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Squeezing the Interest Rate Smoothing Weight with a Hybrid Expectations Model

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NOTA DI LAVORO 6.2003

JANUARY 2003

ETA – Economic Theory and Applications

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Summary

Successful descriptions of short-term nominal interest rates *inertial* behavior have frequently been obtained with small scale macro models in which a Central Banker minimizes a loss function embedding an argument labelled as *interest rate smoothing*. The *rationale* for this argument is not straightforward. Indeed, there has been a lively debate about it in the literature. In this paper we perform an empirical exercise to evaluate the relationship existing between private sector's *rational expectations* and interest rate gradualism. Our findings strongly support rational expectations as an element capable to remarkably reduce the importance of the interest rate smoothing weight in replicating the observed path of the federal funds rate. However, we find a predominance of adaptive expectations in shaping the paths of inflation ad output gap. Our results also suggest that the Fed has followed a 'Strict Inflation Targeting' strategy under Greenspan's regime.

Keywords: Central Banker, interest rate smoothing, rational expectations, hybrid Phillips curve, hybrid IS curve.

JEL: C51, E52

The author thanks Nicola Cantore, Richard Dennis, Carlo Favero, Francesca Monti, Davide Pettenuzzo, Saverio Simonelli, Ulf Söderstrom, and Paolo Surico for valuable comments and suggestions. The usual disclaimers apply.

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1 Introduction

In the recent applied monetary policy literature, a simple framework representing the Central Banker (CB hereafter)'s problem has been extensively exploited. In this framework, the CB's loss function considers variables such as the inflation rate and the output gap (or the unemployment rate), while the economy is represented by a Phillips curve and an IS schedule.[1] Interestingly enough, with this framework the solution of the Central Banker (CB hereafter)'s optimal control problem turns out to be an interest rate path featured by frequent reversals, reversals due to the willingness of the CB to tackle the various shocks affecting the economy. In fact, in reality we observe smooth paths of the policy rates; this tendency has been labeled as *interest rate smoothing*.[2] To capture this feature of the policy rate, many authors have added to the CB's loss function an *interest rate smoothing argument*, i.e. an argument function of the interest rate *change*.

Indeed, there seems to exist a *trade-off* between economic plausibility (of the relative weight μ attributed to the interest rate smoothing volatility in the loss function) and goodness-of-fit (associated to the small-macro scale model in use). Castelnuovo and Surico (2003) consider different studies (i.e. Dennis, 2002; Ozlale, 2003; Favero and Rovelli, 2003) in which researchers have estimated the Fed's relative preferences. In these empirical efforts, there is a common economic model (i.e. Rudebusch and Svensson, 1999,2002), but different econometric techniques are employed. It turns out that when economically sensible (i.e. relatively low) values of the μ parameter are estimated, the optimal simulated interest rate (in first differences) shows a puzzling larger volatility than the historical one. Furthermore, au-

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[1] A very incomplete list includes Ball (1999), Rudebusch and Svensson (1999,2002), Nessén and Vestin (2000), Dennis (2002,2003), Söderlind, Söderström, and Vredin (2002), Favero and Rovelli (2003), Rudebusch (2001,2002a,b,c), Smets (2002), Masuch, Nicoletti Altimari, Pill, and Rostagno (2002), and Aksoy, De Grauwe, Dewachter (2002), Ozlale (2003), and Castelnuovo and Surico (2003).

[2] Rudebusch (1995), Goodhart (1997), Lowe and Ellis (1998), Sack and Wieland (2000), and Srour (2001) are examples of studies focused on the interest rate smoothing evidence. Interestingly, in a recent contribution Rudebusch (2002a) sustains that the monetary policy inertia observed at a quarterly frequency is just an *illusion*. Nevertheless, English, Nelson, and Sack (2003) and Castelnuovo (2003a,b) run a direct test on the existence of the CB's sluggish adjustment strategy, finding it statistically relevant.

thors such as Goodhart (1999), Sack (2000), Sack and Wieland (2000), and Cecchetti (2000) claim that a smooth interest rate may very well be the solution of a problem in which there is *not* any interest rate smoothing targeting. In fact, forward looking agents, uncertainties regarding the dynamics of the economy, and measurement-errors problems could induce monetary authorities to implement a cautious policy. From this standpoint, the interest rate smoothing element embedded into the loss function is just a *residual* capturing what it is left out of the model.

Sack and Wieland (2000)'s considerations motivate this research. In particular, in this paper we focus our attention on the relationship between interest rate smoothing and *forward looking agents* (FLA hereafter). In fact, private sector's expectations play a key role in monetary policy making. Prices and production primarily react to long-term interest rates, which are in turn influenced by expectations on future movements of the short-term ones. Then, the announcement of a small change in the short term policy rate's reference value may trigger important nominal and real effects if private agents *expect* this change to be followed by a sequence of others. Of course, these expectations are formed only if agents *believe* this is going to happen, e.g. if the CB has historically implemented *smooth* patterns of the policy rates. To support this reasoning, Sack and Wieland (2000) report a statement by Otmar Issing (1997), current member of the Executive Board of the European Central Bank and former Chief Economist at the Bundesbank:

> *"If changes in official rates in a certain direction that are confirmed by repetition and not expected to be reversed soon have most influence on longer-term rates, it would seem appropriate for the Bundesbank to adjust its official rates in the smoothest manner."*

Many researchers (e.g. Amato and Laubach, 1999; Levin, Wieland, and Williams, 1999,2002; Rotemberg and Woodford, 1999; Williams, 1999; Woodford, 1999) have investigated this issue from a *normative* standpoint, e.g. they have replied to a question like "Can a credible, inertial policy be beneficial when the private sector is forward looking?". The answer coming from these studies has been unanimously positive. In fact, if agents expect future gradual moves by the CB, they will adjust their inflation and output gap expectations toward the CB's targets, so helping it to stabilize the economy.

Somewhat surprisingly, the importance of FLA in the context of the trade-off pointed out above has not been investigated in the literature. How large is the impact of the FLA component on the interest rate smoothing weight in the CB's penalty function? Is the FLA chunk helpful for tracking the observed federal funds rate path? In this study, we aim at understanding *how much descriptive power* a small macro model may gain when passing from a backward looking formalization of the economy to a representation in which there is room for forward looking agents. In our study, we use an encompassing AD-AS model à la Rudebusch (2002b) that, under some identifying restrictions, may collapse to a backward looking, hybrid, or fully forward looking illustration of the linkages existing among inflation, output gap, and the policy rate. For each different vector of structural parameters identifying the economic framework, we calibrate the weight to be attributed to the interest rate smoothing argument in order to fit the actual federal funds rate at best. The lower the weight, the better the model performs from a positive standpoint.

A comparison of the results obtained with a fully backward looking model with those stemming from our hybrid version of the economy enables us to state that FLA is a very important ingredient capable to dramatically help explaining the observed interest rate persistence. In fact, the gains in terms of descriptive power turn out to be quite large. To our knowledge, this the first effort oriented at quantitatively assessing the role of FLA in designing these small macro models.

Notably, in our simulations the private sector expects an inertial interest rate even under discretion. In fact, private sector knows that the CB aims at minimizing a loss function featured by the presence of a penalty for interest rate volatility. Then, even if the CB re-optimizes in each period, its optimal choice will be history-dependent (Woodford, 1999): That is where optimal inertia comes from. Then, the interest rate smoothing penalty is to be interpreted as a proxy for CB's concerns such as credibility, uncertainties, and learning; these concerns are known by private agents, and provide a *rationale* for private agents' expectations of an inertial rate under discretion.

Our calibration exercises suggest that a hybrid new-Keynesian may very well fit the data. In particular, a low relative concern for output gap volatility, a low degree of 'forward lookingness' in both the Phillips curve and the IS curve, and a high weight the expected real-interest rate are the features of best positive model. In this sense, our findings are in line with those contained in recent works by Söderlind, Söderström, and Vredin (2002) and Dennis (2003). This suggests that much more should be done in order to better understand the role of adjustment costs, rules of thumb, and habit formation in shaping the dynamics of variables such as inflation and the output gap, following examples such as Fuhrer and Moore (1995), Fuhrer (2000), Estrella and Fuhrer (2002) and Amato and Laubach (2003).

