Volume 3, Number 1 March 2007

IJCB
INTERNATIONAL JOURNAL OF CENTRAL BANKING

Special Issue: Transparency, Communication, and Commitment

IJCB International Journal of Central Banking

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The *International Journal of Central Banking* is published quarterly (ISSN: 1815-4654). Online access to the publication is available free of charge at **www.ijcb.org**. Individual print subscriptions are available at an annual rate of $100 (USD).

Print subscription orders may be placed online at www.ijcb.org, by phone (202-452-3245), via fax (202-728-5886), or by e-mail (editor@ijcb.org).

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International Journal of Central Banking
Publications Fulfillment, MS-127
Federal Reserve Board
Washington, DC 20551

Phone: 202-452-3245
Fax: 202-728-5886
E-mail: editor@ijcb.org

ISSN: 1815-4654

Transparency, Communication, and Commitment

Introduction to a Special Issue of the International Journal of Central Banking

Questions about transparency and the optimal way to communicate and commit to a monetary policy are both highly practical and fascinating from a research viewpoint. How far can transparency be taken? Is it better for a central bank to provide information about the future path for the interest rate instrument, or simply to give the staff's economic forecast of inflation and the real economy? How should one model transparency? By assuming that communications are sent and received with error, or by assuming that only a fraction of economic agents get the information? Similarly, how can one model different degrees of commitment? And how can one test and evaluate different models of transparency and commitment?

Progress has been made recently in designing economic models that can be used to answer such questions. Several conferences on this subject have been planned or are now under way, and discussions are taking place among policymakers in a number of central banks around the world. Many technical research papers are being written on the subject. This special issue of the *International Journal of Central Banking* is devoted to these questions of transparency, communication, and commitment. It is the second special issue since the IJCB was founded. The first, *Staggered Pricing Models Face the Facts*, was published in September 2006 as Volume 2, Number 3.

The leadoff paper in this issue is by Carl Walsh. It examines the transparency question in a standard model with staggered price setting and rational expectations. Price shocks result in a policy tradeoff between fluctuations of inflation and real GDP. The model assumes a continuum of different degrees of transparency, measured by the fraction of firms who receive the announcement of a policy change. There is an optimal degree of transparency in the model; it balances (1) the volatility-reducing effect of transparency—due to people being informed that the central bank is reacting either to a supply or demand disturbance—against (2) the volatility-increasing effect of transparency—due to the private sector's reaction to the inevitable noise in the forecast. Optimal transparency can be less than full transparency primarily because of the private sector's reaction to the noise in the central bank's forecast.

Petra Geraats focuses mainly on a model with perfectly flexible prices, though a more complex sticky-price model is considered in an appendix. The paper models varying degrees of transparency differently than Walsh, focusing on the noisiness of the signal sent about the target inflation rate and the target for potential output rather than the fraction of participants who receive the signal. Geraats works within a discretionary policy framework (rather than a rules framework) and finds that more transparency about the inflation target improves outcomes while less transparency about the output target can improve outcomes. A novelty is modeling a situation where people's views about transparency are different from the actual transparency; thus, there is a lack of common knowledge. This is modeled by assuming that people believe there is a larger variance of the noise in the signal than there actually is.

The paper by Gara Mínguez-Afonso delves further into the common-knowledge issue and models how information about policy flows through the market. It examines a situation where the fundamentals of the economy are not common knowledge among the traders, and it is this absence of common knowledge that generates rapid and possibly large discrete changes in rates. Using assumptions somewhat analogous to the Walsh paper, traders sequentially become informed that the price—whether the exchange rate or the interest rate—has moved away from fundamentals, but they are also aware that other traders are not so informed.

The paper by Ewerhart, Cassola, Ejerskov, and Valla looks at the detailed "plumbing" of monetary policy—by actually peering into the microstructure of the money markets where the central bank's targets, or corridors, for the overnight interest rate interact with commercial banks buying and selling in the market. In their model, a bank with private information can cause a non-negligible price change because banks extract information from the observed trading volume and order flows. This type of model is relevant for the analysis of communication policy of the central bank because the stated intentions of the central bank—for example, to take actions to offset the impact of manipulators in the market—can affect the size of market volatility.

Hakan Kara focuses on the problem of commitment by the central bank to a policy rule. A new parameter—measuring the degree of a policymaker's commitment to an optimal monetary policy—is defined in the paper; it ranges from zero commitment to full commitment. A higher commitment parameter results in a monetary policy rule that is more reactive to expected inflation and output than a lower commitment parameter; it also results in more inertia. Using U.S. data, pre- and post-1980, the paper interprets the observed higher reaction coefficients in the policy rule in the later period as a greater degree of commitment. Hence the paper interprets changes in policy rule coefficients as due to changes in the commitment parameter. It also shows the value, in terms of improved performance, of committing to a policy rule.

The final paper, by Michael Ehrmann and Marcel Fratzscher, empirically examines how the market reacts to two different ways of communicating about Federal Reserve policy. Their findings are valuable for determining whether to announce intentions for the paths for future interest rates or economic outlook. They distinguish between the communication approach used during the 1990s period before December 1999 and the "balance of risks" approach followed afterward. In both cases, markets anticipate interest rate moves, but they do so more rapidly in the newer regime than in the older regime, and with less overshooting.

