of the derivations are given in Appendix H, which also illustrates how the endogeneity of the gain introduces nonlinearity into the model.

The solution of the Ramsey problem is stated in the following proposition.

PROPOSITION 1: *Target criterion in the anchoring model*

The targeting rule in the simplified learning model with anchoring is given by

$$(34) \quad \pi_t = -\frac{\lambda_x}{\kappa}x_t + \frac{\lambda_x}{\kappa} \frac{(1-\alpha)\beta}{1-\alpha\beta} \left(k_t + f_{t|t-1}\mathbf{g}_{\pi,t} \right) \\ \left(\mathbb{E}_t \sum_{i=1}^{\infty} x_{t+i} \prod_{j=0}^{i-1} (1 - k_{t+1+j} - f_{t+j|t+j-1}\mathbf{g}_{\pi,t+j}) \right).$$

Proved in Appendix H. For a general target criterion without Assumption 2, see Appendix I.

Here, \mathbb{E}_t is the central bank's expectation. The notation reflects the assumption that the central bank has model-consistent expectations and observes the private sector's expectations. This assumption, which Gaspar, Smets and Vestin (2010) refer to as “sophisticated central banking,” is quite strong. In practice, it is likely that the central bank's measure of private sector expectations is noisy at best. Nevertheless, it is a useful case that can serve as a benchmark for future research.

The interpretation of Equation (34) is that the *intratemporal* tradeoff between inflation and the output gap due to cost-push shocks is complemented by two *intertemporal* tradeoffs: one due to learning in general, and one due to anchoring in particular. The first intertemporal effect comes from the current level of the gain, k_t , which captures how far learning is from converging to rational expectations. The second intertemporal tradeoff is manifest in the derivative of the anchoring function today, $\mathbf{g}_{\pi,t}$, as well as in all expected levels and changes in the gain in the future in the expression $(1 - k_{t+1+j} - f_{t+j|t+j-1}\mathbf{g}_{\pi,t+j})$ in the second bracket on the right-hand side. These expressions say that the presence of anchoring qualify the first intertemporal tradeoff because now the degree and direction in which the gain changes today and is expected to change in the future matter too. In other words, the central bank needs to consider whether its chosen interest rate sequence contributes to anchoring expectations in future periods, or whether it actually serves to unanchor them.

Let me investigate these channels in isolation. To see exactly what the role of anchoring is in the target criterion, consider first the special case of exogenous gain adaptive learning, for simplicity with a constant gain specification. In this case

the anchoring function and the forecast error are irrelevant (since $\mathbf{g}_i = 0, i = \pi, \bar{\pi}$) and (34) boils down to

$$(35) \quad \pi_t = -\frac{\lambda_x}{\kappa} x_t + \frac{\lambda_x (1 - \alpha)\beta}{\kappa (1 - \alpha\beta)} k \left(\sum_{i=1}^{\infty} x_{t+i} (1 - k)^i \right),$$

which is the analogue of Gaspar, Smets and Vestin (2010)'s Equation (24).¹² This result, found also by Molnár and Santoro (2014), suggests that already the presence of learning by itself is responsible for the first intertemporal tradeoff between inflation and output gap stabilization. The fact that the central bank now has future output gaps as a margin of adjustment means that it does not have to face the full tradeoff in the current period. Learning allows the central bank to improve the current output gap without sacrificing inflation stability today; however, this results in a worsened tradeoff in the future. In other words, adaptive learning by itself allows the central bank to postpone the current tradeoff to later periods.

Intuitively, this happens because adaptive expectations are slow in converging to rational expectations. In the transition, the private sector's expectations do not adjust to fully internalize the intratemporal tradeoff. This gives the monetary authority room to transfer the tradeoff to the future.

Contrasting Equations (35) and (34) highlights the role of my novel anchoring channel. With anchoring, the extent to which policy can transfer the intratemporal tradeoff to future periods depends not only on the stance of the learning process, as in (35), but also on whether expectations are anchored, and in which direction they are moving. In fact, not only the current stance and change of anchoring matters, but also all expected future levels and changes.

Anchoring, however, complicates the possibility of transferring today's tradeoff to the future. One can see this in the fact that forecast errors and the derivatives of the anchoring function are able to flip the sign of the second term in (34). This means that anchoring can alleviate or worsen the intertemporal tradeoff. To see the intuition, consider the equation system of first-order conditions from solving the Ramsey problem. While the full system is presented in Appendix H, let us focus solely on Equation (H2), the equation governing the dynamics of observables in the model:

$$(36) \quad 2\pi_t = -2\frac{\lambda_x}{\kappa} x_t + \varphi_{5,t} k_t + \varphi_{6,t} \mathbf{g}_{\pi,t}.$$

The Lagrange multipliers $\varphi_5 \geq 0$ and $\varphi_6 \geq 0$ are the multipliers of the updating equation (21) and the anchoring function respectively. This equation, upon substitution of the solutions for the two multipliers, yields the target criterion. It is therefore easy to read off the intuition at a glance. First, since $\varphi_{5,t} k_t > 0$, one

¹²Gaspar, Smets and Vestin (2010) provide a parsimonious summary of Molnár and Santoro (2014).

immediately obtains the above-discussed conclusion that as long as the adaptive learning equation is a constraint to the policymaker ($\varphi_{5,t} > 0$), the central bank has more room to transfer the contemporaneous tradeoff between inflation and the output gap to the future.¹³

However, whether the anchoring equation alleviates or exacerbates the inflation-output gap tradeoff depends on the sign of $\mathbf{g}_{\pi,t}$. If the derivative is positive, the effect is the same as above, and the central bank has more leeway to postpone the tradeoff to the future. By contrast, if the derivative is negative, that is expectations are becoming anchored, the intratemporal tradeoff is worsened.

Why do unanchored expectations give the central bank the possibility to postpone its current inflation-output gap tradeoff? The reason is that when expectations become unanchored, the learning process is restarted. A not-yet converged learning process implies, as discussed above, that postponing the tradeoff is possible. Restarting the convergence process thus unlocks this possibility.

This seems to suggest that from a smoothing standpoint, the central bank should prefer to have unanchored expectations. As will be shown in Sections IV.B-IV.C, volatility considerations will suggest otherwise. But in fact, even the smoothing viewpoint involves some ambiguity on whether expectations should be anchored from the perspective of the central bank. Clearly, the central bank prefers to face a learning process that on the one hand has not yet converged, and on the other is converging only slowly. A high gain under unanchored expectations implies both a sizable distance from convergence as well as faster learning and thus faster convergence. Therefore, ideally the central bank would like to have expectations anchored but the gain far from zero; a contradiction. Once the gain approaches zero, only unanchored expectations can raise it again to restart the learning process. But once the gain is large, the only way to slow down learning is to anchor expectations, that is, to lower the gain.

TIME-CONSISTENCE OF OPTIMAL PLANS UNDER ADAPTIVE LEARNING

Now simplify the target criterion further, assuming that learning has converged, $k_t = \mathbf{g}_\pi = 0$. We are left with

$$(37) \quad \pi_t = -\frac{\lambda_x}{\kappa} x_t,$$

which corresponds to the optimal discretionary solution for rational expectations in Clarida, Gali and Gertler (1999). This is formalized in the following proposition.

¹³Strictly speaking, φ_5 and φ_6 are never zero in this model. The reason is that exogenous disturbances induce unforecastable variation throughout the lifetime of the economy. Thus, at any point in time, forecast errors can emerge that will unanchor expectations, restarting the learning process. This is in stark contrast with Carvalho et al. (2019), where the gain only depends on the endogenous component of the forecast error. Therefore, in their model, absent regime switches, expectations can never become unanchored once learning has converged.

PROPOSITION 2: *Coincidence of commitment and discretion under adaptive learning*

In an adaptive learning model with exogenous or endogenous gain, the optimal Ramsey policies under commitment and discretion coincide. The optimal Ramsey plan is more akin to discretion than to commitment as it does not involve making promises about future policy actions. Optimal policy is thus not subject to the time-inconsistency problem of Kydland and Prescott (1977).

To illustrate this result in a parsimonious manner, consider a simplified version of the model. The planner chooses $\{\pi_t, x_t, e_t, k_t\}_{t=t_0}^{\infty}$ to minimize

$$\begin{aligned} \mathcal{L} = \mathbb{E}_{t_0} \sum_{t=t_0}^{\infty} \beta^{t-t_0} & \left\{ \pi_t^2 + \lambda x_t^2 + \varphi_{1,t}(\pi_t - \kappa x_t - \beta e_t + u_t) \right. \\ & \left. + \varphi_{2,t}(e_t - e_{t-1} - k_t(\pi_t - e_{t-1})) + \varphi_{3,t}(k_t - \mathbf{g}(\pi_t - e_{t-1})) \right\}, \end{aligned}$$

where the IS curve, $x_t = \mathbb{E}_t x_{t+1} + \sigma e_t - \sigma i_t + \sigma r_t^n$, is a non-binding constraint, and is therefore excluded from the problem. φ_i are Lagrange-multipliers and $\mathbb{E}_t x_{t+1}$ is rational. In this simplified setting, e_t is a stand-in variable capturing inflation expectations and evolves according to a recursive least squares algorithm. The anchoring function $\mathbf{g}(\cdot)$ specifies how the gain k_t changes as a function of the current forecast error according to Assumption 2. Note that the problem involves commitment because the monetary authority internalizes the effects of its actions both on the evolution of expectations and on that of the gain.

After some manipulation, first-order conditions reduce to:

$$(38) \quad 2\pi_t + 2\frac{\lambda_x}{\kappa}x_t - \varphi_{2,t}(k_t + \mathbf{g}_{\pi}(\pi_t - e_{t-1})) = 0,$$

$$(39) \quad -2\beta\frac{\lambda_x}{\kappa}x_t + \varphi_{2,t} - \mathbb{E}_t \varphi_{2,t+1}(1 - k_{t+1} - \mathbf{g}_{\pi}(\pi_{t+1} - e_t)) = 0.$$

Inspection of this system reveals that, unlike the rational expectations case ($e_t = \mathbb{E}_t \pi_{t+1}$), the optimal solution does not involve lagged multipliers. This implies that the monetary authority cannot condition the optimal time path of inflation and the output gap on the past; optimal policy is not history-dependent.