The map of the paper is the following. Section 2 describes the modeling framework we use for our purpose. In Section 3 we discuss our strategy for evaluating the importance of the FLA ingredient. In Section 4 we highlight and comment our findings. Section 5 collects some insights on the importance of FLA. In Section 6 we deepen our analysis with a robustness check. Section 7 reviews some other possible ingredients potentially capable to ulteriorly reduce the interest rate smoothing weight in the loss function. Section 8 concludes. A Technical Appendix explaining the algorithm we use in order to tackle the optimal stochastic regulator problem is provided. References follow.

2 Modeling the Central Banker's problem

Our hypothesis is that the CB determines the optimal path of its control variable, i.e. the short term nominal interest rate. The period loss function reads as follows:

$$L_t = (\overline{\pi}_t - \pi^*)^2 + \lambda(y_t)^2 + \mu(i_t - i_{t-1})^2 \tag{1}$$

where π_t represents the inflation rate, π^* is the inflation target, y_t is the output gap, and i_t is the short-term nominal interest rate (e.g. the federal funds rate).[3] A few comments on this definition of the loss function

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[3] The variables used in our study have been constructed as follows: π_t is the four-

are needed. Regarding the inflation targeted by the CB, we think of it as being an average-inflation; this may better represent the will of the monetary authority to monitor the inflation rate in different periods, rather than just in the 'current one'. Our definition of the output gap implies that the target for the level of output set by the CB is the potential output, as plausibly done by the Fed (Blinder, 1997).[4] Finally, in (1) the weight λ represents the preference of the CB over the output gap relative to inflation. Instead, given our interpretation of the interest rate smoothing argument, the weight μ should be seen as a residual, or a necessary proxy for replicating the observed path of the federal funds rate.

We assume that the CB solves an *intertemporal* optimization problem. We shape the CB's loss function as follows:

$$\underset{\{i_t\}}{Min}\ E_t \sum_{j=0}^{\infty} \delta^j L_{t+j} \tag{2}$$

As shown by Rudebusch and Svensson (1999), when the discount rate $\delta \to 1$, equations (1) and (2) can be rewritten as follows:

$$\underset{\{i_t\}}{Min}\ E(L_t) = Var(\overline{\pi}_t - \pi^*) + \lambda Var(y_t) + \mu Var(i_t - i_{t-1}) \tag{3}$$

So, the conditional mean (2) collapses to its unconditional counterpart, which is equal to the weighted sum of the unconditional variances of the loss function's arguments. Hereafter, we will consider equation (3) as the CB's objective function.

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quarter inflation rate computed on the basis of the GDP chain-weighted price index P_t, i.e. $\pi_t \equiv 4(p_t - p_{t-1})$, where $p_t = 100 \ln P_t$. y_t is the output gap, i.e. $y_t \equiv q_t - q_t^*$, where $q_t \equiv 100 ln Q_t$, while $q_t^* \equiv 100 ln Q_t^*$. Q_t is the real GDP level, while Q_t^* is the potential output. Finally, upper-barred variables indicate simple averages taken over the contemporaneous observation and the previous three lags of the variable in consideration. All the series used in our analysis are downloadable from the Federal Reserve Bank of St. Louis' web-site, i.e. http://research.stlouisfed.org/fred2/. Notice that the potential output series is the one estimated by the Congressional Budget Office.

[4] Indeed, the monopoly-power held by firms in the underlying structure of the economy might lead to think about a CB willing to set a higher target level, given that the equilibrium production in case of monopolistic competition is lower than the socially desirable one. However, by introducing a target greater than the potential output, the CB would face an inflation bias problem (Barro and Gordon, 1983). That is why in our study the output gap target is equal to zero.

We now turn to the representation of the economic environment. We adopt a model à la Rudebusch (2002b), which reads as follows:

$$\pi_{t+1} = \gamma_\pi E_t\ \overline{\pi}_{t+4} + (1-\gamma_\pi)\sum_{j=1}^{4}\alpha_{\pi j}\pi_{t-j+1} + \alpha_y y_t + \varepsilon_{t+1} \tag{4}$$

$$\begin{aligned} y_{t+1} &= \gamma_y E_t y_{t+2} + (1-\gamma_y)\sum_{j=1}^{2}\beta_{yj}y_{t-j+1} \\ &\quad -\gamma_r\beta_r(i_t - E_t\ \overline{\pi}_{t+4}) - (1-\gamma_r)\beta_r(\overline{i}_t - \overline{\pi}_t) + \eta_{t+1} \end{aligned} \tag{5}$$

where γ_π represent the 'degree of forwardness' of the dynamic Phillips curve (4), while γ_y and γ_r are the weights of the FLA elements of the expected demand and the expected real interest rate in the IS equation (5). A few comments are due here. First, following some researchers' example (e.g. Fuhrer and Moore, 1995; Clarida, Galí and Gertler, 1999; Rudebusch and Svensson, 1999, 2002), we admit a stochastic element in the Phillips curve, the *cost-push* shock ε_t, which is responsible for the short-run trade-off existing between inflation and output gap. We also admit a demand shock in the IS curve, namely η_t. In this latter curve, we consider the possibility of having a 'hybrid' representation of the short-term real interest rate; we do so to be consistent with the overall 'hybrid' economic set up we want to take into account performing our exercises. Finally, notice that, when $\gamma_\pi = \gamma_y = \gamma_r = 1$, this model collapses to the well-known 'New Neoclassical Synthesis' model by Goodfriend and King (1997).

The model (4)-(5) may be re-written in its state space form as follows:

$$A_0\begin{bmatrix} x_{1t+1} \\ E_t x_{2t+1}\end{bmatrix} = A_1\begin{bmatrix} x_{1t} \\ x_{2t}\end{bmatrix} + B_1 i_t + v_{t+1} \tag{6}$$

where A_0 and A_1 are squared matrices of size $(n1+n2)$, B_1 is a $((n1+n2)\times 1)$ columns vector, x_{1t} is a $(n1\times 1)$ column vector of predetermined state variables (with $n1 = 9$), which is defined as $x_{1t} = [\pi_t\ \pi_{t-1}\ \pi_{t-2}\ \pi_{t-3}\ \mathrm{y}_t\ \mathrm{y}_{t-1}\ \mathrm{i}_{t-1}\ \mathrm{i}_{t-2}\ \mathrm{i}_{t-3}]'$, and x_{2t} is a $(n2\times 1)$ column vector of forward-looking jump variables (with $n2 = 4$), which is $x_{2t} = [\mathrm{E}_t\pi_{t+3}\ \mathrm{E}_t\pi_{t+2}\ \mathrm{E}_t\pi_{t+1}\ \mathrm{E}_t\mathrm{y}_{t+1}]'$.[5]

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[5] A description on how to conveniently set up and solve the optimal control problem proposed in this paper is provided in the Technical appendix.

The CB's aim is that of optimally setting the path of the interest rate i_t in order to minimize the expected loss (3) subject to the law of motion (6). The timing of the game is the following: At the beginning of each period private agents form their expectations; then, the interest rate level is optimally fixed by the Central Bank; finally, demand and supply shocks strike the economy. Söderlind (1999) proves the optimality of the linear feedback rule

$$i_t = -Fx_{1t} \tag{7}$$

where F is the $(1 \times n1)$ row vector whose elements are convolutions of the structural parameters in (4)-(5) and the coefficients attached to the arguments in the objective function (3).

In our positive exercises we compute the optimal monetary policy under discretion. We do so because we believe that this set up may better approximate the monetary policy management undertaken by the Fed in the last 15 years than the alternative one, i.e. commitment. Our choice is supported both by some academics' opinion (e.g. Jensen, 2002; Söderlind, Södeström, and Vredin, 2002) and by some Governor's official declarations (e.g. Bernanke, 2003).[6]

The model (6)-(7) replicates the dynamics present in the economy. In this framework the transmission of the monetary policy action happens with some lags. This is in line with what the observation of the real economy seems to suggest, i.e. a change in the interest rate level affects the output gap with a certain delay, and the inflation rate even with a larger delay, as underlined in Christiano, Eichembaum and Evans (1998, 2001). Söderlind, Söderström, and Vredin (2002) verify how this model is capable (under some parametrization) to broadly match the features of the historical series in the model.[7] Indeed, the presence of the backward part of the model enables us

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[6] To be precise, Bernanke (2003) defines the concept of "constrained discretion", which is in fact closely related to the policy framework we adopt in our work, i.e. inflation targeting under discretion.