John Taylor, Hyun Shin, Frank Smets,
Kazuo Ueda, Michael Woodford
Editorial Board

Optimal Economic Transparency*

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In this paper, I explore the optimal extent to which the central bank should disseminate information among private agents. Individual firms are assumed to have diverse private information, and the central bank provides public information either implicitly, by setting its policy instrument, or explicitly, by making announcements about its short-run targets. The optimal degree of economic transparency is affected differently by cost and demand shocks. More-accurate central bank forecasts of demand shocks reduce optimal transparency, while more-accurate forecasts of cost shocks increase optimal transparency. Increased persistence in demand (cost) disturbances increases (reduces) optimal transparency.

JEL Codes: E52, E58, E31.

1. Introduction

A major development in central banking in recent years has been the increase in monetary policy transparency. Inflation-targeting central banks in particular have gone the furthest in adopting mechanisms to ensure greater transparency.[1]

*Earlier versions of this paper were presented at "New Developments in the Analysis of Monetary Policy and Institutions," a conference in honor of Alex Cukierman's lifelong contributions to macroeconomics, the Sapir Center, Tel Aviv University, December 15–16, 2005; and the Bank of England's Chief Economists Workshop, May 8–10, 2006. I would like to thank participants at these events, David Archer, Kevin Cowan, Akiva Offenbacher, and Larry Schembri for helpful comments on this and related research. All remaining errors are my own. E-mail: walshc@ucsc.edu.

[1] In recent years, even central banks that have not formally adopted inflation targeting have become more transparent. Eijffinger and Geraats (2006) provide an index of transparency for a set of developed economies that includes some inflation targeters (Australia, Canada, New Zealand, Sweden, and the United Kingdom) as well as nontargeters (Japan, Switzerland, and the United States).

Transparency has many dimensions. Geraats (2002) identifies five different forms of transparency: political, procedural, economic, policy, and operational. Briefly, these correspond to transparency about objectives, about the internal decision-making process, about the central bank's forecasts and models, about the central bank's communications of its policy actions, and about its instrument setting and control errors.

Most of the existing theoretical literature on central bank transparency has focused on political and operational transparency, employing models in which only policy surprises have real effects, the central bank's preferences are stochastic and unknown, and the central bank's policy instrument, taken to be the money supply, is observed with error.[2] Private agents observe the current money growth rate but are unable to disentangle the effects of control errors from shifts in central bank preferences. Thus, there is opaqueness about political objectives and operational implementation. Transparency was typically modeled as a reduction in the noise in the signal on the policy instrument. Under a less transparent regime, disinflations are more costly, as it takes private agents longer to recognize that the central bank's preferences have shifted away from greater output expansion. However, a more transparent regime allows private agents to assess better the shifting preferences of the central bank, and this reduces the ability of the central bank to create economic expansions when they are most desired. These two competing forces determine the optimal degree of transparency, and Cukierman and Meltzer (1986) show that the central bank may prefer to adopt a less efficient operating procedure than is technically feasible (i.e., not reduce the control-error variance to its minimum possible level).[3]

They find that between 1998 and 2002 transparency increased for virtually all the central banks they studied. Even the Federal Reserve, which has so far resisted calls to establish a formal inflation target, has moved to make its policy practices more transparent.

[2]See, for example, Cukierman and Meltzer (1986) and Faust and Svensson (2002).

[3]See also Faust and Svensson (2002), who show that when the choice of transparency is made under commitment, patient central banks with small inflation biases will prefer minimum transparency. They argue that this result might account for the (then) relatively low degree of transparency that characterized the U.S. Federal Reserve.

In contrast to these earlier models, standard policy models today imply that predictable policies are most effective, the preferences of inflation-targeting central banks are known, and the policy instrument is likely to be a nominal interest rate that is easily observable. Thus, results from models that emphasized unpredictable policies and money-supply control may not carry over. And while modern central banks may be operationally transparent, they may still be opaque with respect to internal forecasts about the economy; economic transparency may be incomplete.

In this paper, I examine the optimal degree of economic transparency. The model developed in the paper contrasts in several ways with previous work on monetary policy transparency. First, I employ a New Keynesian model of price setting rather than the type of Lucas supply curve commonly employed in the earlier literature on transparency.[4] Second, I ignore the issue of the central bank's intentions and focus on inflation-targeting central banks that have already developed a reputation for maintaining low and stable inflation. The public understands that the policymaker will maintain average inflation at zero; the public also understands the manner in which the bank will respond to shocks that lead to short-run fluctuations in inflation and the output gap. Private agents still face uncertainty about monetary policy, however, because they have only imperfect knowledge of the information on which the central bank bases its policy. A transparent central bank reveals its information about the economy to the public.[5]

[4] Jensen (2002) studies transparency using a two-period model in which inflation is forward looking in a manner consistent with recent monetary policy models. His focus, like that of Faust and Svensson (2002), is on political transparency. Greater transparency implies that policy has a larger impact on future expectations and therefore on current inflation. This leads to greater caution on the part of the central bank in its policy actions. Transparency improves welfare if the central bank is prone to an inflation bias, but it can limit stabilization policy if the central bank's output objective is already consistent with the economy's natural rate of output.