This result is not specific to endogenous gain models, but generalizes to any adaptive learning. It has been demonstrated in the case of constant gain learning by Molnár and Santoro (2014), and for decreasing gain models by Mele, Molnár and Santoro (2019).

The intuition behind this result is easy to see if one compares rational expectations and adaptive learning in an infinitely repeated game setting. Under rational expectations, the lagged multiplier appears in the solution because expected inflation is a jump variable. This reflects that expectations fulfill a form of optimality, rendering the private sector a strategic player. The adjustment of expectations

under rational expectations enables the central bank to make promises about future policy that are incorporated into expectations.

Not so for adaptive expectations. Learning agents look exclusively to past data to form expectations. Their expectations thus cannot incorporate the policy-maker's promises about the future course of policy. In fact, a private sector with adaptive expectations has a pre-specified, non-strategic expectation formation. Therefore, households and firms act as an automaton, leaving the central bank unable to make promises that have any effect on expectations.

Should we be surprised that adaptive learning involves no distinction between discretion and commitment? Not at all if we recall that the rational expectations revolution had as one of its aims to remedy this feature of expectations. The seminal Lucas-critique, for instance, emphasizes that reduced-form regressions are not ideal guiding principles for policy precisely because they miss the time-varying nature of estimated coefficients due to model-consistent expectations that incorporate promises about policy action (Lucas (1976)).

One might be concerned that a model of anchoring that is not immune to the Lucas-critique may not be a desirable normative model for policy. But recall that the anchoring model is a description of the economy in transition, not of one at its ergodic mean. It characterizes expectation formation en route to becoming model-consistent as the private sector learns the underlying DGP.

Moreover, data suggest that in terms of positive implications, learning models fare much better than rational expectations models do. Since the seminal work by Coibion and Gorodnichenko (2015), rational expectations as a structural model for expectations has been rejected in numerous empirical papers. At the same time, the literature cited in the Introduction demonstrates the success of learning models in fitting both the properties of expectations in the data and in improving the business cycle dynamics of other model variables. To the extent that adaptive expectations offer an alternative structural model of the expectations process that captures main features of the data, in particular the feature of unanchoring, investigating their role for policy is a valuable exercise.

There are also avenues to address the Lucas-critique in learning models. One option is to reintroduce a sense of optimality to expectation formation directly, as in the literature on central bank reputation. (See Cho and Matsui (1995) and Ireland (2000)). Another possible remedy is to retain a sufficient degree of forward-looking expectations as in the finite-horizon planning approach advocated by Woodford (2019). A third possibility is to model communication by the central bank in the form of news shocks that enter the state vector, and thus show up in the information set of agents, as in Dombeck (2017). All in all, Proposition 2 does not render the advances of the rational expectations revolution void. Instead, it points to the fact that as long as the private sector extracts information from data to form beliefs, expectations will quantitatively resemble adaptive expectations. Thus, the policy predictions of adaptive expectations can complement our understanding of monetary policy from rational expectations with novel, empirically

relevant insights.

B. Implementing the Ramsey policy: the optimal interest rate sequence

Having a characterization of optimal policy in the anchoring model as a first-order condition, the next relevant question is how the central bank should set its interest rate tool in order to implement the target criterion in (34). In other words, we would like to know what time-path of interest rates implements the optimal sequence of inflation and output gaps. As emphasized in Section IV.A, the nonlinearity of the model does not admit an analytical answer to this question. I therefore solve for the optimal interest rate policy numerically using global methods. I rely on the calibration presented in Tables 1 and 2 and the estimated parameters of the expectations process in Section III. Furthermore, I set the central bank's weight on output gap fluctuations, λ_x , to 0.05, the value estimated by Rotemberg and Woodford (1997).

Appendix J outlines my preferred solution procedure, the parameterized expectations approach, while Appendix K gives the details of the parametric value function iteration approach I implement as a robustness check. The main output of this procedure is an approximation of the optimal interest rate policy as a function of the vector of state variables. Due to Assumption 2, the relevant state variables are expected mean inflation and the exogenous states at time t and $t-1$, rendering the state vector five-dimensional:

$$(40) \quad X_t = (\bar{\pi}_{t-1}, r_t^n, u_t, r_{t-1}^n, u_{t-1}).$$

As a first step, I plot how the approximated policy function depends on $\bar{\pi}_{t-1}$, while keeping all the other states at their mean. The result, depicted on Panel (a) of Fig. 4, suggests that optimal interest-rate setting responds linearly and very sensitively to the stance of expectations, $\bar{\pi}_{t-1}$. If expected mean inflation decreases by 5 basis points, the interest rate drops by about 250 basis points.¹⁴

This is a large response. Clearly, optimal policy involves subduing unanchored expectations by injecting massive negative feedback to the system. One may then wonder why optimal policy is so aggressive on unanchored expectations when the analysis of the target criterion in Section IV.A suggested that learning can alleviate the stabilization tradeoff between output and inflation.

The reason is that the anchoring expectation formation introduces another intertemporal tradeoff to monetary policy: a volatility tradeoff. One can see this on Fig. 5, portraying the dynamics of the system following a two-standard-deviation inflationary cost-push shock, conditional on a Taylor rule with baseline

¹⁴This result is qualified if one relaxes Assumption 1. If the private sector learns about all observables, not just inflation, interest rate expectations play a major role in determining forecasts of future inflation and thus add a stabilizing channel that is absent from the current specification. In the more general case, then, an order of magnitude smaller responses in the current interest rate are sufficient.

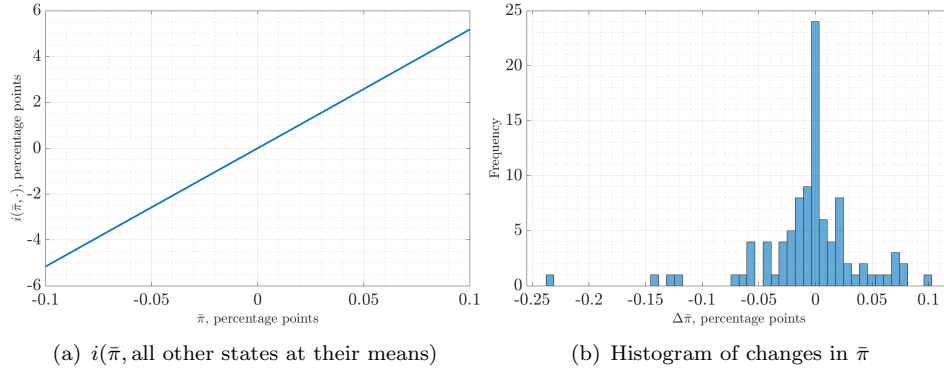


FIGURE 4. POLICY FUNCTION AND IMPLIED VOLATILITY IN LONG-RUN EXPECTATIONS

parameters. The figure contrasts the rational expectations version of the model with a well-anchored, weakly anchored and strongly unanchored scenario in the anchoring model.

The same shock that under rational expectations completely vanishes by the second period, triggers a large, persistent and oscillatory response in the anchoring model.¹⁵ Clearly, the size and persistence of the shock, as well as the magnitude of oscillations increase the more unanchored expectations are. This comes from the fact that if expectations are anchored, stable expectations lower the pass-through between shocks and observables. Instead, if expectations are unanchored, they become volatile, passing through the shocks and amplifying them. Having unanchored expectations, then, comes at a volatility cost in the central bank's target variables. This volatility cost dictates that, in the long run, the central bank wishes to have expectations anchored.

From the viewpoint of the central bank, this problem is amplified by the fact that anchoring expectations itself comes at a convex volatility cost. Anchoring expectations requires an aggressive interest response because by these means the central bank can introduce negative feedback to the system. But innovations to the interest rate surprise the private sector, raising forecast errors. The more unanchored expectations are, the more volatility the interest rate movement inflicts on the economy.

We can see from the policy function how optimal policy resolves this tradeoff: it reacts extremely aggressively to movements in long-run expectations. This way, the central bank hopes to avoid even larger interventions that would become necessary were expectations to unanchor further. To avoid having to pay so high

¹⁵As periodically noted in the literature, adaptive learning models tend to produce impulse responses that exhibit damped oscillations. Authors making explicit note of this phenomenon include Evans and Honkapohja (2001), Evans et al. (2013) and Anufriev and Hommes (2012). The reason is that under an adaptive learning framework, forecast errors following an impulse are oscillatory. In fact, the higher the learning gain, the higher the amplitude of forecast error oscillations. Appendix L presents a simple illustration for why this is the case.

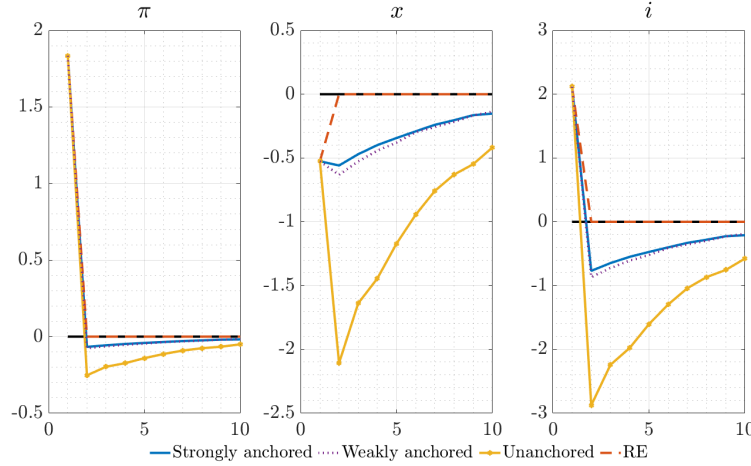


FIGURE 5. IMPULSE RESPONSES AFTER A COST-PUSH SHOCK

Note: Shock imposed at $t = 25$ of a sample length of $T = 400$ (with 5 initial burn-in periods), cross-sectional average with a cross-section size of $N = 100$. The remark on whether expectations are anchored or not refers to whether the gain is below the 10th, in the neighborhood of the 50th, or above the 90th percentile of simulated gains at the time the shock hits.

a price, the central bank is extra aggressive in the short run to prevent massive unanchoring from ever materializing. Thus the optimal response to the volatility tradeoff is to temporarily increase volatility in order to reduce it in the long-run. In this way, the central bank's aggressiveness in the model is driven by the desire to prevent upward (downward) drifting long-run expectations from becoming a self-fulfilling inflationary (deflationary) spiral.