[7] In particular, they find that a CB with a small concern for output stability, but a large preference for inflation and interest rate stability, delivers a path for these three variables very much in line with the data. Furhermore, they estimate a small degree of forward-looking behavior for the inflation process, and a larger one for the output gap.

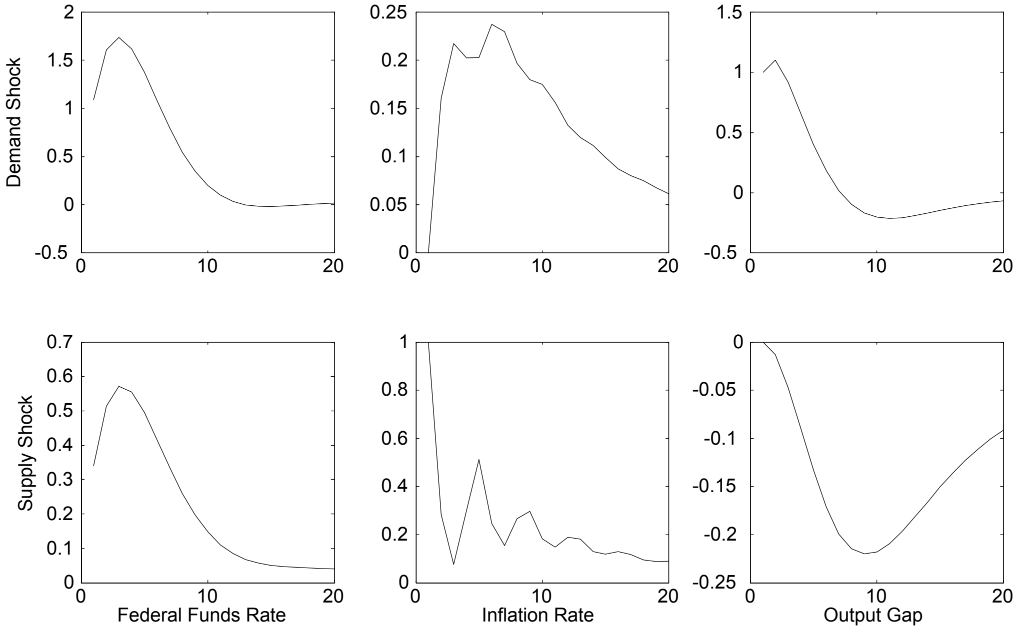

Figure 1: Impulse response functions of the hybrid new-Keynesian model (unitary shocks)

to introduce the FLA component without inducing counterfactual dynamics in the system; for a contribution about this point, see Estrella and Fuhrer (2002).

Figure 2 shows some impulse response functions.[8] It is immediate to notice that shocks to output and inflation are followed by *gradual* movements of the policy rate; this gradualism finds its rationale in the presence of a strictly positive interest rate smoothing weight. After a positive demand shock, the central bank must drive downwards the output gap rendering it negative, in order to tackle the inflationary pressure. Instead, in response to a cost-push shock, the CB raises the short-term nominal interest rate, so depressing the real economy. This induces the return of the average inflation rate to its target, at the cost of periods of under-production. The volatile

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[8] These impulse response functions are computed by considering the following key parameters' values: $\lambda = 0.5$, $\mu = 0.5$, $\gamma_\pi = 0.1$, $\gamma_y = 0.2$, $\gamma_r = 1$.

pattern shown by the inflation rate in both these cases may be due to the will of the CB to target annual inflation.

With this model at hand, we can calibrate the value of the weight μ in order to find the optimal simulated interest rate that most closely replicate Greenspan's federal funds rate. In the next section we describe our econometric strategy.

3 Econometric strategy

The aim of our exercise is to fit the policy rate set by Alan Greenspan in the sample 1987Q3-2001Q1.[9] In doing so, we consider two different set of identification restrictions of equations (4)-(5). The first one - our benchmark model, i.e. our fully backward looking specification - is featured by $\gamma_\pi = \gamma_y = \gamma_r = 0$.[10] The Benchmark study will deliver us with the weight that we have to assign to the parameter μ in order to replicate the historical path of the federal fund rate while employing a backward looking model. The second set of restrictions identify our Hybrid version of the model, featured by the presence of RE. Referring once more to equations (4)-(5), we are in this case allowing for the presence of strictly positive values for the parameters γ_π, γ_y, and γ_r. Notice that we are not exogenously fixing those weights; instead, we want to calibrate them to get the best possible fit of the federal fund rate. So, when the Hybrid version of the model is considered, we will *jointly* calibrate the weight μ and the parameters γ_π, γ_y, and γ_r.

The choice of performing a calibration exercise deserves an explanation. Indeed, the optimal stochastic regulator problem offers the possibility of estimating the parameters of the economy and those in the CB's preferences

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[9] The choice of Greenspan's period is suggested both by sample-length considerations (he has been in charge since the third quarter of 1987, a sample longer than those of the other chairmen) and by our willingness to compare our findings with the available literature, which mostly concentrates on the post-Volcker era. Also, we think it is plausible to consider the Fed's preferences as being chairman-specific.

[10] A fully backward looking framework like this has been used for monetary policy analyses by Ball (1999), Rudebusch and Svensson (1999, 2002), Peersman and Smets (1999), Favero and Milani (2001), Rudebusch (2001), Masuch *et al* (2002), Aksoy *et al* (2002), Ozlale (2003), Favero and Rovelli (2003), and Castelnuovo and Surico (2003), among the others.

via Maximum Likelihood, both in case of a fully backward looking representation (e.g. Ozlale, 2003) and when a hybrid economy is taken into account (e.g. Dennis, 2003). In fact, Dennis (2003) shows that both the backward and the hybrid economic framework may satisfy familiar rank and order conditions for their parameters to be identified. Of course, Maximum Likelihood estimates have the plus of allowing for formal tests on the estimated coefficients. However, this possibility does not come for free. In fact, with Maximum Likelihood we have to assume normality of the errors, something that we are not required to do when performing our calibration exercise. Moreover, Söderlind, Söderström, and Vredin (2002) underline how Maximum Likelihood is quite sensitive to sample selection and outliers. Finally, our focus is that of understanding the impact of FLA on the interest rate smoothing parameter μ in the loss function. Then, we do want to keep all the other parameters of the model constant when moving from the fully backward looking representation of the economy to the hybrid one; this would not be possible if we employed Maximum Likelihood.[11]

In order to assign values to the parameters of the model (3) and (6), i.e. λ, μ, γ_π, γ_y, γ_r, α_s, and β_s, we implement the following calibration strategy:

1) We OLS estimate the parameters α_s and β_s of our backward looking specification, i.e. we estimate equations (4)-(5) subject to the constraint $\gamma_\pi = \gamma_y = \gamma_r = 0$. Our estimates are reported in Table 1.

A key parameter for the transmission of the monetary policy is the interest rate elasticity β_r. Notably, our point estimate - 0.073 - is statistically in line with that of Rudebusch (2002b).[12]

2) We exogenously fix a value for the relative preference λ. We do so to concentrate our attention on the parameters playing a key-role in our story, i.e. μ, γ_π, γ_y, and γ_r. Notice that λ is a structural preference of our set-up, i.e. the relative weight that Alan Greenspan has attributed to the volatility of the output gap versus the volatility of the average inflation rate

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[11] In fact, to tackle this issue we could employ a Bayesian estimator. However, the limitations listed above and referring to the Maximum Likelihood estimator would still apply.

[12] Instead, probably due to the different samples considered, it is much lower than those provided by Clark, Laxton and Rose (1996) - 0.16 - and Smets (2002) - 0.9.