[5] Walsh (1999, 2003) also investigates aspects of economic transparency. In Walsh (1999), the ability of the central bank to announce a state-contingent inflation target improves stabilization policy, while in Walsh (2003), transparency about the central bank's information improves monitoring by the public and makes it optimal for the central bank to place greater weight on achieving its inflation objectives.

Third, I drop the standard assumption that private agents have common information, assuming instead that information is diverse, with individual firms receiving idiosyncratic signals about current aggregate cost and demand shocks. Since firms care about their price relative to other firms, individual firms must form expectations about what other firms are expecting. Thus, higher-order expectations (expectations of expectations of expectations . . .) play a role, and this can influence the way public information about monetary policy affects inflation. Morris and Shin (2002) have argued that, when private agents have individual sources of information, there can be a cost to providing more-accurate public information.[6] Agents may overreact to public information, making the economy more sensitive to any forecast errors in the public information.[7]

Fourth, I model transparency, not in terms of a control-error variance but in terms of the extent to which the central bank disseminates information about its views on the state of the economy. At one extreme, the central bank may make no announcements. At the other extreme, it may undertake to publish detailed inflation reports that are widely read and discussed by the public. In between these extremes, the central bank may partially publicize information through speeches, less widely read press releases, or other means that reach a limited audience. The extent to which information on the central bank's short-run targets is made available to private agents provides a measure of transparency.

In modeling transparency in this way, I follow Cornand and Heinemann (2004), who demonstrate that the partial release of information in the Morris-Shin model can be useful. Wide release of

[6]Woodford (2003) has investigated the role of higher-order expectations in inducing persistent adjustments to monetary shocks in the Lucas-Phelps islands model. See also Hellwig (2002).

[7]The possibility that the private sector may overreact to central bank announcements does capture a concern expressed by some policymakers. For example, in discussing the release of Federal Open Market Committee (FOMC) minutes, Janet Yellen expressed the view that "financial markets could misinterpret and overreact to the minutes" (Yellen 2005). However, Svensson (2006) has argued that the Morris-Shin result is not a general one. He shows that welfare is increased by more-accurate public information in the Morris-Shin model for all but unreasonable parameter values. A similar result is found by Hellwig (2004).

information causes public information to coordinate expectations, and this can make the economy sensitive to any noise in the public information; this is the cost of announcements. The gain is that they provide information that leads the public to have more-accurate expectations. When it is costly for the central bank to provide information, it may still pay to engage in a limited release of information. If only a few agents receive the central bank's information, private-sector expectations will, on average, be more accurate, but because only a few agents receive the information, it has little effect on the typical agent's expectations of what others are expecting. The impact of the noise in the public information is limited.

Just as the earlier literature on transparency employed models at odds with current policy frameworks (only surprises mattered, money supply was the instrument), the analysis of Morris and Shin (2002) is conducted within a framework that fails to capture important aspects of actual monetary policy. For example, the public information in Morris and Shin (2002) is a signal on an exogenous disturbance, yet most of the monetary policy debate on transparency has focused on the *endogenous* signals a central bank might release. When private agents observe a change in the central bank's instrument or receive announcements about the central bank's inflation forecast, they are obtaining public signals that depend on both the central bank's policy objectives and its assessment of economic conditions.

Amato and Shin (2003) have cast the Morris-Shin analysis in a more standard macro model. In their model, the central bank has perfect information about the underlying shocks. This ignores the uncertainty policymakers themselves face in assessing the state of the economy. Nor do Amato and Shin (2003) allow the private sector to use observations on the policy instrument to draw inferences about the central bank's information. They also assume one-period price setting and represent monetary policy by a price-level targeting rule. In Hellwig (2004), prices are flexible and policy is given by an exogenous stochastic supply of money; private and public information consists of signals on the nominal quantity of money. In contrast, I employ a standard Calvo-type model of imperfect price flexibility, modifying it by assuming that those firms adjusting each period must do so before observing the actual aggregate price level. Thus, the need to infer what other firms are doing is present, as in

Amato and Shin (2003) and in Hellwig (2004), but the approach is more consistent with standard New Keynesian models.[8]

Walsh (2006) examines how the degree of economic transparency affects the monetary transmission mechanism and shows that the impact of an interest rate change on inflation depends importantly on the information revealed by the central bank and on the quality of that information. In the model used in that paper, however, as in the related model of Baeriswyl and Cornand (2005), firms adjusting prices do so before observing any actual shocks. This means that inflation responds to expected cost shocks and not to the actual realizations of the shock. Transparency, by revealing information, can make expectations more volatile and increase the variability of inflation. Thus, a central bank concerned with stabilizing inflation may prefer to limit transparency. Walsh (2006) also assumed that firms received private information on the cost shock but not on an aggregate demand shock.[9] In the present paper, I allow firm-specific cost shocks (and not just expectations of these shocks) to directly affect price-setting behavior, and I assume that firms receive private signals on both the cost shock and the shock to aggregate demand, and the underlying cost and demand shocks are allowed to display persistence. This last aspect is important when current inflation depends on expectations of future inflation.