The large interest-rate responses resemble the idea advocated by Goodfriend (1993) that the central bank moves to offset “inflation scare” (or “deflation scare”) episodes. As Goodfriend shows, it was historically not uncommon to move the interest rate by hundreds of basis points to subdue inflation scares. For example, in March 1980, the Fed raised the interest rate by 230 bp to convince the public that it would not tolerate high inflation. The optimal policy function prescribes that this is exactly what the policymaker should do to fight unanchored expectations.

What Fig. 4 also suggests is that acting aggressively in the short run indeed delivers the long-run benefits of stabilizing economic fluctuations. As Panel (b) depicts, employing the optimal policy implies that realized changes in long-run inflation expectations are very small. As seen on the histogram of $\Delta\bar{\pi}$, with the optimal policy in place, the model spends most of its time in the region of minuscule fluctuations in $\bar{\pi}$. The mode of the distribution is a change of 0.3 basis points in absolute value, implying that in normal times, the central bank only needs to raise or lower the interest rate by 15 basis points. In other words, the aggressive nature of optimal policy allows the central bank to keep expectations anchored or quickly reanchor them following shocks. In this way, the monetary

authority eliminates as much volatility stemming from unanchored expectations as it possibly can.

C. Optimal Taylor rule under anchoring

Monetary policy is often formulated using a Taylor rule. Proponents of such a characterization, like Taylor (1993) himself, emphasize the benefits of having a simple, time-invariant and easily verifiable rule. Also in the anchoring model, a policymaker may thus be interested in using a Taylor-type approximation to optimal policy in order to combine the benefits of having a simple, yet near-optimal rule.¹⁶ Therefore I now consider the restricted set of Taylor-type policy rules and ask what value of the time-invariant Taylor-rule coefficient on inflation is optimal in the case of the anchoring model.

In this section, I thus restrict attention to a standard Taylor rule:

$$(41) \quad i_t = \psi_\pi(\pi_t - \pi^*) + \psi_x(x_t - x^*) + \bar{i}_t,$$

where ψ_π and ψ_x represent the responsiveness of monetary policy to inflation and the output gap respectively. Lastly, \bar{i}_t is a monetary policy shock. I also assume that when the Taylor rule is in effect, the central bank publicly announces this. Thus Equation (41) is common knowledge and is therefore not the object of learning. In an extension, I consider the case where the Taylor rule is not known (or not believed) by the public and therefore is learned together with the relations (10) and (11). This only changes model dynamics for a short period of time as long as the Taylor rule has not yet been learned. In the approximately five quarters where the public's learning is in progress, the model's responses are dampened; afterwards, the model dynamics are identical to those of the baseline.

I compute the optimal Taylor rule coefficient on inflation numerically by minimizing the central bank's expected loss in a cross-section of $N = 100$ simulations of both the rational expectations and learning versions of the model. I continue to use the calibration of Tables 1 and 2 and to parameterize the anchoring function using the estimated $\hat{\gamma}$ from Section III.

Table 3 presents the optimal Taylor rule coefficient ψ_π for the rational expectations and anchoring models. The table also compares the baseline parameterization with an alternative in which the central bank attaches no weight to output gap stabilization. One notices that if the central bank has no concern to stabilize the output gap ($\lambda_x = 0$), ψ_π is infinity for RE, but strictly below infinity for the anchoring model. For the rational expectations version of the model, this is because if the central bank suffers no loss upon output variation, then the fact that the divine coincidence is violated does not pose a problem. An infinite inflation

¹⁶Recall from Woodford (2003) that even under rational expectations, a standard Taylor rule is not fully optimal because its purely forward-looking nature precludes the use of promises of future policy. Since Proposition 2 tells us that in the anchoring model there is no distinction between commitment and discretion, this point may be less relevant here than for rational expectations.

coefficient then allows the authority to eliminate inflation fluctuations altogether.

TABLE 3—OPTIMAL COEFFICIENT ON INFLATION, RE AGAINST ANCHORING FOR ALTERNATIVE WEIGHTS ON OUTPUT

	$\psi_{\pi}^{*,RE}$	$\psi_{\pi}^{*,Anchoring}$
Baseline ($\lambda_x = 0.05$)	2.2101	1.1083
$\lambda_x = 0$	∞	1.4421

Not so for the anchoring model. Even for $\lambda_x = 0$, the optimal inflation coefficient is below infinity. Also for the baseline calibration, the monetary authority finds it optimal to choose a significantly lower ψ_{π} in the anchoring model than under RE. Why this is the case can be gleaned from Fig. 6, which depicts the central bank's loss as a function of the inflation coefficient ψ_{π} for the baseline calibration.

As seen on Fig. 6, both models predict a sharp increase in the loss as ψ_{π} is lowered for low values of ψ_{π} . This is intuitive: the lower ψ_{π} , the more inflation fluctuation the central bank tolerates. This leads to losses in both models. In the anchoring model, the loss is further increased by the fact that inflation volatility leads to higher forecast errors. This implies higher fluctuations in expectations, which in turn feed back into inflation. In this manner, the positive feedback loop in the anchoring model in general leads to higher inflation fluctuations in the anchoring model than in the RE version, resulting in a higher loss as well.

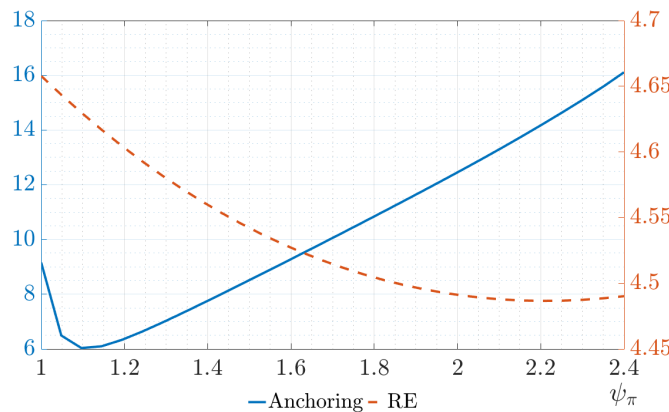


FIGURE 6. CENTRAL BANK LOSS AS A FUNCTION OF ψ_{π}

Note: Sample length is $T = 100$ with a cross-section of $N = 100$.

But Fig. 6 has a more surprising implication too. As opposed to RE, the loss is strongly convex in the anchoring model. In fact, this remains the case

also if the central bank has no concern for output gap stabilization ($\lambda_x = 0$). In the anchoring model, then, the losses caused by tolerating too much inflation volatility cannot be eliminated by raising ψ_π infinitely. This means that beyond a threshold, raising ψ_π actually increases inflation volatility, instead of decreasing it. For this reason, as seen in Table 3, the optimal choice involves a much smaller inflation coefficient under anchoring than under RE (1.1 instead of 2.2). How does this come about?

The mechanism is the following. As the IS curve of Equation (10) makes explicit, the private sector relies on expectations of not just future inflation and output gaps, but also of interest rates when choosing its actions today. A high ψ_π , together with the assumption that the private sector knows the Taylor rule, means that if conditions today cause the private sector to expect high inflation in the future, the private sector will internalize future policy responses and therefore also expect high interest rates down the line. This implies a shift in the entire term structure of expectations, adding fuel to the positive feedback between expectations and outcomes. But not only that. The fact that agents can anticipate future policy actions induces oscillatory expectations, as adverse shocks today are expected to be offset by expansionary policy, et vice versa.¹⁷ In the case of the private sector internalizing the policymaker's reaction function, then, anticipation effects of future interest rates play a key role in determining the conduct of policy.

We can see how this plays out by contrasting impulse responses of the model for various levels of inflation aggressiveness ψ_π , depicted on Fig. 7, again for an inflationary cost-push shock. A small value of $\psi_\pi = 1.01$ imposes too little negative feedback to get inflation back to its pre-shock value fast. A too high value of ψ_π has the contrary effect: the impulse responses overshoot. In fact, the higher ψ_π , the larger the overshooting. This highlights the anticipation effects of future interest rates. When the contractionary monetary policy shock hits, inflation and the output gap fall on impact. By the next period, expectations update, initially implying lower future inflation and output gaps. But an internalized Taylor rule means that the private sector connects low future inflation with expansionary policy going forward. This expectation causes the overshoot.

The model dynamics here resemble the predictions of Ball (1994) of expansionary disinflation. Ball (1994) observes that an overlooked implication of rational expectations New Keynesian models is that disinflations are expansionary. Since the prediction that disinflation is costless, indeed expansionary, is at odds with data, Ball concludes that central bank announcements must suffer from credibility issues that render expectations unresponsive to the announcement of a coming disinflation.

Note that in the present context, as seen on Fig. 5, the amplitude of the oscillations depends positively on the size of the gain. In other words, the more

¹⁷In a more general specification of the model where the private sector does not initially know the Taylor rule, impulse responses take time to become oscillatory because as long as the Taylor rule is not yet learned, intertemporal anticipation effects cannot play out. But eventually as the Taylor rule is internalized, impulse responses oscillate exactly as in the present version of the model.

unanchored expectations are, the more impulse responses look as Ball (1994) predicts: we obtain an expansionary disinflation. This feature indicates that the key difference between Ball's interpretation and my model is what channel generates the unresponsiveness of expectations. Thus I arrive at a different conclusion than Ball (1994); instead of credibility issues, it is anchored expectations that are responsible for the absence of expansionary disinflations.

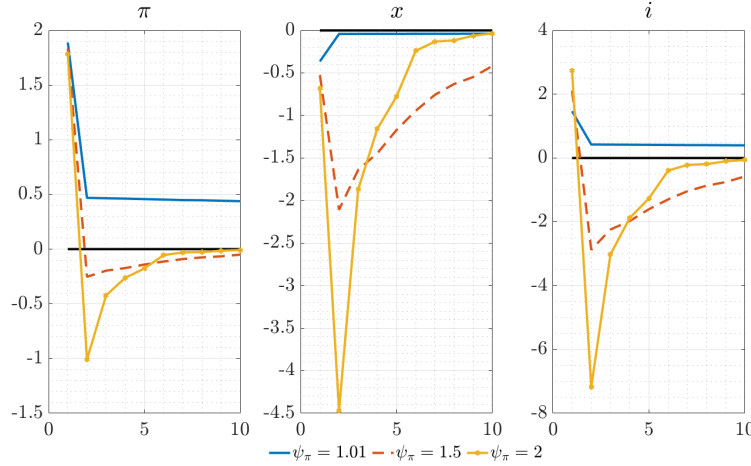


FIGURE 7. IMPULSE RESPONSES FOR UNANCHORED EXPECTATIONS FOR VARIOUS VALUES OF ψ_π

Note: Cost-push shock imposed at $t = 25$ of a sample length of $T = 400$ (with 5 initial burn-in periods), cross-sectional average with a cross-section size of $N = 100$.