Phillips curve: $\pi_{t+1} = \alpha_{\pi1}\pi_t + \alpha_{\pi2}\pi_{t-1} + \alpha_{\pi3}\pi_{t-2} + \alpha_{\pi4}\pi_{t-3} + \alpha_y y_t + \varepsilon_{t+1}$					
Parameter	$\alpha_{\pi1}$	$\alpha_{\pi2}$	$\alpha_{\pi3}$	$\alpha_{\pi4}$	α_y
Point Estimate	0.282	-0.025	0.292	0.385	0.141
Standard Deviation	0.133	0.134	0.134	0.136	0.054
Adjusted R^2: 0.58; σ_ε=0.66.					
AD curve: $y_{t+1} = \beta_{y1}y_t + \beta_{y2}y_{t-1} + \beta_r(\bar{i}_t - \bar{\pi}_t) + \eta_{t+1}$					
Parameter	β_{y1}	β_{y2}	β_r		
Point Estimate	1.229	-0.244	-0.073		
Standard Deviation	0.136	0.149	0.078		
Adjusted R^2: 0.93; σ_η=0.51.					
Variables demeaned before estimation, so no constants appear.					
Sample: 1987Q3-2001Q1.					

Table 1: Estimates of the AD-AS backward looking structure

in deviations from the target.

Indeed, it is possible to find many different sensible values for the relative preference parameter λ in the literature. Focusing on backward representations of the economy à la Rudebusch and Svensson (1999,2002), Favero and Rovelli (2003) estimate with GMM the Euler conditions of the CB's problem, finding a (statistically insignificant) value of 0.00125. Ozlale (2001) exploits Kalman-filtering and estimates a value of 0.525, Dennis (2002) gets 0.815 with a FIML approach, while Castelnuovo and Surico (2003) calibrate a value equal to 1. With a slightly different underlying representation of the economy, Cecchetti, Flores-Lagunes, and Krause (2001) find negligible values for sub-samples regarding the '80s and '90s, while Cecchetti and Ehrmann (2001)'s results support a value of about 1/4. For the same period, but with a VAR representation of the economy, Salemi (1995) finds very low relative weights for the output gap with respect to inflation. Finally, Dennis (2003) designs a hybrid representation of the economy, and estimate a value equal to zero. We somehow arbitrarily fix a benchmark value of $\lambda = 0.5$; however, we check for the robustness of our results by considering also values such as 0.0, 0.2, and 1.0.

3) Given steps 1) and 2), we can perform the calibration of the remaining

parameters μ, γ_π, γ_y, and γ_r.[13] We do so by implementing a grid-search based on a minimum-distance criterium. In particular, we compute, *per each battery* $j : [\mu^j, \gamma_\pi^j, \gamma_y^j, \gamma_r^j]$, an optimal simulated interest rate $i^{sim,j}$ to be compared with the actual one i^{actual}.[14] For our calibration we exploit the following measure of Distance:

$$Distance(i^{simulated}, i^{actual}) = \sqrt{\frac{\sum_{t=1}^{T} (i_t^{simulated} - i_t^{actual})^2}{T}} \tag{8}$$

With this measure of distance we can pick up the simulated interest rate $\mathrm{i}^{sim,j*}$ (i.e. the one delivering the minimum distance) implied by the calibrated vector $[\mu^*, \gamma_\pi^*, \gamma_y^*, \gamma_r^*]$. We recall here that, when the backward looking model is employed, the calibration exercise just regards the weight μ, given the identifying restriction $\gamma_\pi = \gamma_y = \gamma_r = 0$.[15]

Notice that our calibration strategy relies on the assumption of optimal behavior undertaken by the Fed in the period analyzed. As pointed out by Cecchetti, McConnell, and Perez-Quiros (2002), this is equivalent to assume that Greenspan has operated along the efficiency-frontier that defines the trade-off between inflation and output gap, otherwise labelled as 'Taylor Curve' (Taylor, 1979). Moreover, our search for the optimal weight μ assumes that the parameters of our economy remains unvaried after a modification of the monetary policy conduct. Given the presence of FLA, the calibration of our hybrid model is not affected by the Lucas (1976) critique.

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[13] To have a more easily manageable problem, we demean all the variables involved in our study. As argued by Dennis (2000), this operation does not affect the derivation of the CB's weights in the loss function, but it constraints the average inflation target π^* to be equal to zero, which is to say its sample mean (2.49 in the sample we concentrate on) in an undemeaned world. Actually, our analysis is meant to identify the weights of the CB's loss rather than the targets *per se.* A number of papers cover this latter issue, including Judd and Rudebusch (1998), Sack (2000), Dennis (2002,2003), and Favero and Rovelli (2003).

[14] For our calibration exercise, we consider values belonging to the interval [0.1 - 1.0] for the forwardness coefficients γ_π and γ_y, while [0.0 - 1.0] for γ_r. We also take into account a value of 10^{-4} for γ_π and γ_y. Finally, for the weight μ we take into account values belonging to the interval [0.0 - 10.0]. The step-lenght of our grid search is 0.1.

[15] In performing these calibrations we do not deal with the Zero Lower Bound issue (see Amirault and O'Reilly, 2001, for a survey on this problem, and Eggertsson and Woodford, 2003, for a recent contribution).

Instead, our exercise with the backward looking specification of the economy is potentially concerned by this critique. Of course, if a variation in the policy rule implied a change of the structural parameters of the economy, our empirical analysis would risk to be flawed. However, the empirical relevance of the Lucas critique in this context seems to be discussable. In fact, Rudebusch (2002c) shows that with an AD-AS backward looking model like the one used in this study the empirical relevance of the critique turns out to be negligible. We now turn to the analysis of our results.

4 Findings

In this section we present our findings. In Table 2/Panel a) we collect the results of our joint calibration, the calibration concerning the parameter μ and, in case of the Hybrid model, the parameters γ_π, γ_y, and γ_r. Indeed, in absence of FLA, the value of this parameter is quite large, and we judge it as being economically implausible . If we believed that the CB could indeed have an interest rate smoothing goal, this goal would surely not be 2.1 times more important than the volatility of inflation. Since we think of the smoothing argument as being a sort of 'catch all' approximating omitted (potentially important) components, then such a large value might signal the existence of an omitted variable problem. In fact, when adding FLA to the model, our results change quite dramatically. The weight attached to the smoothing argument collapses to 0.5, so indicating FLA as being a central element for correctly representing the economic dynamics. Some descriptive statistics support this intuition. In fact, both for the mean and for the standard deviation of the interest rate *level* the simulated interest rate is much closer than the one deriving from the Benchmark model. As far as the standard deviation of the interest rate *change* is concerned, it is actually difficult to distinguish between the two models; however, we recall that the Benchmark formulation needs an incredible value of 2.1 to replicate the historical data.

What if we control for the weight μ? Table 2/Panel b) collects the results coming from simulations in which the value 0.5 (the calibrated weight μ in the Hybrid model case) has been imposed also to our backward looking. This

Panel a): Calibration of the parameter μ

Interest rate	μ	$E(i_t)$	$\sigma(i_t)$	$\sigma(\Delta i_t)$
Actual	-	0	1.7273	0.4961
Backward	2.1	0.8074	2.9924	0.6364
Hybrid	0.5	0.5692	1.7942	0.5074

Panel b): Conditional comparison ($\mu = 0.5$)

Interest rate	$E(i_t)$	$\sigma(i_t)$	$\sigma(\Delta i_t)$	$\rho(i_{act}, i_{sim})$	$D(i_{act}, i_{sim})$	Dist. reduct.
Actual	0	1.7273	0.4961	-	-	-
Backward	0.8431	3.4839	0.9272	0.9087	2.1445	-
Hybrid	0.5692	1.7942	0.5074	0.9411	0.8519	60.24%

Backward model: γ_π=0.0001; γ_y=0.0001; γ_r=0.
Hybrid model: γ_π=0.1; γ_y=0.2; γ_r=1.
Moments of the Actual interest rate refer to the demeaned rate.

Table 2: Calibration outcomes and descriptive statistics with $\lambda = 0.5$

is done in order to *quantitatively* assess the role of FLA. Notably, all the descriptive statistics are clearly in favor of the Hybrid Model. In particular, with such a low μ, the backward looking model's simulated policy exhibits an excessive volatility both in levels and in first differences. Moreover, the distance reduction gained when passing from the B model to the Hybrid one is about 60%. This can loosely be seen as a measure of the bit of the observed smoothness that the Benchmark model is not capable to justify - so implying such a high value of μ - and that FLA help explaining. Figure 3 graphs the difference between the Backward Model (i.e. Benchmark) and the FLA-augmented one.[16]

5 The importance of FLA

What is the economic *rationale* for this result? Why are forward looking agents so important in describing the observed smooth path of the policy rate, which is to say in *squeezing the interest rate smoothing weight*? A

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[16] The path of simulated interest rates deriving form the two models is the one that the federal funds rate would have followed if the Fed had hystorically implemented the optimal policy rule. Notice that all the policy rates have been demeaned. Key parameters featuring the benchmark model: $\lambda = 0.5$, $\mu = 0.5$, $\gamma_\pi = 0.0001$, $\gamma_y = 0.0001$, $\gamma_r = 0$. Instead, those featuring the hybrid model are $\lambda = 0.5$, $\mu = 0.5$, $\gamma_\pi = 0.1$, $\gamma_y = 0.2$, $\gamma_r = 1$.