Geraats (2005) also analyzed the role played by the release of central bank forecasts. However, she assumes that agents do not observe the bank's policy instrument prior to forming expectations and she employs a traditional Lucas supply function. Her focus is on reputational equilibria in a two-period model with a stochastic inflation target. Thus, the model and the questions addressed are quite different than those pursued here.

Besides providing a new framework for analyzing transparency, several new insights into optimal transparency are obtained. First, improved central bank forecasting can have ambiguous effects on the optimal degree of transparency. If the central bank obtains

[8] Hellwig (2004) provides a more microfounded analysis that I pursue here, showing that this can be important for assessing the welfare effects of better information. Some comments on how results might differ if a welfare-based measure were used are discussed in the concluding section.

[9] Baeriswyl and Cornand (2005) make a similar assumption.

more-accurate signals on cost shocks, optimal transparency increases; if it obtains more-accurate signals on demand shocks, optimal transparency decreases. Optimal transparency is also affected differently by changes in the stochastic processes governing the cost and demand shocks. Thus, much as in the classic Poole analysis of instrument choice, the properties of exogenous shocks matter for determining the optimal degree of transparency.

The remainder of the paper is organized as follows. Section 2 sets out the basic model. Equilibrium with partial announcements is discussed in section 3. In section 4, numerical results are reported that examine the optimal degree of transparency and how it is affected by changes in various aspects of the model. Conclusions are summarized in section 5.

2. The Model

Assume that there are a continuum of firms of measure one, each producing a differentiated product using an identical technology. Firms face a Calvo-type fixed probability of adjusting their price each period. I assume that firms do not observe the current aggregate cost or demand shocks or the prices set by other firms until the period is over. Since any firm that is setting its price is concerned with its price relative to those of other firms, it will need to form expectations about the factors that determine its optimal relative price *and* about the behavior of other firms, since it must forecast the average price of other firms. Each period, private firms receive noisy signals on aggregate shocks. Each firm's signal is private information to that firm, so individual firms will have different information. The central bank also has private, noisy information on aggregate shocks. The central bank may make an announcement about its output-gap target.[10] It then sets its policy instrument. I assume that firms that adjust their price in period t do so after observing the central bank's instrument. Because the central bank receives information about the aggregate cost and demand shocks,

[10] In the model, this is equivalent to announcing an inflation target. Given the structure of the model, it is more convenient to view any announcement as an announcement about the output-gap target.

firms cannot infer perfectly the central bank's information on each of the two shocks by only observing the instrument.

2.1 Price-Setting Behavior

Suppose firm j is setting its price in period t. Let p^*_{jt} denote the log price it chooses. It will be convenient to treat $\pi^*_{jt} \equiv p^*_{jt} - p_{t-1}$ as the choice variable, where p_{t-1} is last period's aggregate log price level. Let $\bar{\pi}^*_t$ be the average of π^*_{jt} across the firms adjusting in period t, and let π_t be the aggregate inflation rate.

The probability that a firm does not have the opportunity to adjust its price is ω. Thus,

$$p_t = (1-\omega)\bar{p}^*_t + \omega p_{t-1}, \tag{1}$$

where $\bar{p}^*_t = \int_0^1 p^*_{jt} dj$. Equation (1) implies that $\bar{p}^*_t - p_t = \omega(\bar{p}^*_t - p_{t-1})$ and

$$\pi_t = p_t - p_{t-1} = (1-\omega)\left(\bar{p}^*_t - p_{t-1}\right) = \left(\frac{1-\omega}{\omega}\right)\left(\bar{p}^*_t - p_t\right). \tag{2}$$

Let φ denote log real marginal cost and assume a steady-state inflation rate of zero. If firm j can adjust its price, it sets its current price equal to the expected discounted value of current and future nominal marginal cost $\varphi + p$. Future marginal cost is discounted by the probability that the firm has not received another opportunity to adjust, ω, and by the discount factor, β. I assume the price of firm j is also affected by a cost shock s_{jt} that alters the firm's desired price. Hence,

$$p^*_{jt} = (1-\omega\beta)\sum_{i=0}^{\infty}(\omega\beta)^i\left(E^j_t\varphi_{t+i} + E^j_t p_{t+i} + E^j_t s_{jt+i}\right), \tag{3}$$

where E^j_t denotes the expectations based on the information available to firm j. Equation (3) can be rewritten as

$$p^*_{jt} = (1-\omega\beta)\left(E^j_t p_t + E^j_t\varphi_t + s_{jt}\right) + \omega\beta E^j_t p^*_{jt+1}.$$

Note that it has been assumed that the firm observes its own firm-specific cost shock, s_{jt}, prior to setting its price but that it does not observe the current aggregate price level or current realized nominal marginal cost.

Individual firms may set different prices because they base expectations on different information sets. And, if information sets differ, each adjusting firm's expectations about what it would do if it is again able to adjust in $t+1$ may also differ. To simplify, I assume that any idiosyncratic information is i.i.d. and that all aggregate information is revealed at the end of each period. This will imply that $E_t^j p_{jt+1}^* = E_t^j \bar{p}_{t+1}^*$; each firm expects that, if it can adjust in $t+1$, it will set the same price as other adjusting firms.