In contrast to the conventional wisdom in the adaptive learning literature, as exemplified for example by Orphanides and Williams (2004), I thus find that monetary policy specified as a Taylor rule should be *less* aggressive on inflation than what would be optimal under rational expectations. Technically speaking, the difference stems from two sources. The first is whether one models the aggregate relationships of the model as corresponding to the learning assumptions concerning individual agents. As suggested in Section II, the majority of the papers in the learning literature consider Euler-equation learning. This implies that long-horizon expectations do not enter the IS and Phillips curves.

By contrast, relying on Preston (2005)'s long-horizon learning approach reintroduces the full term structure of expectations into the IS and Phillips curves and thus assigns a role to interest-rate expectations. Eusepi, Giannoni and Preston (2018) is the first to use the long-horizon approach to investigate the interaction between long-horizon learning and interest-rate expectations. Unsurprisingly, they reach the same conclusions as I do: anticipation effects coming from interest-rate expectations force the central bank to be less aggressive on inflation than it would be under rational expectations.

Secondly, the anchoring mechanism is responsible for the lower optimal value of the inflation coefficient. Standard specifications of the gain in the adaptive learning tradition involve no channel through which monetary policy could affect the learning of agents. Whether the gain is constant or deterministically decreasing, there is no link between the interest-rate setting of the central bank and the gain.

Here, however, the anchoring mechanism relates the gain to forecast errors. Forecast errors, in turn, arise as a function of central bank action, in particular of whether the central bank is able keep inflation at the private sector's perceived mean. Movements in the interest rate, then, are a double-edged sword: in contributing to get inflation to the target, they can close forecast errors and thus stabilize long-run expectations. But any central bank intervention also results in adjustments in expectations (either because it takes the private sector by surprise, or because the private sector understands its implications for future policy), increasing the volatility of observables.

This highlights that the time-varying nature of optimal policy is its key characteristic. The ability to take the stance of anchoring into account is what enables the central bank to be exceedingly aggressive if and only if expectations are about to unanchor, and maintain a dovish stance otherwise. Thus it seems reasonable to expect that if the central bank were allowed to select time-varying Taylor-rule coefficients, it would choose low coefficients when expectations are anchored and high ones when expectations show signs of unanchoring. Such a central bank, as well as one following the optimal policy, would appear to the econometrician as time-varying, echoing the findings of Lubik and Matthes (2016).

V. Conclusion

Central bankers frequently voice a concern to anchor expectations, that is, to render expectations of long-run inflation unresponsive to short-run economic conditions. The contribution of this paper is to lay out a simple behavioral model which captures the time-varying sensitivity of long-run expectations to short-run conditions and to investigate how this affects the conduct of monetary policy. I quantify my novel anchoring mechanism by estimating the form of the function that determines the degree of unanchoring. I use the model to characterize monetary policy both analytically and numerically.

The simulated method of moments estimation establishes that the anchoring function provides a realistic description of expectations. On the one hand, expectations become more sensitive to forecast errors when the private sector made larger mistakes in predicting inflation in the past. On the other hand, like in Hebden et al. (2020), negative mistakes unanchor expectations more than positive ones of the same magnitude do. Moreover, I use the estimated anchoring function to back out an implied time series for the gain, the model's metric for the degree of unanchoring. The median gain, 0.098, is in line with estimates in the literature such as Milani (2014) and Carvalho et al. (2019), and implies that agents in the model discount observations older than 10 quarters when updating

their long-run expectations.

Using the thus quantified model, I provide three sets of results on monetary policy. I first consider the Ramsey policy of the central bank, deriving an analytical target criterion that prescribes how the monetary authority should respond to shocks. I show that the presence of my novel anchoring channel makes it desirable and feasible to smooth out shocks over time. However, the extent this is feasible varies over time in tandem with the current and expected future degree of unanchoring.

Second, I use global methods to solve the nonlinear system of first-order conditions of the Ramsey problem numerically. I thus obtain an approximation to the optimal policy function, providing the fully optimal path of interest rates conditional on the sequence of exogenous disturbances. Like in Goodfriend (1993)'s account of US monetary policy, the optimal policy involves responding aggressively when expectations unanchor in order to suppress the volatility that high degrees of unanchoring cause. By contrast, the central bank need not intervene when expectations are anchored, resulting in accommodating inflation fluctuations in this case.

Lastly, I explore the implications of the model for the most common specification of monetary policy, the Taylor rule. As my numerical solution for the optimal inflation coefficient demonstrates, the central bank should be less aggressive on inflation in my model than under rational expectations. The first reason is that a time-invariant Taylor rule involves the same response to a given movement in inflation regardless of the degree of unanchoring. Second, as in Eusepi, Giannoni and Preston (2018), interest-rate expectations impose limits on how aggressive the policymaker can be. Therefore, the central bank induces additional volatility into the model if it responds too aggressively to fluctuations in inflation. An optimal inflation coefficient in my model is able to eliminate the majority of such additional volatility.

A number of interesting questions emerge from the analysis of monetary policy and the anchoring expectation formation. One may wonder whether the central bank can use tools other than its leading interest rate to anchor expectations. Especially concerns around a binding zero lower bound would motivate the use of alternative monetary policy tools. Thus the interaction between anchoring and central bank communication, in particular forward guidance, would be worthwhile to examine. In future work, I plan to make explicit the communication policy of the central bank to investigate whether the anchoring expectation formation could help to resolve the forward guidance puzzle.

This, however, requires overcoming the implication of Proposition 2 that adaptive expectations are not able to incorporate any information that is not embedded in the current state vector. One option is to model central bank communication similarly to news shocks in the sense of Beaudry and Portier (2006). In this case, the anchoring model is likely to deliver differing predictions regarding the effectiveness of Delphic versus Odyssean forward guidance (Campbell et al. (2012))

because sharing the central bank's forecasts would not constitute a questioning of the interest rate reaction function, while committing to a future interest rate path would.

From this perspective, it is desirable to extend models of adaptive expectations in general to allow the private sector to internalize promises of the policymaker. As discussed in Section IV.A, the inability to incorporate communication stems from the fact that adaptive expectations involve a sub-optimal expectation formation. Viewed from the lens of an infinitely repeated game, the private sector is an automaton. One would thus need to reintroduce some notion of optimality into expectation formation that would render the private sector a strategic player. Such an extension would likely be akin to the reputation-building literature à la Cho and Matsui (1995) or to the finite planning-horizon model of Woodford (2019).

Presumably, there are variables other than long-run inflation where expectations exhibit varying degrees of unanchoring. For instance, fixed exchange rate regimes might become subject to speculative attacks the moment when the peg is no longer believed by the public. Exploring the causes and timing of currency crises is thus a natural application of my model which I plan investigate in future research.

In general, extensions to the anchoring expectation formation proposed here would be of interest. The determination of the gain could be endogenized using approaches that allow the private sector to choose its forecasting behavior in an optimizing fashion, perhaps by selecting among competing forecasting models as in Branch and Evans (2011) or by picking the size of the gain to minimize the estimated forecast error variance.

Lastly, a foray into the empirics of anchoring expectation formation is important to get a clearer idea of the expectation formation process of the public. In practice, it is likely that this process is heterogenous, not just across households and firms, but also within various demographic groups or sectors of the economy. If so, then monetary policy would need to collect and monitor a host of long-run expectations time series to manage the challenge of keeping expectations anchored.

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ROBUSTNESS OF ROLLING REGRESSION RESULTS

I investigate the following alternative specifications. As a first check, I replace the forecast error with realized CPI inflation. Thus Equation (1) becomes

$$(A1) \quad \Delta \bar{\pi}_t^i = \beta_0 + \beta_1^w \pi_t + \epsilon_t^i.$$

I then consider the original specification of Equation (1), adding realized CPI inflation to control for inflation levels.¹⁸ This results in the following regression:

$$(A2) \quad \Delta \bar{\pi}_t^i = \beta_0^w + \beta_1^w f_{t|t-1}^i + \beta_2^w \pi_t + \epsilon_t^i.$$

In the last alternative specification, I replace both the ten and the one-year ahead CPI inflation expectation with PCE core. The regression equation thus looks identical to Equation (1) but cleans out the effects of movements in oil prices:

$$(A3) \quad \Delta \bar{\pi}_t^i = \beta_0^w + \beta_1^w f_{t|t-1}^i + \epsilon_t^i.$$

The three alternative time series of the estimate $\hat{\beta}_1^w$ are depicted in Fig. A1. Qualitatively, the same conclusion obtains as in the specification in the main text: the coefficients are time-varying in size and in statistical significance. In particular, large sensitivity in the 1990s gives way to an insignificant coefficient in the early 2000s, to drift back up shortly after 2010. The data is much shorter for the PCE core specification, but also in this case one observes the upward drift in the estimated coefficient starting around 2010.

ALTERNATIVE MEASURES OF LONG-RUN INFLATION EXPECTATIONS

Measuring long-run expectations is challenging. In particular, two dimensions of expectations are hard to line up between models and data: the identity of the economic agent forming expectations, and the forecast horizon. To start with the former, one would ideally wish to measure the expectations of the private sector, firms and households, since their expectations correspond to the ones in economic models. As for the forecast horizon, no single horizon is an exact counterpart to the concept of expectations of average inflation. Arguably, the longer the forecast horizon, the closer the measured expectation is to expectations of the average.

These considerations can lead the researcher to utilize breakeven inflation, that is, the difference between Treasury yields and Treasury Inflation Protected Securities (TIPS) (top panel of Fig. B1). There are two main advantages of constructing

¹⁸In a separate specification, I have similarly added uncertainty as a control, but it is so similar that I suppress it here.