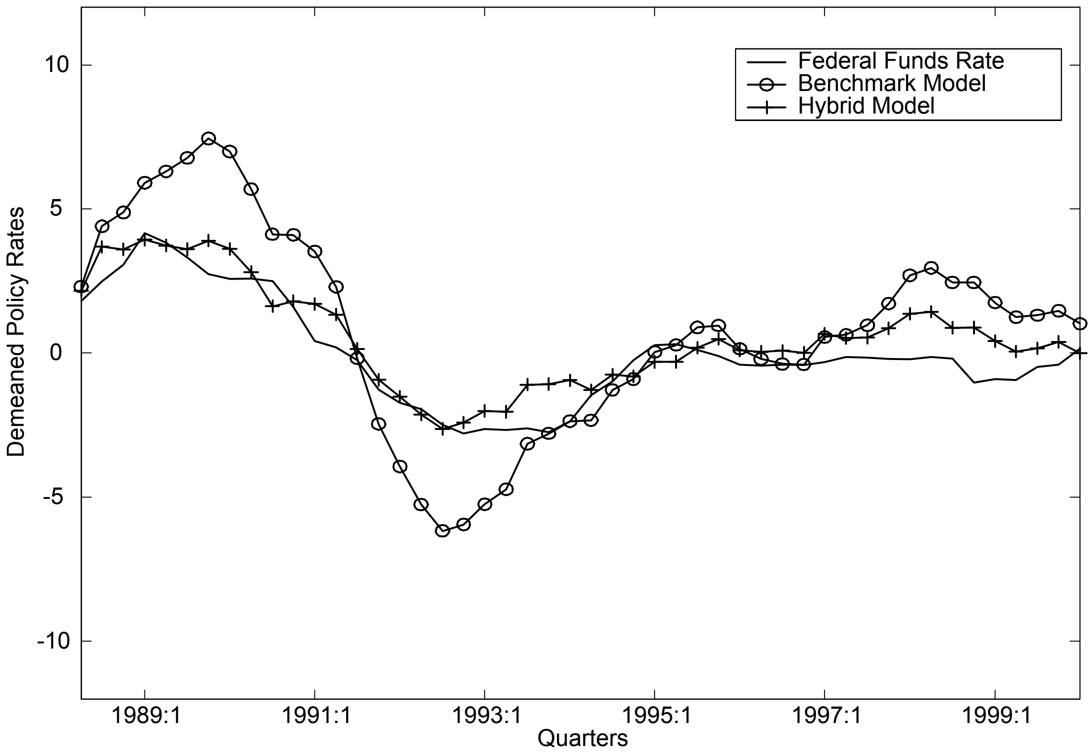

Figure 2: Policy rates behavior: benchmark versus hybrid model

sentence by Woodford (2001) represents a good starting point for our discussion. Woodford (2001, page 15) writes:

> "*When the effects of policy depends crucially upon private sector expectations about future policy as well, it is generally optimal for policy to be history-dependent, so that the anticipation of later policy responses can help to achieve the desired effect upon private sector behavior.*"

The presence of FLA implies that current inflation and output gaps are influenced by both current and future expected policy rates. Given the interest rate smoothing penalty in the loss function, private sector agents expect an inertial policy rate, and move their expectations toward the targets, so moving also the current realizations of inflation and output gap toward their steady-state values. This implies that the optimal policy rate, set by following the rule (7), it will be less volatile, because with small changes in the short-term policy rate will be possible to exert a large impact on the macro-variables of interest. Therefore, an optimally determined policy rate will show, *ceteris paribus*, a higher degree of inertia in presence of FLA than when just a fully adaptive private sector is taken into account. Of course, the introduction of the expectations channel will have an impact on the calibrated weight μ. Given that our aim is to replicate the observed smooth actual rate, it should be clear that with an economy featured by FLA, just a moderate weight attached to the interest rate argument in the loss function will be sufficient to trigger beneficial, stabilizing expectations. By contrast, in an economy characterized by fully adaptive agents, Woodford's intuition regarding optimal monetary policy inertia would not find any room; in this case, the optimal policy rate will be less inertial, so forcing a researcher to impose a high weight on the interest rate smoothing argument in order to fit the facts.[17]

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[17] Another way to understand this result is the following. Suppose that the calibrated fully backward looking model, i.e. the fully backward model that fits at best the federal funds rate, is featured by the weight $\mu^*_{FullyBackward}$. Now, suppose that we add the expectations channel to the model, but still keep the same weight $\mu^*_{FullyBackward}$, Private sector agents will expect a quite smooth future path for the policy rate; this will lead them to move expectations toward the targets. Given this additional channel, the resulting

6 Robustness check: Some considerations

We perform a robustness check of our results focusing on the value of the relative preference parameter λ. The figures concerning this check are contained in Tables 3-5, and refer to values such as 0.0, 0.2, and 1.0. We list here some intuitions that may be gained when looking at our sensitivity analysis:

1) From a descriptive viewpoint, FLA dramatically reduce the importance of the interest rate smoothing argument in the loss function. In fact, the distance reductions got when embedding FLA into the model span from a minimum of 46.67% (case with $\lambda = 1.0$) up to 81.12% ($\lambda = 0.0$).

2) As far as the *real* interest rate in the AD equation is concerned, FLA seem to be particularly important. Indeed, all along our sensitivity exercises, γ_r turns out to be equal to 1. Instead, the percentage of firms and households fully forward looking seems to be low: γ_π assumes values such as 0.1 or 0.2, while γ_y figures like 0.2 or 0.3. Notably, these figures are in line with those contained in many empirical investigations: nevertheless, FLA play a key role in our positive exercise.[18]

3) The smallest value of our distance measure is the one related to the framework in which the output gap weight is zero. This means that if we calibrated the preference λ over the grid [0.0; 0.2; 0.5; 1.0] we would find that the first figure is the one that most closely represents Greenspan's preferences. A possible interpretation of this result is provided by Dennis (2002) and Favero and Rovelli (2003), who underline the role of the output gap as leading indicator for future inflation. In other words, the output gap would not have had a big relevance in Greenspan's penalty function, but still it would be an important element for setting the optimal policy rate. An alternative possible explanation, in the spirit of the evidence on output gap uncertainty in Smets (2002) and Estrella and Mishkin (1999) is

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optimal policy rate will turn out to be *smoother* than the one computed in absence of FLA, then also smoother than the actual one! This implies that, to fit the data with a hybrid model, we will have to *reduce* μ^*, i.e. $\mu^*_{Hybrid} < \mu^*_{FullyBackward}$.

[18] For similar estimates concerning the Phillips curve, see e.g. Roberts (1998,2001), Lindè (2002), Rudd and Whelan (2001), Rudebusch (2001), Söderlind, Söderström, and Vredin (2002). Relatively to the IS equation, see Fuhrer and Rudebusch, 2002.

Panel a): Calibration of the parameter μ

Interest rate	μ	$E(i_t)$	$\sigma(i_t)$	$\sigma(\Delta i_t)$
Actual	-	0	1.7273	0.4961
Backward	10	0.5369	2.5432	0.3876
Hybrid	0.4	0.1890	1.5930	0.4026

Panel b): Conditional comparison ($\mu = 0.4$)

Interest rate	$E(i_t)$	$\sigma(i_t)$	$\sigma(\Delta i_t)$	$\rho(i_{act}, i_{sim})$	$D(i_{act}, i_{sim})$	Dist. reduct.
Actual	0	1.7273	0.4961	-	-	-
Backward	0.6079	4.7276	1.0106	0.8672	3.3049	-
Hybrid	0.1890	1.5930	0.4026	0.9478	0.6241	81.12%

Backward model: γ_π=0.0001; γ_y=0.0001; γ_r=0.
Hybrid model: γ_π=0.1; γ_y=0.3; γ_r=1.
Moments of the Actual interest rate refer to the demeaned rate.