Using (2) and the definition of π_{jt}^*, one obtains, after some manipulation,

$$\pi_{jt}^* = (1-\omega)E_t^j\bar{\pi}_t^* + (1-\omega\beta)E_t^j\varphi_t + (1-\omega\beta)s_{jt} + \left(\frac{\omega\beta}{1-\omega}\right)E_t^j\pi_{t+1}, \quad (4)$$

where $\bar{\pi}_t^* = \bar{p}_t^* - p_{t-1}$.[11] Assume that real marginal cost is linearly related to an output-gap measure x_t: $\varphi_t = \kappa x_t$. Then

$$\pi_{jt}^* = (1-\omega)E_t^j\bar{\pi}_t^* + (1-\omega\beta)\kappa E_t^j x_t + (1-\omega\beta)s_{jt} + \left(\frac{\omega\beta}{1-\omega}\right)E_t^j\pi_{t+1}. \quad (5)$$

Hence, firm j adjusts its price based on its signal on the cost shock, its expectations of what other adjusting firms are choosing ($E_t^j\bar{\pi}_t^*$),

[11] Equation (4) has the form

$$\pi_{jt}^* = (1-\omega)E_t^j\bar{\pi}_t^* + \omega E_t^j\theta_t,$$

where

$$E_t^j\theta_t \equiv \left(\frac{1-\omega\beta}{\omega}\right)\left(E_t^j\varphi_t + s_{jt}\right) + \left(\frac{\beta}{1-\omega}\right)E_t^j\pi_{t+1}.$$

This is the basic form of the decision rule at the heart of the Morris-Shin analysis. The adjustment by firm j depends on the firm's expectations about θ_t and on what firm j expects other firms to do. In the present analysis, however, decisions depend on expectations of future inflation, not just on expectations concerning current variables.

its expectations about the output gap, and its forecast of next-period aggregate inflation.[12]

2.2 Aggregate Demand

Monetary policy is represented by the central bank's choice of an instrument x_t^I and by any announcements the central bank might make. I assume x_t^I is observed at the start of the period so that any firm that sets its price in period t can condition its choice on x_t^I. The output gap differs from x_t^I by a demand shock v_t:

$$x_t = x_t^I + v_t. \tag{6}$$

2.3 Information

There are two primitive, aggregate disturbances in the model: (i) s_t, representing cost factors that, for a given output gap and expectations of future inflation, generate inefficient inflation fluctuations and (ii) v_t, an aggregate demand disturbance. Each is assumed to follow independent $AR(1)$ processes given by

$$s_t = \rho_s s_{t-1} + \xi_t$$

and

$$v_t = \rho_v v_{t-1} + \varphi_t.$$

[12]In the standard Calvo model in which all firms have identical information sets and are able to observe the current disturbances, $\pi_{jt}^* = \bar{\pi}_t^*$ for all j, so (5) becomes

$$\bar{\pi}_t^* = \left(\frac{1-\omega\beta}{\omega}\right)\kappa x_t + \left(\frac{1-\omega\beta}{\omega}\right)s_t + \frac{\beta}{1-\omega}E_t\pi_{t+1}.$$

Then using (2), this becomes

$$\pi_t = (1-\omega)\pi_t^* = \left[\frac{(1-\omega)(1-\omega\beta)}{\omega}\right]\left(\kappa x_t + s_t\right) + \beta E_t\pi_{t+1},$$

which differs from the standard form only in the coefficient on the cost shock. This is due to the fact that I include the shock in the equation for the firm's optimal price (3) rather than adding it on after the equation for inflation has been derived.

Firms (in setting prices) and the central bank (in setting its policy instrument) must act before learning the actual realizations of the aggregate shocks. Firm j's idiosyncratic cost shock s_{jt} is related to the aggregate shock according to

$$s_{jt} = s_t + \phi_{j,t}.$$

In addition, the firm receives a noisy signal v_{jt} about the aggregate demand shock, where

$$v_{jt} = v_t + \psi_{j,t}.$$

For convenience, both $\phi_{j,t}$ and $\psi_{j,t}$ will be referred to as noise terms, but ϕ_{jt} is actually the idiosyncratic component of the firm's cost shock. The noise terms ϕ_j and ψ_j are identically and independently distributed across firms. These signals are private in the sense that they are unobserved by other agents.

In a similar manner, the central bank receives private signals on the two aggregate disturbances:

$$s_{cb,t} = s_t + \phi_{cb,t}$$
$$v_{cb,t} = v_t + \psi_{cb,t}.$$

The noise terms ϕ_{cb} and ψ_{cb} are assumed to be independently distributed and to be independent of ϕ_j and ψ_j for all j and t. All stochastic variables are assumed to be normally distributed.

2.4 Monetary Policy

The central bank's objective is to minimize a standard quadratic loss function that depends on inflation variability and output-gap variability. Specifically, loss is given by

$$L = \left(\frac{1}{1-\beta}\right)\left(\sigma_\pi^2 + \lambda\sigma_x^2\right), \tag{7}$$

where σ_π^2 and σ_x^2 are the variances of inflation and the output gap.