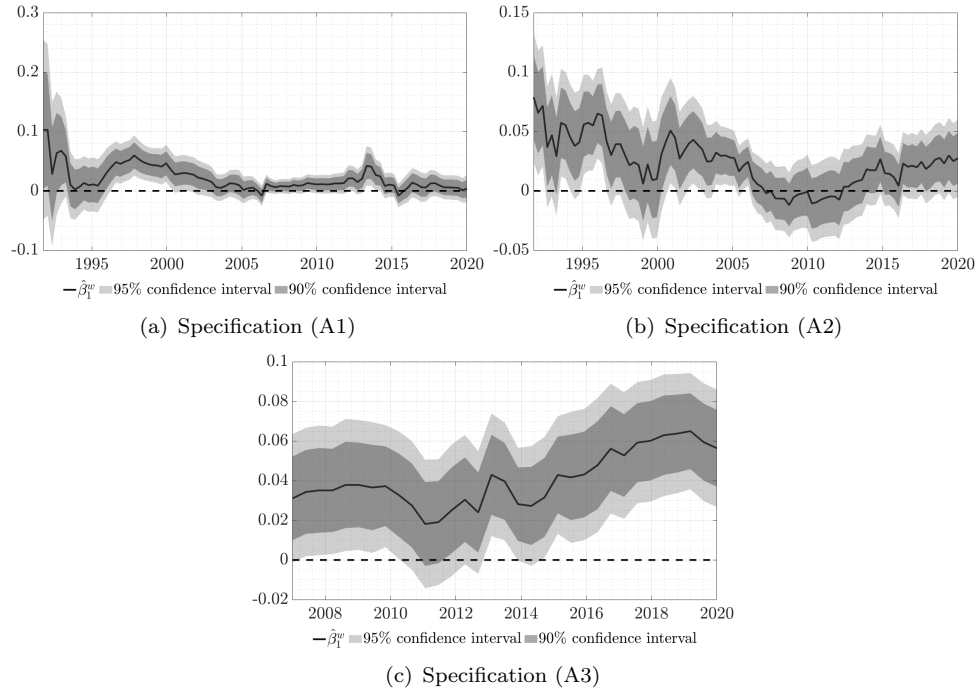


FIGURE A1. TIME SERIES OF RESPONSIVENESS OF LONG-RUN INFLATION EXPECTATIONS TO INFLATION

Note: Appendix B discusses alternative measures of long-run inflation.

inflation expectation measures from TIPS. First, since this measure is based on trades that happened in the Treasury market, it pertains to agents who are active in a market where inflation expectations matter. Such expectations are therefore a good proxy for the private sector's expectations in economic models. Second, the fact that breakeven inflation is not elicited from surveys allows the econometrician to bypass many of the challenges that survey data involve. It has been widely documented that survey participants may have poor understanding of the economic concept elicited, may misunderstand the survey questions or be unduly influenced by the wording. Most troubling is the fact that there is no way the econometrician could control for the noise thus introduced in survey data.

Breakeven inflation measures are not a panacea, however. The illiquidity of TIPS markets introduces a distortion into the measured expectations in the form of a time-varying liquidity premium (Appendix C corrects for this by filtering out an approximate liquidity premium series from the 10-year expectation series.) One could also contend that many firms and the majority of households are not active on the TIPS market, and therefore that breakeven inflation is not representative of the economy-wide expectation. For this reason, I turn to alternative long-run inflation measures.

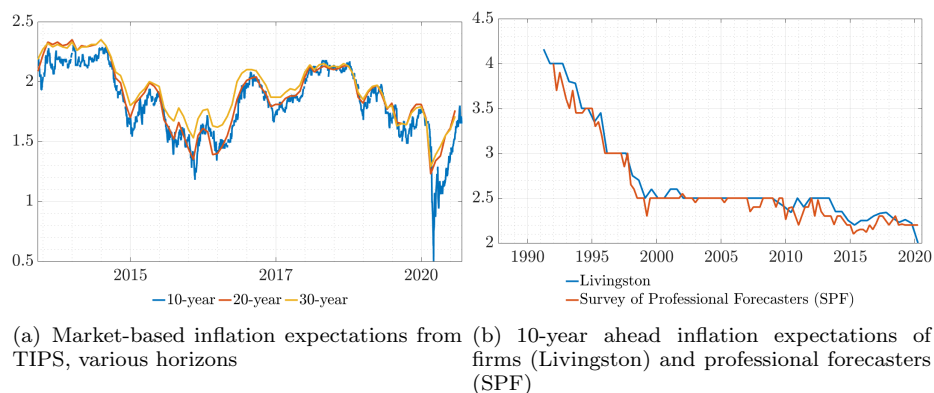


FIGURE B1. ALTERNATIVE LONG-RUN INFLATION EXPECTATIONS MEASURES

Note: All inflation rates are annualized percentages. The series are at the following frequency: daily (10-year TIPS), monthly (20- and 30-year TIPS), quarterly (SPF), twice per year (Livingston).

The forecast horizon is a binding constraint: consumer expectations data have a maximal forecast horizon of three (New York Fed Survey of Consumer Expectations (SCE)) or five years (University of Michigan Survey of Consumers). To have at least a forecast horizon of ten years, I thus resort to the Livingston Survey of the Philadelphia Fed and the Survey of Professional Forecasters (SPF). Another advantage of the SPF is that comprehensive individual-level data is available, a feature which I exploit for the regressions in the Introduction and in Appendix A.

Fig. B1 plots the breakeven inflation series for a horizon of 10, 20 and 30 years (top panel) alongside Livingston and SPF (bottom panel). The breakeven inflation measures are clearly and consistently below the Livingston and SPF measures. Part of this may be driven by liquidity premia, which I control for in Appendix C. At the same time, both the Livingston and the SPF expectations may potentially suffer from representativeness issues. The fact that the two expectations series are so closely aligned indicates that the Livingston survey may only be reaching a subset of firms.¹⁹ This subset seems to be highly correlated with the set of professional forecasters filling out the SPF. This is a concern because it suggests that the elicited expectations may not be representative of the economy-wide firm expectations. Moreover, if professional forecasters respond to the survey by running a (by assumption stationary) econometric model, then the survey responses may not even accurately reflect their held beliefs.

But all these caveats notwithstanding, there is a single element that is consistent across all of these measures of long-run inflation expectations: following 2010,

¹⁹The category codes of individual survey participants in the Livingston survey seems to underscore this. According to the documentation, the surveyed businesses fall into the following categories: academic institution, commercial banking, consulting, Federal Reserve, government, industry trade group, insurance company, investment banking, labor, non-financial business and other.

they all shift downward. In other words, they all show responsiveness to the fact that the Federal Reserve has undershot the 2% inflation target. Given that the Livingston and SPF measures are initially above the 2% target, one may argue that expectations are only adjusting following the 2012 announcement of an official target on the part of the Fed.

However, the 2% target was already understood prior to the 2012 announcement. Moreover, the Fed's target is specified in terms of PCE inflation, while the Livingston and SPF forecasts pertain to CPI inflation. The fact that the latter tends to be higher than the former also helps to explain why expectations of CPI inflation are above the Fed's PCE inflation target.

FILTERING OUT LIQUIDITY RISK FROM TIPS

Some caution is needed when inferring inflation expectations from TIPS. The underlying idea is that the difference between real (indexed to inflation) and nominal yields should be a good metric for the market's expectations of inflation on average for the duration of the particular maturity. But since TIPS markets face liquidity issues, especially for seasoned securities, the TIPS yield also incorporates a liquidity premium. The positive bias in the TIPS yield thus leads to a negative bias in expected inflation.

To gauge the presence of liquidity risk in TIPS, I rely on Andreasen, Christensen and Riddell (2018)'s estimation of the liquidity premium. Since their series only covers the period between July 11, 1997 - Dec 27, 2013, I make use of the fact that they demonstrate a high correlation between liquidity risk and uncertainty. In particular, a regression of their average TIPS liquidity premium measure on the VIX index and controls yields an estimated coefficient of 0.85 (significant at the 1 percent level), with a constant of -5.21. Thus I can use the VIX to back out a fitted Andreasen, Christensen and Riddell (2018) estimate of the TIPS liquidity premium after 2013. Doing so, I subtract this fitted liquidity premium series from the TIPS yields, allowing me to construct an estimate of breakeven inflation corrected for the liquidity risk bias. Fig. C1 presents the original breakeven inflation series, along with the bias-corrected estimate.

In line with Andreasen, Christensen and Riddell (2018)'s findings, I obtain a negative bias in the inflation expectations series throughout the sample. This bias averages -0.0966 pp, which is sizable, but not as significant as one might have suspected. Also in analogy with Andreasen, Christensen and Riddell (2018)'s results, I find that liquidity issues in the TIPS market pose a bigger problem in recessions, when the market worries more about future TIPS becoming illiquid. In particular once the Covid-19-shock raises worries at the end of the sample, the estimated liquidity premium hits its highest value of 0.6508 pp. Even this large upward correction in breakeven inflation does not change the overall picture, however. The conclusion that long-run inflation expectations trend downward in the second half of the decade remains solid.

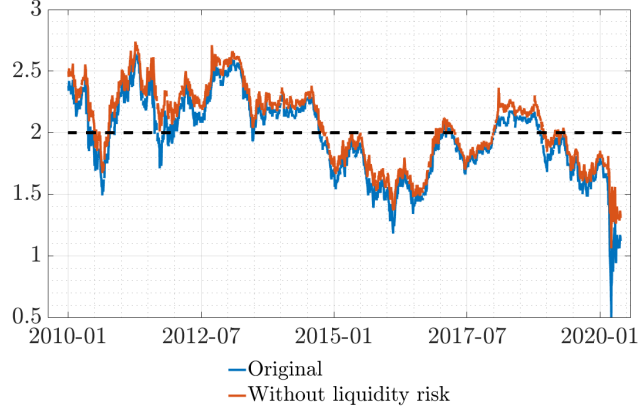


FIGURE C1. MARKET-BASED INFLATION EXPECTATIONS, 10 YEAR, AVERAGE, %

Note: reakeven inflation, constructed as the difference between the yields of 10-year Treasuries and 10-year TIPS (blue line), difference between 10-year Treasury and 10-year TIPS, the latter cleaned from liquidity risk (red line).