Table 3: Calibration outcomes and descriptive statistics with $\lambda = 0.0$

Panel a): Calibration of the parameter μ

Interest rate	μ	$E(i_t)$	$\sigma(i_t)$	$\sigma(\Delta i_t)$
Actual	-	0	1.7273	0.4961
Backward	7.4	0.6303	2.5787	0.4309
Hybrid	0.5	0.4443	1.9436	0.4968

Panel b): Conditional comparison ($\mu = 0.5$)

Interest rate	$E(i_t)$	$\sigma(i_t)$	$\sigma(\Delta i_t)$	$\rho(i_{act}, i_{sim})$	$D(i_{act}, i_{sim})$	Dist. reduct.
Actual	0	1.7273	0.4961	-	-	-
Backward	0.7198	3.8366	0.9031	0.9060	2.4134	-
Hybrid	0.4443	1.9436	0.4968	0.9474	0.7721	68.01%

Backward model: γ_π=0.0001; γ_y=0.0001; γ_r=0.
Hybrid model: γ_π=0.2; γ_y=0.2; γ_r=1.
Moments of the Actual interest rate refer to the demeaned rate.

Table 4: Calibration outcomes and descriptive statistics with $\lambda = 0.2$

Panel a): Calibration of the parameter μ

Interest rate	μ	$E(i_t)$	$\sigma(i_t)$	$\sigma(\Delta i_t)$
Actual	-	0	1.7273	0.4961
Backward	2.6	0.9166	2.7908	0.6353
Hybrid	1.3	0.6977	1.6167	0.4314

Panel b): Conditional comparison ($\mu = 1.3$)

Interest rate	$E(i_t)$	$\sigma(i_t)$	$\sigma(\Delta i_t)$	$\rho(i_{act}, i_{sim})$	$D(i_{act}, i_{sim})$	Dist. reduct.
Actual	0	1.7273	0.4961	-	-	-
Backward	0.9395	3.0101	0.7677	0.8916	1.8648	-
Hybrid	0.6977	1.6167	0.4314	0.9248	0.945	46.67%

Backward model: γ_π=0.0001; γ_y=0.0001; γ_r=0.
Hybrid model: γ_π=0.1; γ_y=0.2; γ_r=1.
Moments of the Actual interest rate refer to the demeaned rate.

Table 5: Calibration outcomes and descriptive statistics with $\lambda = 1.0$

that monetary authorities may have placed a low weight on the most poorly measured goal, or yet, that the market productivity growth of the 90s may have drastically reduced any concern of output stabilization. A similar result is also present in Cecchetti, Flores-Lagunes, and Krause (2001). Finally, this result also arises in studies that take into account analogous hybrid models (e.g. Söderlind, Söderström, and Vredin, 2002, and Dennis, 2003) and in studies in which authors take into account the model uncertainty issue (e.g. Castelnuovo and Surico, 2003). Table 6 summarizes the parameters values featuring our best (in terms of descriptive power) model.

Our calibration strategy concentrates on the federal funds rate. Table 7 reports some descriptive statistics relative to the actual and simulated series of the inflation rate and the output gap. Importantly, these statistics are quite close to each other, and the correlation rates reported are fairly satisfactory. We take these figures as evidence in favor of our calibration strategy, i.e. our strategy turns out to produce sensible results also for the other variables of our economic system.

Still a positive μ: possible reasons

The presence of forward looking agents in the economic framework squeezes

Model components	**Parameters**	**Values (Assignment Strategy)**
Loss function	λ	0.000 (imposed)
	μ	0.400 (calibrated)
Phillips curve	γ_π	0.100 (calibrated)
	$\alpha_{\pi 1}$	0.282 (OLS estimated)
	$\alpha_{\pi 2}$	-0.025 (OLS estimated)
	$\alpha_{\pi 3}$	0.292 (OLS estimated)
	$\alpha_{\pi 4}$	0.385 (OLS estimated)
	α_y	0.141 (OLS estimated)
	σ_ε	0.660 (OLS estimated)
AD curve	γ_y	0.300 (calibrated)
	β_{y1}	1.229 (OLS estimated)
	$\beta_{\pi 2}$	-0.244 (OLS estimated)
	γ_r	1.000 (calibrated)
	β_r	-0.073 (OLS estimated)
	σ_η	0.510 (OLS estimated)

Table 6: Best model: List of parameters values

Inflation rate	$E(\pi_t)$	$\sigma(\pi_t)$	$\sigma(\Delta\pi_t)$	$\rho(\pi_{act}, \pi_{sim})$
Actual	0	1.0031	0.8438	-
Simulated	0.1579	0.8517	0.8468	0.5503
Output gap	$E(y_t)$	$\sigma(y_t)$	$\sigma(\Delta y_t)$	$\rho(y_{act}, y_{sim})$
Actual	-0.2612	1.8182	0.5230	-
Simulated	-0.3547	1.0269	0.3975	0.6518
Moments of the Actual variables refer to the demeaned processes.				

Table 7: Best model: Descriptive statistics of inflation and output gap

the value of the parameter μ needed in order to track Greenspan's federal funds rate. Nevertheless, μ is still strictly positive. Then, what is this model missing in order to fully explain the observed policy gradualism? Sack and Wieland (2000) suggest that also parameter uncertainty and measurement error affecting real-time data may imply optimal gradualism. As far as the former explanation is concerned, Söderström (1999) and Sack (2000), working on an idea originally proposed by Brainard (1967), show that parameter uncertainty may contribute to rationalize the observed cautiousness. However, Estrella and Mishkin (1999), Peersman and Smets (1999), and Rudebusch (2001) claim that parameter uncertainty is not so important from a quantitative viewpoint. Moreover, robust-control oriented work (e.g. Onatski and Stock, 2002) tend to suggest an optimally aggressive conduct of monetary policy.

Does learning enhance gradualism? Sack (1998) shows how a CB that periodically refines his estimates of the key-parameters linking the variables of interest in a given framework may choose to act gradually. This result is due to the stochastic features of the economic dynamics, that render particularly informative the most recent observations. As a result, the Fed faces more uncertainty about the reaction of the economy as it moves the funds rate away from its recent levels. However, Sack (1998) himself and Wieland (2000) point out that there exist a dynamic trade-off between gradualism and learning, i.e. it may become optimal in a dynamic set-up to implement an aggressive policy in order to learn how the economy react to new, different monetary policy shocks. Indeed, an aggressive policy might speed up the learning process. However, this approach, termed *experimentation* (see Bertocchi and Spagat, 1993, and Caplin and Leahy, 1996), do not seem to be supported by Policy Makers' official declarations.[19]

McCallum (1999) sustains that a good policy rule is the one that is capable to perform well across many different models. In fact, not only a CB is uncertain about the key-parameters of the equations formalizing the economy; indeed, he is uncertain regarding the structure of the economy itself.

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[19] Regarding this point, it is worth to signal a comment by a former Vice-Chairman of the Fed, Alan Blinder (1998, p.11): "You don't conduct experiments on a real economy solely to sharpen your econometric estimates".

From the descriptive side, recent empirical contributions by Favero and Milani (2001) and Castelnuovo and Surico (2003), conducted in a class of linear backward looking models, show that model uncertainty helps explaining the observed policy rate behavior.

Finally, a positive value of the μ parameter might also be the expression of the concern that the CB has for the financial markets, markets that are thought as being very reactive to large swings of the nominal interest rate (Goodfriend, 1991; Blinder, 1997; Mishkin, 1999).[20]

7 Conclusions

The interest rate smoothing argument has been debated quite intensively in the past few years. From a positive perspective this argument is needed in order to generate the observed policy rate persistence. In fact, in small scale fully backward looking models the interest rate smoothing weight has usually got a puzzling high relative value in the CB's loss function.

In this paper we show that the 'forward looking agents' ingredient may play a big role in partially solving this puzzle. Indeed, by comparing the outcomes stemming from a fully backward looking model with those deriving from a calibrated hybrid one, we found that this ingredient dramatically reduces the interest rate smoothing puzzle otherwise arising. Implicitly, this suggests that the Fed has seriously taken Greenspan has seriously taken into account private sector's expectations taking its policy decisions.