I consider linear policy rules of the form

$$x_t^I = \delta_1 x_{t-1} + \delta_2 E_t^{cb} s_t + \delta_3 E_t^{cb} v_t, \tag{8}$$

where the δ_i coefficients are chosen to minimize (7) subject to the equilibrium process for inflation and the information structure faced by the central bank and firms. Rules of this form are consistent with optimal policy under both commitment and discretion in the standard New Keynesian model. Under optimal discretion, policy is a function of the state, and $\delta_1 = 0$, as s_t and v_t are the only state variables. Under optimal commitment, inertia is introduced by policy actions, making x_{t-1} an additional state variable in the equilibrium solution of the model.

Since $x_t = x_t^I + v_t$, the central bank's time t implicit target for the output gap is

$$x_t^T \equiv x_t^I + E_t^{cb} v_t = \delta_1 x_{t-1} + \delta_2 E_t^{cb} s_t + (1 + \delta_3) E_t^{cb} v_t. \tag{9}$$

Equation (9) and the aggregate version of (5) also imply an implicit time t target for inflation. These targets for the output gap and the inflation rate can be interpreted as short-run targets. Under a credible inflation-targeting regime, the long-run inflation target is zero.

From the distributional assumptions about the central bank's information, $E_t^{cb} s_t = \rho_s s_{t-1} + \theta_s^{cb}(s_{cb,t} - \rho_s s_{t-1})$, where $\theta_s^{cb} = \sigma_\xi^2 / \left(\sigma_\xi^2 + \sigma_{\phi,cb}^2\right)$, σ_ξ^2 is the variance of ξ_t, and $\sigma_{\phi,cb}^2$ is the variance of $\phi_{cb.t}$. Similarly, $E_t^{cb} v_t = \rho_v v_{t-1} + \theta_v^{cb}(v_t^{cb} - \rho_v v_{t-1})$, where $\theta_v^{cb} = \sigma_\varphi^2 / \left(\sigma_\varphi^2 + \sigma_{\psi,cb}^2\right)$.

Firms that set prices must form expectations about what other firms are expecting, as in Amato and Shin (2003), but they must also form expectations about the central bank's output-gap target, which implicitly involves forming expectations about the central bank's expectation of shocks (and implicitly, therefore, about what other firms are expecting that the central bank is expecting). Because firm j has private information on the aggregate shocks, its expectations of s_t and v_t may differ from what it thinks the central bank's expectations are. For example, $E_t^j(E^{cb} s_t) \neq E_t^j s_t$. Because the private sector may have different information than the central bank has, private expections of shocks can differ from the central bank's expectations of those shocks. To predict the output gap, firms must guess what the central bank thinks the aggregate cost shock is, for example, and not simply guess what the cost shock is.

3. Equilibrium with Partial Announcements

Discussions of transparency generally focus on actions by the central bank that are designed explicitly to provide information. For example, the publication of the central bank's forecasts for inflation or output or its announcement of short-run targets for inflation are among the forms of public information designed to increase policy transparency. Private agents will use the central bank's announcements to infer something about the central bank's assessment of the state of the economy. This means that errors in the central bank's assessment of the economy will similarly infect private-sector forecasts and expectations. This may introduce undesirable volatility into private-sector expectations.

Even in the absence of announcements, the public can infer something about the central bank's information by observing the short-term interest rate used as the policy instrument, and changes in the policy interest rate are typically widely publicized. However, observing the central bank's instrument imperfectly reveals the central bank's forecasts of demand and cost shocks (see (8)). A change in x^I could reflect the central bank's belief that a cost shock has occurred, or it could indicate that a demand shock has occurred. These have different implications for the expected output gap, and if they could be disentangled, they would affect firms' price-setting decisions differently. Private agents will be uncertain whether an interest movement arises because the central bank is attempting to neutralize inflation and output in response to a demand shock or because it is actively adjusting the output gap to stabilize inflation in the face of a cost shock. For example, if x^I is decreased to neutralize the effects of a positive demand shock, the fall in x^I will be interpreted partially as the central bank's reaction to a positive cost shock. Firms will revise their expectations about the cost shock and about the output gap, and, as a result, actual inflation ends up being affected by the demand shock. If the central bank announces its output-gap target x^T, the private sector has two public signals (x^I and x^T) from which it will generally be able to disentangle the central bank's forecasts of the aggregate cost shock $E_t^{cb} s_t$ from the central bank's forecast of the aggregate demand shock $E_t^{cb} v_t$.

Intuitively, one would expect that announcing the central bank's output-gap target would improve economic outcomes.[13] Since private firms are now able to distinguish between interest rate movements that are designed to offset demand disturbances and those reflecting the central bank's estimate of the cost shock, the central bank could neutralize demand shocks without introducing any volatility into the inflation rate. At the same time, releasing information on x_t^T in no way hampers the central bank's ability to achieve its output-gap target. Thus, greater transparency should improve welfare. However, providing more public information may make private-sector expectations more sensitive to the announced target than they were to the instrument. Consequently, any errors the central bank makes in forecasting the cost shock will generate greater volatility in the inflation rate. If this channel dominates the reduction in volatility that occurs because demand shocks no longer affect inflation, loss can actually rise when targets are announced. Whether transparency reduces or increases loss will depend on the quantitative characteristics of the economy.