COMPACT MODEL NOTATION

The A matrices are given by

$$A_a = \begin{pmatrix} g_{\pi a} \\ g_{x a} \\ \psi_{\pi} g_{\pi a} + \psi_x g_{x a} \end{pmatrix}, \quad A_b = \begin{pmatrix} g_{\pi b} \\ g_{x b} \\ \psi_{\pi} g_{\pi b} + \psi_x g_{x b} \end{pmatrix},$$

$$A_s = \begin{pmatrix} g_{\pi s} \\ g_{x s} \\ \psi_{\pi} g_{\pi s} + \psi_x g_{x s} + [0 \quad 1 \quad 0] \end{pmatrix},$$

with

$$g_{\pi a} = \left(1 - \frac{\kappa \sigma \psi_{\pi}}{w}\right) [(1 - \alpha)\beta, \kappa \alpha \beta, 0],$$

$$g_{x a} = \frac{-\sigma \psi_{\pi}}{w} [(1 - \alpha)\beta, \kappa \alpha \beta, 0],$$

$$g_{\pi b} = \frac{\kappa}{w} [\sigma(1 - \beta \psi_{\pi}), (1 - \beta - \beta \sigma \psi_x), 0],$$

$$g_{x b} = \frac{1}{w} [\sigma(1 - \beta \psi_{\pi}), (1 - \beta - \beta \sigma \psi_x), 0],$$

$$g_{\pi s} = \left(1 - \frac{\kappa \sigma \psi_{\pi}}{w}\right) [0 \quad 0 \quad 1] (I_3 - \alpha \beta h)^{-1} - \frac{\kappa \sigma}{w} [-1 \quad 1 \quad 0] (I_3 - \beta h)^{-1},$$

$$g_{x s} = \frac{-\sigma \psi_{\pi}}{w} [0 \quad 0 \quad 1] (I_3 - \alpha \beta h)^{-1} - \frac{\sigma}{w} [-1 \quad 1 \quad 0] (I_3 - \beta h)^{-1},$$

$$w = 1 + \sigma \psi_x + \kappa \sigma \psi_{\pi}.$$

The matrices of the state transition equation (15) are

$$(D1) \quad h \equiv \begin{pmatrix} \rho_r & 0 & 0 \\ 0 & \rho_i & 0 \\ 0 & 0 & \rho_u \end{pmatrix}, \quad \epsilon_t \equiv \begin{pmatrix} \varepsilon_t^r \\ \varepsilon_t^i \\ \varepsilon_t^u \end{pmatrix}, \quad \text{and} \quad \eta \equiv \begin{pmatrix} \sigma_r & 0 & 0 \\ 0 & \sigma_i & 0 \\ 0 & 0 & \sigma_u \end{pmatrix}.$$

Note that this is the formulation for the case where a Taylor rule is in effect and is known by the private sector. It is straightforward to remove any of these two assumptions.

THE OBSERVATION MATRIX FOR LEARNING

Instead of the matrix g in the rational expectations observation equation

$$(E1) \quad z_t = g s_t,$$

agents in the anchoring model use the estimated matrix g^l

$$(E2) \quad g_{t-1}^l = [F_{t-1} \quad G_{t-1}],$$

with

$$(E3) \quad F_{t-1} = \left(A_a \frac{1}{1 - \alpha\beta} + A_b \frac{1}{1 - \beta} \right) a_{t-1},$$

$$(E4) \quad G_{t-1} = A_a b_{t-1} \left(I_3 - \alpha\beta h \right)^{-1} + A_b b_{t-1} \left(I_3 - \beta h \right)^{-1} + A_s.$$

ALTERNATIVE SPECIFICATIONS FOR THE ANCHORING FUNCTION

The general law of motion for the gain in the main text is given by Equation (23), reproduced here for convenience:

$$(F1) \quad k_t = \mathbf{g}(k_{t-1}, f_{t|t-1}).$$

The baseline specification of the anchoring function \mathbf{g} (Equation (31) in the main text) is

$$(F2) \quad \mathbf{g} = \sum_i \gamma_i b_i(f_{t|t-1}),$$

where $b_i(f_{t|t-1})$ is the piecewise linear basis at node i and $\hat{\gamma}$ are the coefficients estimated in Section III.

To my knowledge, there are only two other papers that consider an endogenous gain as a model for anchored expectations. The first one, more related to this paper, is Carvalho et al. (2019). In their model, the anchoring function is a discrete choice function as follows. Let θ_t be a criterion to be defined. Then, for

a threshold value $\tilde{\theta}$, the gain evolves according to

$$(F3) \quad k_t = \begin{cases} (k_{t-1} + 1)^{-1} & \text{if } \theta_t < \tilde{\theta}, \\ \bar{g} & \text{otherwise.} \end{cases}$$

In other words, agents choose a decreasing gain when the criterion θ_t is lower than the threshold $\tilde{\theta}$; otherwise they choose a constant gain. The criterion employed by Carvalho et al. (2019) is computed as the absolute difference between subjective and model-consistent expectations, scaled by the variance of shocks:

$$(F4) \quad \theta_t = \max|\Sigma^{-1}(\phi_{t-1} - [F_{t-1} \ G_{t-1}])|,$$

where Σ is the VC matrix of shocks, ϕ_{t-1} is the estimated matrix and $[F, G]$ is the ALM (see Appendix E).

As a robustness check, Carvalho et al. (2019) also compute an alternative criterion.²⁰ Let ω_t denote agents' time t estimate of the forecast error variance and θ_t be a statistic evaluated by agents in every period as

$$(F5) \quad \omega_t = \omega_{t-1} + \tilde{\kappa}k_{t-1}(f_{t|t-1}f'_{t|t-1} - \omega_{t-1}),$$

$$(F6) \quad \theta_t = \theta_{t-1} + \tilde{\kappa}k_{t-1}(f'_{t|t-1}\omega_t^{-1}f_{t|t-1} - \theta_{t-1}),$$

where $\tilde{\kappa}$ is a parameter that allows agents to scale the gain compared to the previous estimation and $f_{t|t-1}$ is the most recent forecast error, realized at time t . Indeed, this is a multivariate time series version of the squared CUSUM test.²¹

It is interesting to compare the two discrete anchoring functions with my smooth specification. On the one hand, Carvalho et al. (2019)'s preferred specification requires the private sector to evaluate model-consistent expectations, which runs counter to the maintained informational assumptions. It is more consistent with the present model, then, to assume that firms and households employ a statistical test of structural change, as is the case with the CUSUM-based and smooth functions. These are therefore more appealing on conceptual grounds.

On the other hand, simulation of the model using the different anchoring specifications reveals that Carvalho et al. (2019)'s preferred functional form leads to the opposite comparative statics of anchoring with respect to monetary policy aggressiveness as the smooth or the CUSUM-based specifications. In particular, policy that is more aggressive on inflation (a higher ψ_π in the Taylor rule) leads to more anchoring in a model with the smooth or the CUSUM-inspired criterion. If one uses Carvalho et al. (2019)'s criterion, the same comparative static involves *less* anchoring. This comes from the fact that Carvalho et al. (2019)'s criterion endows the private sector with capabilities to disentangle volatility due to the

²⁰Note that for both criteria, I present the matrix generalizations of the scalar versions considered by Carvalho et al. (2019).

²¹See Brown, Durbin and Evans (1975) and Lütkepohl (2013) for details.

learning mechanism from that owing to exogenous disturbances. Thus agents in the Carvalho et al. (2019) model are able to make more advanced inferences about the performance of their forecasting rule and understand that a higher ψ_π causes more learning-induced volatility. This is however not possible for agents who process data in real time without knowledge of the model. Therefore my smooth and the discrete CUSUM-inspired specifications are preferable both on conceptual and quantitative grounds.

There are two main reasons I opt for a smooth anchoring function instead of the discrete CUSUM criterion. First, the analytical analysis of this paper requires derivatives of the anchoring function to exist. In such a case, the smooth specification is necessary. Second, a smooth anchoring function can capture varying degrees of unanchoring, which is a feature of the data I document in the Introduction.

The second paper with an anchoring function is Gobbi, Mazzocchi and Tamborini (2019). In their model, which is a three-equation New Keynesian model, firms and households entertain the possibility that the model may switch from a “normal” regime to a liquidity trap regime that the authors name the “new normal.” Expectations are a probability-weighted average of the regime-specific expectations. The concept of unanchoring in the model is when p , the probability of the liquidity trap regime, rises significantly. The function governing the evolution of p , which Gobbi, Mazzocchi and Tamborini (2019) refer to as the deanchoring function (DA), is the analogy of my anchoring function. The authors use the following logistic specification for the DA function:

$$(F7) \quad p = h(y_{t-1}) = A + \frac{BCe^{-Dy_{t-1}}}{(Ce^{-Dy_{t-1}} + 1)^2},$$

where y_{t-1} denotes the output gap and A, B, C and D are parameters.

ESTIMATION PROCEDURE

The estimation of Section III is a simulated method of moments (SMM) exercise. As elaborated in the main text, I target the autocovariances of CPI inflation, the output gap, the federal funds rate and the 12-months ahead inflation forecasts coming from the Survey of Professional Forecasters. For the autocovariances, I consider lags $0, \dots, 4$. The target moment vector, Ω , is the vectorized autocovariance matrices for the lags considered, 80×1 .

Let Θ denote the set of parameters in the New Keynesian model that I calibrate. Then, for each proposed coefficient vector γ , the estimation procedure consists of simulating the model conditional on γ , Θ and N different sequences of disturbances, then computing model-implied moments for each simulation, and lastly choosing γ such that the squared distance between the data- and model-implied mean moments is minimized. Thus

$$(G1) \quad \hat{\gamma} = \left(\Omega^{data} - \frac{1}{N} \sum_{n=1}^N \Omega^{model}(\gamma, \Theta, \{e_t^n\}_{t=1}^T) \right)' W^{-1} \left(\Omega^{data} - \frac{1}{N} \sum_{n=1}^N \Omega^{model}(\gamma, \Theta, \{e_t^n\}_{t=1}^T) \right),$$

where the observed data is of length $T = 151$ quarters. Here $\{e_t^n\}_{t=1}^T$ is a sequence of disturbances of the same length as the data; note that I use a cross-section of N such sequences and take average moments across the cross-section to wash out the effects of particular disturbances. Experimentation with the number N led me to choose $N = 1000$, as estimates no longer change upon selecting larger N .