Interestingly enough, when looking at some recent contributions in the literature, it seems to be possible to state that our conclusion on the relationship between forward looking agents and policy rate gradualism holds even when learning is taken into account. Wieland (2002) obtains the same result in a model in which both the Central Banker and the private sector

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[20] An interesting point tackling this view is provided by Cecchetti (2000). In fact, he claims that large jumps in the policy instruments could be disruptive only if financial markets are relatively certain that it will never happen. Instead, if market participants expect that new information can precipitate large and sudden interest rate changes, then they will defend themselves by building up institutions that can withstand the potential disruptions this would otherwise cause. In synthesis, the only reason that people believe smooth interest rates enhance financial stability is because interest rate has been smooth up to now.

are uncertain about the relationship between inflation and unemployment, and learn on that. We see this evidence as a further confirmation on the robustness of our findings.

Our calibration exercises suggest that a hybrid new-Keynesian model may very well fit the data. In particular, a low relative concern for output gap volatility with respect to inflation volatility, a low degree of 'forward lookingness' in both the Phillips curve and the IS curve, and a high weight for future inflation in the expected real interest rate are the features of our best positive model. In this sense, our findings are in line with those contained in a recent work by Söderlind, Söderström, and Vredin (2002), and suggest that much more should be done in order to better understand the role of adjustment costs, rules of thumb, and habit formation in shaping the dynamics of variables such as inflation and the output gap. It is worth signalling that efforts in this direction have already been undertaken by e.g. Fuhrer and Moore (1995), Fuhrer (2000), Estrella and Fuhrer (2002) and Amato and Laubach (2003).

Although very much important, the presence of forward looking agents in small scale macroeconomic models is not sufficient to get rid of the interest rate smoothing argument when performing positive exercises. Apart from model uncertainty and real-time data (ingredients already suggested by Sack and Wieland in their survey), an interesting attempt could be that of investigating if a framework admitting 'quasi-commitment' solutions of the monetary authorities' optimal control problem might reduce further (if not completely eliminate) the interest rate smoothing penalty in the loss function. In fact, Schaumburg and Tambalotti (2003) and Hakan Kara (2003) notice how the observed monetary policy gradualism is lower than the one suggested by the optimal solution under commitment, but higher than that featuring the optimal solution under full discretion. Following their approach, the introduction of a credibility parameter in the set up analyzed in this paper could lead to having an optimal solution featured by a large degree of inertia even in absence of the interest rate smoothing penalty. This effort is the next one in our research agenda.

Technical appendix

The algorithm to solve the optimal control problem faced by the CB is more easily understandable if the model representing the economy is written in its state-space form. Consider equations (4) and (5), which we rewrite here below:

$$\begin{aligned}\pi_{t+1} &= \gamma_\pi E_t\left(\frac{\pi_{t+1}+\pi_{t+2}+\pi_{t+3}+\pi_{t+4}}{4}\right) \\ &\quad +(1-\gamma_\pi)(\alpha_{\pi 1}\pi_t+\alpha_{\pi 2}\pi_{t-1}+\alpha_{\pi 3}\pi_{t-2}+\alpha_{\pi 4}\pi_{t-3})+\alpha_y y_t+\varepsilon_{t+1}\end{aligned} \tag{9}$$

$$\begin{aligned}y_{t+1} &= \gamma_y E_t y_{t+2}+(1-\gamma_y)(\beta_{y1}y_t+\beta_{y2}y_{t-1}) \\ &\quad -\beta_r\gamma_r\left[i_t-E_t\left(\frac{\pi_{t+1}+\pi_{t+2}+\pi_{t+3}+\pi_{t+4}}{4}\right)\right] \\ &\quad -\frac{\beta_r(1-\gamma_r)}{4}(i_t+i_{t-1}+i_{t-2}+i_{t-3}-\pi_t-\pi_{t-1}-\pi_{t-2}-\pi_{t-3})+\eta_{t+1}\end{aligned} \tag{10}$$

To solve the optimal control problem, we basically have to compute the expectations terms $E_t\pi_{t+4}$ and $E_t y_{t+2}$. Noticing that $\pi_{t+1}=E_t\pi_{t+1}+\varepsilon_{t+1}$ and $y_{t+1}=E_t y_{t+1}+\eta_{t+1}$ (where ε_{t+1} and η_{t+1} are white noise), it is then possible to write (9) and (10) as follows:

$$\begin{aligned}\frac{\gamma_\pi E_t\pi_{t+4}}{4} &= \left(1-\frac{\gamma_\pi}{4}\right)E_t\pi_{t+1}-\frac{\gamma_\pi}{4}E_t\pi_{t+2}-\frac{\gamma_\pi}{4}E_t\pi_{t+3} \\ &\quad -(1-\gamma_\pi)(\alpha_{\pi 1}\pi_t+\alpha_{\pi 2}\pi_{t-1}+\alpha_{\pi 3}\pi_{t-2}+\alpha_{\pi 4}\pi_{t-3})-\alpha_y y_t\end{aligned} \tag{11}$$

$$\begin{aligned}\gamma_y E_t y_{t+2}+\beta_r\gamma_r E_{t+4} &= E_t y_{t+1}-(1-\gamma_y)(\beta_{y1}y_t+\beta_{y2}y_{t-1}) \\ &\quad +\beta_r\gamma_r\left[i_t-E_t\left(\frac{\pi_{t+1}+\pi_{t+2}+\pi_{t+3}}{4}\right)\right] \\ &\quad +\frac{\beta_r(1-\gamma_r)}{4}\sum_{j=0}^{3}(i_{t-j}-\pi_{t-j})\end{aligned} \tag{12}$$

As already specified in the text, we aim at computing the discretionary solution of the problem, given that it is time-consistent. To find it, we use Söderlind (1999)'s strategy.[21] This strategy requires a precise distinction of the elements involved in the problem between state (predetermined) and jump (forward-looking) variables. So, we define the $(n1x1)$ vector of predetermined state variables as follows $(n1 = 9)$:

$$x_{1t} = \left[\begin{array}{ccccccccc} \pi_t & \pi_{t-1} & \pi_{t-2} & \pi_{t-3} & y_t & y_{t-1} & i_{t-1} & i_{t-2} & i_{t-3} \end{array} \right]' \tag{13}$$

and the $(n2x1)$ vector of forward-looking jump ones as here below $(n2 = 4)$:

$$x_{2t} = \left[\begin{array}{cccc} E_t\pi_{t+3} & E_t\pi_{t+2} & E_t\pi_{t+1} & E_t y_{t+1} \end{array} \right]' \tag{14}$$

Since we are solving a stochastic problem, we also define the $(n1x1)$ vector of shocks to the predetermined variables as:

$$v_{1t} = \left[\begin{array}{cccc} \varepsilon_t & 0_{1x3} & \eta_t & 0_{1x4} \end{array} \right]' \tag{15}$$

Then, the state-space representation of the problem is the following:

$$A_0 \left[\begin{array}{c} x_{1t+1} \\ E_t x_{2t+1} \end{array} \right] = A_1 \left[\begin{array}{c} x_{1t} \\ x_{2t} \end{array} \right] + B_1 i_t + v_{t+1} \tag{16}$$

where

$$v_{t+1} = \left[\begin{array}{c} v_{1t+1} \\ 0_{n2x1} \end{array} \right] \tag{17}$$

and where the matrices A_0, A_1, and B_1 read as follows:

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[21] The Gauss and Matlab routines for solving the optimal stochastic regulator problem presented in this Technical Appendix can be found in Söderlind's webpage, i.e. http://www.hhs.se/personal/PSoderlind/.

$$A_0 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{\gamma_\pi}{4} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{\beta_r\gamma_r}{4} & 0 & 0 & \gamma_y \end{bmatrix}$$

$$A_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ \widetilde{\alpha}_{\pi1} & \widetilde{\alpha}_{\pi2} & \widetilde{\alpha}_{\pi3} & \widetilde{\alpha}_{\pi4} & -\alpha_y & 0 & 0 & 0 & 0 & -\frac{\gamma_\pi}{4} & -\frac{\gamma_\pi}{4} & (1-\frac{\gamma_\pi}{4}) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ \widehat{\beta}_r & \widehat{\beta}_r & \widehat{\beta}_r & \widehat{\beta}_r & \widetilde{\beta}_{y1} & \widetilde{\beta}_{y2} & -\widehat{\beta}_r & -\widehat{\beta}_r & -\widehat{\beta}_r & -\frac{\beta_r\gamma_r}{4} & -\frac{\beta_r\gamma_r}{4} & -\frac{\beta_r\gamma_r}{4} & 1 \end{bmatrix}$$

$$B_1 = \begin{bmatrix} 0_{1x6} & 1 & 0_{1x5} & \beta_r\gamma_r - \widehat{\beta}_r \end{bmatrix}'$$

where $\widetilde{\alpha}_{\pi j} = -(1-\gamma_\pi)\alpha_{\pi j}, \widehat{\beta}_r = -\frac{\beta_r(1-\gamma_r)}{4}, \widetilde{\beta}_{yj} = -(1-\gamma_y)\beta_{yj}$.