Rather than comparing the case of no announcement with the case in which all firms have information on the output-gap target, I consider the partial release of information along the lines of Cornand and Heinemann (2004). Suppose the central bank announces x_t^T in a manner such that only a fraction P of all firms receive the information.[14] Firms will be in one of three classes each period: (i) those that do not receive an opportunity to adjust their price, (ii) those that do adjust but do not receive the central bank's announcement, and (iii) those that adjust and receive the announcement. Consider first those adjusting firms that receive information about x_t^T. There are a fraction P of such firms. For these informed firms, their expectations of the current shocks will depend on their private information, on the central bank's instrument setting, and on the announced output-gap target. For the $1 - P$ fraction of adjusting firms that do not observe x_t^T, expectations can be based only on private signals and the central

[13]As noted previously, this is equivalent to announcing an inflation target.

[14]One might interpret this partial release of information in terms of the notion of rational inattention emphasized by Mankiw and Reis (2002). Perhaps all firms observe the announcement but only a fraction P actually incorporate the new information into their decisions.

bank's instrument. Firms that adjust prices in period t must form expectations about what other firms are expecting, and this will now depend on the fraction of firms that receive information about the central bank's output-gap target.

3.1 Expectations

The information problems faced by informed and uninformed firms differ. Consider first those firms that receive information about x_t^T. These firms observe $s_{j,t}$, $v_{j,t}$, x_t^I, and the central bank's output-gap target x_t^T. Let j index such a firm. The new information for informed firm j is

$$\zeta_{jt} \equiv \begin{bmatrix} s_{jt} - E_{t-1}s_{jt} \\ v_{jt} - E_{t-1}v_{jt} \\ x_t^I - E_{t-1}x_t^I \\ x_t^T - E_{t-1}x_t^T \end{bmatrix} = \begin{bmatrix} \xi_t + \phi_{j,t} \\ \varphi_t + \psi_{j,t} \\ \delta_2\theta_s^{cb}(\xi_t + \phi_{cb,t}) + \delta_3\theta_v^{cb}(\varphi_t + \psi_{cb,t}) \\ \delta_2\theta_s^{cb}(\xi_t + \phi_{cb,t}) + (1+\delta_3)\theta_v^{cb}(\varphi_t + \psi_{cb,t}) \end{bmatrix}$$

$$= M \begin{bmatrix} \xi_t + \phi_{jt} \\ \varphi_t + \psi_{jt} \\ \xi_t + \phi_{cb,t} \\ \varphi_t + \psi_{cb,t} \end{bmatrix},$$

where

$$M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \delta_2\theta_s^{cb} & \delta_3\theta_v^{cb} \\ 0 & 0 & \delta_2\theta_s^{cb} & (1+\delta_3)\theta_v^{cb} \end{bmatrix}.$$

Define $Z_t' = [s_t \ v_t \ x_t]$ and $\Omega_t' = [\xi_t \ \varphi_t \ \phi_{cb,t} \ \psi_{cb,t}]$. We can write the processes for the exogenous shocks and the output gap as

$$Z_t = CZ_{t-1} + D\Omega_t, \tag{10}$$

where

$$C = \begin{bmatrix} \rho_s & 0 & 0 \\ 0 & \rho_v & 0 \\ \delta_2\rho_s & (1+\delta_3)\rho_v & \delta_1 \end{bmatrix}$$

and

$$D = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \delta_2\theta_s^{cb} & \left(1+\delta_3\theta_v^{cb}\right) & \delta_2\theta_s^{cb} & \delta_3\theta_v^{cb} \end{bmatrix}.$$

Now let $V_{\zeta\Omega}$ be the 4×4 covariance matrix between ζ_{jt} and the unobserved variables Ω_t, and let $V_{\zeta\zeta}$ be the 4×4 covariance matrix of ζ_{jt}. Then firm j's expectation of Ω_t is equal to

$$E_t^j \Omega_t = H\zeta_{jt},$$

where $H = V_{\Omega\zeta}V_{\zeta\zeta}^{-1}$.

Those firms that do not receive the announcement (the uninformed firms), denoted by h, must base their expectations about current aggregate shocks on their private signals and the central bank's instrument. We can write the information of these firms as

$$z_{ht} = W\zeta_{ht},$$

where

$$W = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}.$$

Hence, for these firms,

$$E_t^h \Omega_t = GW\zeta_{ht},$$

where $G = V_{\Omega\zeta}W'(WV_{\zeta\zeta}W')^{-1}$.

In Morris and Shin (2002), Amato and Shin (2003), and Hellwig (2004), the weights placed on private and public information in the individual firm's forecast are independent of any aspect of the central bank's policy decisions. This is not true in the present case, because the public signals are the central bank's instrument and, for a subset of firms, the central bank's output-gap target. Thus, both H and G will depend on the policy parameters δ_i.