Before computing moments, I filter both the observed and model-generated data using the Baxter and King (1999) filter, with thresholds at 6 and 32 quarters and truncation at 12 lags, the recommended values of the authors. I then compute the moments by fitting a reduced-form VAR to the filtered series and using the estimated coefficients to back out autocovariances. Because there are four observables to three structural shocks and occasionally low volatility in the expectation series, I estimate the VAR coefficients by ridge regression with a tuning parameter of 0.001. This is to ensure that the VAR coefficients are estimated with a lower standard error, so that estimated variances of the moments are more accurate. As the weighting matrix of the quadratic form in the moments, I use the inverse of the estimated variances of the target moments, W^{-1} , computed from 10000 bootstrapped samples.

To improve identification, I also impose restrictions on the estimates. First, I require that the γ -coefficients be convex, that is, that larger forecast errors in absolute value be associated with higher gains. Second, since forecast errors close to zero render the size of the gain irrelevant (cf. the learning equation (21)), I impose that the coefficient associated with a zero forecast error should be zero. Both restrictions are implemented with weights penalizing the loss function, and the weights are selected by experimentation.

Both additional assumptions reflect properties that the anchoring function should reasonably exhibit. The convexity assumption captures the very notion that larger forecast errors in absolute value suggest bigger changes to the forecasting procedure are necessary. This is thus a very natural requirement. As for the zero gain for zero forecast error assumption, the idea here is to supply the estimation with information where it is lacking. Since the updating of learning coefficients corresponds to gain times forecast error, as Equation (21) recalls, a zero forecast error supplies no information for the value of the gain. To impose a zero value here also seems natural, given that since forecast errors switch sign at zero, one would expect the zero forecast error point to be an inflection point

in the anchoring function. By the same token, Gobbi, Mazzocchi and Tamborini (2019) also impose a related restriction when they require that their deanchoring function should yield a zero value at the zero input. Lastly, the objective function does not deteriorate upon imposing either assumption, suggesting that they are not at odds with the data.

Lastly, I supply 100 different initial points and select the estimate involving the lowest value for the loss (G1). Fig. G1 presents the autocovariances of the observed variables for the estimated coefficients so obtained.

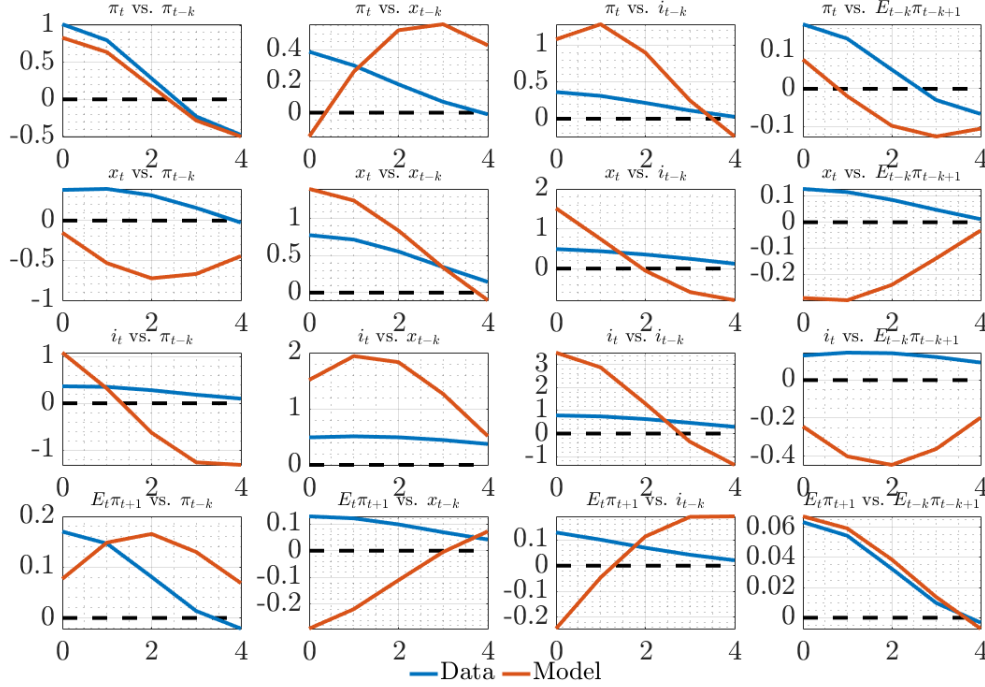


FIGURE G1. AUTOCOVARIOGRAM

Note: Estimates for $N = 1000$.

THE POLICY PROBLEM IN THE SIMPLIFIED BASELINE MODEL

Denote by $\mathbf{g}_{i,t} \in (0, 1)$, $i = \pi, \bar{\pi}$, the potentially time-varying derivatives of the anchoring function \mathbf{g} . In this simplified setting, $\bar{\pi}_t = e_1 a_t$, the estimated constant for the inflation process. As in the main text, e_i is a selector vector, selecting row i of the subsequent matrix. I also use the notation $b_i \equiv e_i b$. The planner chooses $\{\pi_t, x_t, f_{a,t}, f_{b,t}, \bar{\pi}_t, k_t\}_{t=t_0}^{\infty}$ to minimize

(H1)

$$\begin{aligned}
\mathcal{L} = & \mathbb{E}_{t_0} \sum_{t=t_0}^{\infty} \beta^{t-t_0} \left\{ (\pi_t^2 + \lambda_x x_t^2) \right. \\
& + \varphi_{1,t} \left(\pi_t - \kappa x_t - (1-\alpha)\beta f_{a,t} - \kappa\alpha\beta b_2(I_3 - \alpha\beta h)^{-1} s_t - e_3(I_3 - \alpha\beta h)^{-1} s_t \right) \\
& + \varphi_{2,t} \left(x_t + \sigma i_t - \sigma f_{b,t} - (1-\beta)b_2(I_3 - \beta h)^{-1} s_t + \sigma\beta b_3(I_3 - \beta h)^{-1} s_t \right. \\
& \left. \left. - \sigma e_1(I_3 - \beta h)^{-1} s_t \right) \right. \\
& + \varphi_{3,t} \left(f_{a,t} - \frac{1}{1-\alpha\beta} \bar{\pi}_{t-1} - b_1(I_3 - \alpha\beta h)^{-1} s_t \right) \\
& + \varphi_{4,t} \left(f_{b,t} - \frac{1}{1-\beta} \bar{\pi}_{t-1} - b_1(I_3 - \beta h)^{-1} s_t \right) \\
& + \varphi_{5,t} \left(\bar{\pi}_t - \bar{\pi}_{t-1} - k_t(\pi_t - (\bar{\pi}_{t-1} + b_1 s_{t-1})) \right) \\
& \left. + \varphi_{6,t} \left(k_t - \mathbf{g}(\pi_t - \bar{\pi}_{t-1} - b_1 s_{t-1}) \right) \right\},
\end{aligned}$$

where ρ_i are Lagrange-multipliers on the constraints. After a little bit of simplifying, the first-order conditions boil down to the following three equations:

$$(H2) \quad 2\pi_t + 2\frac{\lambda_x}{\kappa}x_t - \varphi_{5,t}k_t - \varphi_{6,t}\mathbf{g}_{\pi,t} = 0,$$

$$(H3) \quad -\frac{2(1-\alpha)\beta}{1-\alpha\beta}\frac{\lambda_x}{\kappa}\mathbb{E}_t x_{t+1} + \varphi_{5,t} - (1-k_t)\mathbb{E}_t \varphi_{5,t+1} + \mathbf{g}_{\bar{\pi},t}\mathbb{E}_t \varphi_{6,t+1} = 0,$$

$$(H4) \quad \varphi_{6,t} = (\pi_t - \bar{\pi}_{t-1} - b_1 s_{t-1})\varphi_{5,t}.$$

Note that Equation (H2) is the analogue of Gaspar, Smets and Vestin (2010)'s Equation (22) (or, equivalently, of Molnár and Santoro (2014)'s (16)), except that there is an additional multiplier, φ_6 . This multiplier reflects the fact that in addition to the constraint coming from the expectation process itself, with shadow value φ_5 , learning involves the gain equation as a constraint as well. One can also clearly read off Proposition 2: when the learning process has converged such that neither expectations nor the gain process are constraints ($\varphi_5 = \varphi_6 = 0$), the discretionary inflation-output gap tradeoff familiar from Clarida, Gali and Gertler (1999) obtains. Combining the above three equations and solving for $\varphi_{5,t}$, using the notation that $\prod_0^0 \equiv 1$, one obtains the target criterion (34).

The system of first-order conditions (38)-(39) and model equations for this simplified system also reveal how the endogenous gain introduces nonlinearity to

the equation system. In particular, notice how in equations (38)-(39), the gain k_t shows up multiplicatively with the Lagrange multiplier, $\varphi_{2,t}$. In fact, the origin of the problem is the recursive least squares learning equation for the learning coefficient $\bar{\pi}_t$

$$(H5) \quad \bar{\pi}_t = \bar{\pi}_{t-1} + k_t f_{t|t-1}$$

where the first interaction terms between the gain and other endogenous variables show up. This results in an equation system of nonlinear difference equations that does not admit an analytical solution.

Considering equation (H5) is instructive to see how it is indeed the endogeneity of the gain that causes these troubles. Were we to specify a constant gain setup, k_t would merely equal the constant \bar{g} and the anchoring function $\mathbf{g}(\cdot)$ would trivially reduce to zero as well. In such a case, all interaction terms would reduce to multiplication between endogenous variables and parameters; linearity would be restored and a solution for the optimal time paths of endogenous variables would be obtainable. Similarly, a decreasing gain specification would also be manageable since for all t , the gain would simply be given by t^{-1} , and the anchoring function would also be deterministic and exogenous.