To obtain the standard state-space representation, we just have to premultiply (16) by A_0^{-1}, so obtaining

$$\begin{bmatrix} x_{1t+1} \\ E_t x_{2t+1} \end{bmatrix} = A \begin{bmatrix} x_{1t} \\ x_{2t} \end{bmatrix} + Bi_t + v_{t+1} \tag{18}$$

with $A = A_0^{-1}A_1$ and $B = A_0^{-1}B_1$.[22]

It is useful to express also the CB's objective function in a compact form. To do so, it is necessary to write down the vector of the arguments targeted by the CB. This vector is defined as:

$$z_t = \begin{bmatrix} \bar{\pi}_t & y_t & \Delta i_t \end{bmatrix}' \tag{19}$$

Notice that, given our choice of working with demeaned variables which renders easier the management of the optimal stochastic regulator problem, π^* is normalized to be equal to zero.

The goal variables included in vector (19) can be expressed via the following formula:

$$z_t = C_x x_t + C_i i_t \tag{20}$$

where

$$C_x = \begin{bmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

and

$$C_i = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}'$$

The CB attributes to the quadratic transformation of the arguments in (19) different weights. We normalize the weight on the average inflation rate to one, and we attribute relative weights to the other targets, as follows:

$$L_t = \bar{\pi}_t^2 + \lambda y_t^2 + \mu \Delta i_t^2 \tag{21}$$

which can be re-expressed as:

---

[22] Notice that $A_0^{-1}v_{t+1} = v_{t+1}$, since A_0 is block diagonal with an identity matrix as its upper left block and the lower block of $v_{t+1}$is equal to zero. Notice also that the requirement for having $det(A_0) \neq 0$ is that $\gamma_\pi, \gamma_y \neq 0$. That is why, when identifying the Benchmark model (i.e. fully backward looking model) in our exercise, we do not set those weights to a zero value. Instead, we set them equal to 10^{-4}. This is a drawback deriving from our choice of using the procedure elaborated by Paul Söderlind (1999) for solving RE models. Richard Dennis made us notice that, if we were to solve for the optimal discretionary rule using the *structural* form of the model rather than the *state-space* form, this problem would vanish. For further information abour this point, see Dennis (2000).

$$L_t = z_t^{'} K z_t \tag{22}$$

where K is a $3x3$ diagonal matrix containing the relative concerns of the CB. K is shaped in this way:

$$K = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & \mu \end{bmatrix} \tag{23}$$

Using (20), the period loss function (22) can be re-expressed as follows:

$$\begin{aligned} L_t &= \begin{bmatrix} x_t^{'} & i_t^{'} \end{bmatrix} \begin{bmatrix} C_x^{'} \\ C_i^{'} \end{bmatrix} K \begin{bmatrix} C_x & C_i \end{bmatrix} \begin{bmatrix} x_t \\ i_t \end{bmatrix} \\ &= x_t^{'} C_x^{'} K C_x x_t + x_t^{'} C_x^{'} K C_i i_t + i_t^{'} C_i^{'} K C_x x_t + i_t^{'} C_i^{'} K C_i i_t \\ &= x_t^{'} Q x_t + x_t^{'} U i_t + i_t^{'} U' x_t + i_t^{'} R i_t \end{aligned}$$

where $x_t = \begin{bmatrix} x_{1t} \\ x_{2t} \end{bmatrix}$,

and where $Q = C_x^{'} K C_x$, $U = C_x^{'} K C_i$, $R = C_i^{'} K C_i$.

Hence the CB's optimal control problem is given by the intertemporal penalty function

$$J_t = E_t \sum_{\tau=t}^{\infty} \delta^{\tau-t} (x_\tau^{'} Q x_\tau + x_\tau^{'} U i_\tau + i_\tau^{'} U' x_\tau + i_\tau^{'} R i_\tau) \tag{24}$$

subject to the law of motion of the economy (18). As already written in the text, it turns out that the optimal discretionary policy is a rule for the interest rate as a linear function of the predetermined variables in the vector x_{1t}, i.e.

$$i_t = -F x_{1t} \tag{25}$$

The law of motion of the predetermined variables is given by

$$x_{1t+1} = M x_{1t} + v_{1t+1} \tag{26}$$

while the jump variables are defined as

$$x_{2t} = N x_{1t} \tag{27}$$

Details on how to compute the matrices M and N are provided by Söderlind (1999).

Notice an important result. Rudebusch and Svensson (1999) underline how, when the discount factor $\delta \rightarrow 1$, the intertemporal loss function (24) approaches the unconditional mean of the period loss function. Hence, we can write it as

$$E(L_t) = Var(\overline{\pi}_t) + \lambda Var(y_t) + \mu Var(\Delta i_t) \tag{28}$$

After having

1) initialized the vector x_{10} with historical observations,

2) attributed to the vector x_{20} nil values,

3) set the values of the key-coefficients $\alpha_s, \beta_s, \gamma_\pi, \gamma_y$, and γ_r in the matrices A_0, A_1, and B,

4) stored the structural residuals into the vector v_t,

5) determined the relative weights λ and μ in the loss function (28), and

6) computed the optimal feedback coefficients in F,

we can exploit expressions (18) and (25) in order to simulate how the economy would have evolved if the CB had implemented the policy rule solution of the optimal control problem. Finally, given the simulated time-series for π, y, and i, it is easy to compute the value of the expected loss (28).

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(l) This paper was presented at the Workshop "Growth, Environmental Policies and Sustainability" organised by the Fondazione Eni Enrico Mattei, Venice, June 1, 2001

(li) This paper was presented at the Fourth Toulouse Conference on Environment and Resource Economics on "Property Rights, Institutions and Management of Environmental and Natural Resources", organised by Fondazione Eni Enrico Mattei, IDEI and INRA and sponsored by MATE, Toulouse, May 3-4, 2001

(lii) This paper was presented at the International Conference on "Economic Valuation of Environmental Goods", organised by Fondazione Eni Enrico Mattei in cooperation with CORILA, Venice, May 11, 2001

(liii) This paper was circulated at the International Conference on "Climate Policy – Do We Need a New Approach?", jointly organised by Fondazione Eni Enrico Mattei, Stanford University and Venice International University, Isola di San Servolo, Venice, September 6-8, 2001

(liv) This paper was presented at the Seventh Meeting of the Coalition Theory Network organised by the Fondazione Eni Enrico Mattei and the CORE, Université Catholique de Louvain, Venice, Italy, January 11-12, 2002

(lv) This paper was presented at the First Workshop of the Concerted Action on Tradable Emission Permits (CATEP) organised by the Fondazione Eni Enrico Mattei, Venice, Italy, December 3-4, 2001

(lvi) This paper was presented at the ESF EURESCO Conference on Environmental Policy in a Global Economy "The International Dimension of Environmental Policy", organised with the collaboration of the Fondazione Eni Enrico Mattei , Acquafredda di Maratea, October 6-11, 2001

(lvii) This paper was presented at the First Workshop of "CFEWE – Carbon Flows between Eastern and Western Europe", organised by the Fondazione Eni Enrico Mattei and Zentrum fur Europaische Integrationsforschung (ZEI), Milan, July 5-6, 2001

(lviii) This paper was presented at the Workshop on "Game Practice and the Environment", jointly organised by Università del Piemonte Orientale and Fondazione Eni Enrico Mattei, Alessandria, April 12-13, 2002

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