RELAXING ASSUMPTION 2

Consider the general anchoring mechanism of Equation (23):

$$(I1) \quad k_t = \mathbf{g}(k_t, f_{t|t-1}).$$

With this assumption, the FOCs of the Ramsey problem are

$$(I2) \quad 2\pi_t + 2\frac{\lambda_x}{\kappa}x_t - k_t\varphi_{5,t} - \mathbf{g}_{\pi,t}\varphi_{6,t} = 0,$$

$$(I3) \quad c\mathbb{E}_t x_{t+1} + \varphi_{5,t} - (1 - k_t)\mathbb{E}_t \varphi_{5,t+1} + \mathbf{g}_{\bar{\pi},t}\mathbb{E}_t \varphi_{6,t+1} = 0,$$

$$(I4) \quad \varphi_{6,t} + \mathbb{E}_t \varphi_{6,t+1} = f_{t|t-1}\varphi_{5,t},$$

where the multiplier $\varphi_{6,t+1}$ is the new element vis-à-vis the case where the anchoring function is specified in levels ($k_t = \mathbf{g}(f_{t|t-1})$), and I am using the shorthand notation

$$(I5) \quad c = -\frac{2(1-\alpha)\beta}{1-\alpha\beta} \frac{\lambda_x}{\kappa},$$

$$(I6) \quad f_{t|t-1} = \pi_t - \bar{\pi}_{t-1} - b_1 s_{t-1}.$$

One can simplify this three-equation-system to:

$$(I7) \quad \varphi_{6,t} = -cf_{t|t-1} \mathbb{E}_t x_{t+1} + \mathbb{E}_t \left(1 + \frac{f_{t|t-1}}{f_{t+1|t}} (1 - k_{t+1}) - f_{t|t-1} \mathbf{g}_{\pi,t} \right) \varphi_{6,t+1} \\ - \mathbb{E}_t \frac{f_{t|t-1}}{f_{t+1|t}} (1 - k_{t+1}) \varphi_{6,t+2},$$

$$(I8) \quad 0 = 2\pi_t + 2\frac{\lambda_x}{\kappa} x_t - \left(\frac{k_t}{f_{t|t-1}} + \mathbf{g}_{\pi,t} \right) \varphi_{6,t} + \frac{k_t}{f_{t|t-1}} \mathbb{E}_t \varphi_{6,t+1}.$$

Thus a central bank that follows the target criterion has to compute $\varphi_{6,t}$ as the solution to (I8), and then evaluate (I7) as a target criterion. The solution to (I8) is given by:

$$(I9) \quad \varphi_{6,t} = -2 \mathbb{E}_t \sum_{i=0}^{\infty} \left(\pi_{t+i} + \frac{\lambda_x}{\kappa} x_{t+i} \right) \prod_{j=0}^{i-1} \frac{\frac{k_{t+j}}{f_{t+j|t}}}{\frac{k_{t+j}}{f_{t+j|t}} + \mathbf{g}_{\pi,t+j}}.$$

The interpretation of (I9) is that the anchoring constraint is not binding ($\varphi_{6,t} = 0$) if the central bank always hits the target ($\pi_{t+i} + \frac{\lambda_x}{\kappa} x_{t+i} = 0, \forall i$); or expectations are always anchored ($k_{t+j} = 0, \forall j$).

PARAMETERIZED EXPECTATIONS ALGORITHM (PEA)

The objective of the parameterized expectations algorithm is to solve for the sequence of interest rates that solves the model equations including the target criterion, representing the first-order condition of the Ramsey problem. For con-

venience, I list the model equations:

$$\begin{aligned}
(\text{J1}) \quad & x_t = -\sigma i_t + [\sigma \quad 1 - \beta \quad -\sigma\beta] f_{b,t} + \sigma [1 \quad 0 \quad 0] (I_3 - \beta h)^{-1} s_t, \\
(\text{J2}) \quad & \pi_t = \kappa x_t + [(1 - \alpha)\beta \quad \kappa\alpha\beta \quad 0] f_{a,t} + [0 \quad 0 \quad 1] (I_3 - \alpha\beta h)^{-1} s_t, \\
(\text{J3}) \quad & f_{a,t} = \frac{1}{1 - \alpha\beta} \bar{\pi}_{t-1} + b(I_3 - \alpha\beta h)^{-1} s_t, \\
(\text{J4}) \quad & f_{b,t} = \frac{1}{1 - \beta} \bar{\pi}_{t-1} + b(I_3 - \beta h)^{-1} s_t, \\
(\text{J5}) \quad & f_{t|t-1} = \pi_t - (\bar{\pi}_{t-1} + b_1 s_{t-1}), \\
(\text{J6}) \quad & k_t = \sum_i \gamma_i b_i (f_{t|t-1}), \\
(\text{J7}) \quad & \bar{\pi}_t = \bar{\pi}_{t-1} + k_t f_{t|t-1}, \\
(\text{J8}) \quad & \pi_t = -\frac{\lambda_x}{\kappa} \left\{ x_t - \frac{(1 - \alpha)\beta}{1 - \alpha\beta} \left(k_t + f_{t|t-1} \mathbf{g}_{\pi,t} \right) \right. \\
& \quad \left. \left(\mathbb{E}_t \sum_{i=1}^{\infty} x_{t+i} \prod_{j=0}^{i-1} (1 - k_{t+1+j} - f_{t+1+j|t+j} \mathbf{g}_{\bar{\pi},t+j}) \right) \right\}.
\end{aligned}$$

Denote the expectation on the right hand side of (J8) as E_t . The idea of the PEA is to approximate this expectation and to solve model equations given the approximation \hat{E}_t . The algorithm is as follows:²²

Objective: Obtain the sequence $\{i_t\}_{t=1}^T$ that solves Equations (J1) - (J8) for a history of exogenous shocks $\{s_t\}_{t=1}^T$ of length T .

- 1) Conjecture an initial expectation $\hat{E}_t = \beta^0 s(X_t)$.
The expectation is approximated as a projection on a basis, $s(X_t)$, where β^0 are initial projection coefficients, and $X_t = (k_t, \bar{\pi}_{t-1}, r_t^n, u_t)$ is the state vector. I use a monomial basis consisting of the first, second and third powers of X_t .
- 2) Solve model equations given conjectured \hat{E}_t for a given sequence of shocks $\{s_t\}_{t=1}^T$.
Compute residuals to the model equations (J1) - (J8) given $\{s_t\}_{t=1}^T$ and $\{\hat{E}_t\}_{t=1}^T$. Obtain a sequence $\{i_t\}_{t=1}^T$ that sets the residuals to zero. The output of this step is $\{v_t\}_{t=1}^T$, the simulated history of endogenous variables (Christiano and Fisher (2000) refer to this as a “synthetic time series”).
- 3) Compute realized analogues of $\{E_t\}_{t=1}^T$ given $\{v_t\}_{t=1}^T$.
- 4) Update β regressing the synthetic E_t on $s(X_t)$.
The coefficient update is $\beta^{i+1} = (s(X_t)' s(X_t))^{-1} s(X_t)' E_t$. Then iterate until convergence by evaluating at every step $||\beta^i - \beta^{i+1}||$.

²²For a thorough treatment of the PEA, see Christiano and Fisher (2000).

PARAMETRIC VALUE FUNCTION ITERATION

This is an alternative approach I implement as a robustness check to the PEA. The objective is thus the same: to obtain the interest rate sequence that solves the model equations. The general value function iteration (VFI) approach is fairly standard, for which reason I refer to the Judd (1998) textbook for details. Specific to my application is that the state vector is five-dimensional, $X_t = (\bar{\pi}_{t-1}, r_t^n, u_t, r_{t-1}^n, u_{t-1})$, and that I approximate the value function using a cubic spline. Thus the output of the algorithm is a cubic spline approximation of the value function and a policy function for each node on the grid of states. Next, I interpolate the policy function using a cubic spline as well. As a last step I pass the state vector from the PEA simulation, obtaining an interest rate sequence conditional on the history of states. Fig. K1 shows the resulting interest rate sequence, obtained through the two approaches, conditional on a simulated sequence for the exogenous states.

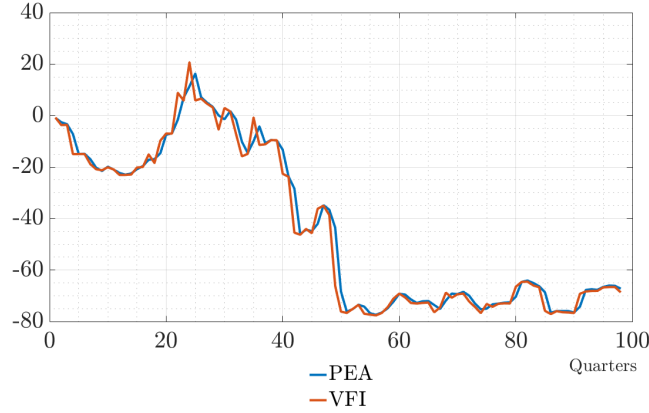


FIGURE K1. POLICY FUNCTION FOR A PARTICULAR HISTORY OF STATES, PEA AGAINST VFI

OSCILLATORY DYNAMICS IN ADAPTIVE LEARNING MODELS

Here I present an illustration for why adaptive learning models produce oscillatory impulse responses if the gain is high enough. Consider a stylized adaptive learning model in two equations:

$$\begin{aligned} \text{(L1)} \quad & \pi_t = \beta e_t + u_t, \\ \text{(L2)} \quad & e_t = e_{t-1} + k(\pi_t - e_{t-1}). \end{aligned}$$

The reader can recognize in (L1) a simplified Phillips curve in which I am abstracting from output gaps to keep the presentation as clear as possible. Like in

the simple model of Section IV.A in the main text, e_t represents the one-period inflation expectation $\hat{\mathbb{E}}_t \pi_{t+1}$. (L2), then, represents the simplest possible recursive updating of the expectations e_t . My notation of the gain as k indicates a constant gain specification, but the intuition remains unchanged for decreasing (or endogenous) gains.

Combining the two equations allows one to solve for the time series of expectations

$$(L3) \quad e_t = \frac{1-k}{1-k\beta} e_{t-1} + \frac{k}{1-k\beta} u_t,$$

which, for β close but smaller than 1, is a near-unit-root process. (In fact, if the gain were to go to zero, this would be a unit root process.) Defining the forecast error as $f_{t|t-1} \equiv \pi_t - e_{t-1}$, one obtains

$$(L4) \quad f_{t|t-1} = -\frac{1-\beta}{1-k\beta} e_{t-1} + \frac{1}{1-k\beta} u_t.$$

Equation (L4) shows that in this simple model, the forecast error loads on a near-unit-root process with a coefficient that is negative and less than one in absolute value. Damped oscillations are the result.

Note that even if the gain would converge to zero, the coefficient on e_{t-1} would be negative and less than one in absolute value. Thus even for decreasing gain learning, one obtains oscillations, but the lower the gain, the more damped the oscillations become. This corroborates my findings in the impulse responses of Fig. 5. But importantly, the opposite extreme, when $k \rightarrow 1$, results in a coefficient of exactly -1 , giving perpetual oscillations. This clearly illustrates how the oscillatory behavior of impulse responses comes from the oscillations in the forecast error that obtain when the gain is sufficiently large.