Finally, because the ideosyncratic firm information averages to zero across firms, define the aggregate information (over all firms) as

$$\zeta_t \equiv M \begin{bmatrix} \xi_t \\ \varphi_t \\ \xi_t + \phi_{cb,t} \\ \varphi_t + \psi_{cb,t} \end{bmatrix} = L\Omega_t,$$

where

$$L = M \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix}.$$

3.2 Inflation and the Output Gap

As detailed in the appendix, the equilibrium strategy of informed firms, those receiving the central bank's announcement, is given by

$$\pi^*_{j,t} = a_{i,1} Z_{t-1} + a_{i,2}\zeta_{j,t}.$$

The equilibrium strategy for an uninformed firm is

$$\pi^*_{h,t} = a_{u,1} Z_{t-1} + a_{u,2} W \zeta_{h,t}.$$

Note that while $a_{i,2}$ in (13) is 1×4, $a_{u,2}$ in (15) is 1×3. Since Z_{t-1} is common information to both types of firms, $a_{i,1} = a_{u,1} \equiv a_1$. The appendix shows that

$$a_1 = \left(\frac{1-\omega\beta}{\omega}\right)[\kappa e_3 + e_1]C(I_3 - \beta C)^{-1}. \tag{11}$$

Given a_1, the appendix shows how the equilibrium values of $a_{i,2}$ and $a_{u,2}W$ can be found.

Once a_1, $a_{i,2}$, and $a_{u,2}$ have been obtained, equilibrium inflation is given by

$$\begin{aligned} \pi_t &= (1-\omega)\left[P\int \pi^*_{jt}dj + (1-P)\int \pi^*_{ht}dh\right] \\ &= (1-\omega)[a_1 Z_{t-1} + (Pa_{i,2} + (1-P)a_{u,2}W)L\Omega_t], \end{aligned}$$

while the equilibrium output gap is

$$x_t = e_3(CZ_{t-1} + D\Omega_t),$$

where $e_3 = [0\ 0\ 1]$.

4. Results

To explore the impact of transparency on the behavior of inflation and the output gap, the model is numerically solved. I set $\omega = 0.5$, $\kappa = 1.8$, and $\beta = 0.99$. A value of 0.5 for ω is consistent with evidence on the frequency of price adjustment in the United States (Bils and Klenow 2004). In microfounded models, κ is the sum of the coefficient of relative risk aversion and the inverse of the wage elasticity of labor supply. Values of 1 for relative risk aversion and 0.8 for the inverse of the wage elasticity of labor supply are not uncommon in the literature, yielding $\kappa = 1.8$. The value chosen for the discount factor β is standard when dealing with quarterly data. I set the variances of the cost and demand shocks equal to each other and normalize so that $\sigma_\xi^2 = \sigma_\varphi^2 = 1$. For the benchmark case, I assume that the private-sector noise variances $\sigma_{\phi,j}^2$ and $\sigma_{\psi,j}^2$ both equal 0.4. While Amato and Shin (2003) assume that the central bank has perfect information on the shocks, I assume that the noise variances in the central bank's signals $\sigma_{\phi,cb}^2$ and $\sigma_{\psi,cb}^2$ also equal 0.4. For the baseline case, I set $\rho_s = \rho_v = 0$.

4.1 Policy Incentive Effects

In a standard New Keynesian model of optimal monetary policy with a loss function given by (7), the central bank would neutralize demand shocks to prevent them from affecting either the output gap or inflation. The central bank would partially stabilize inflation from the effects of cost shocks. Thus, both inflation and the output gap would fluctuate in the face of cost shocks, while neither would move in response to demand shocks. If the central bank faces a signal extraction problem, certainty equivalence still holds, and the central bank would offset expected demand shocks completely (i.e., $\delta_3 = -1$) and stabilize in response to expected cost shocks (i.e., $\delta_2 < 0$).

In the present model, a lack of transparency has what Geraats (2002) labels an incentive effect on policy. Suppose the central bank attempts to fully insulate the output gap from demand shocks. As it moves its instrument in response to forecasts of demand shocks, private agents will attribute some of the change in x^I as due to cost shocks. This will result in firms altering their assessment of the aggregate cost shock, and inflation will be affected. Inflation is not fully insulated from demand shocks when $\delta_3 = -1$, and, as a consequence, the central bank will no longer find it optimal to set $\delta_3 = -1$.

Because firms partially attribute movements in x^I to the central bank's forecast of a cost shock, there are actually three effects of a change in x^I on inflation. First, firms will use the information they extract from x^I to reassess their expectations about the aggregate cost shock and therefore about what they expect other price-adjusting firms to do. Second, any reassessment of the aggregate cost shock will affect expectations of future inflation. Third, firms will alter their expectations about the aggregate output gap. This directly affects price-adjusting firms' decisions about their own price and it alters such firms' expectations about the prices other firms are setting.

Under a regime of complete transparency, the central bank announces its target to all firms. Private agents can now infer the central bank's forecast of demand and cost shocks. By setting $\delta_3 = -1$, the central bank neutralizes the expected effect of demand shocks on both inflation and the output gap; the resulting movements in its instrument are no longer confused with responses to the cost shock. This should make inflation more stable, since expected demand shocks are completely neutralized. Thus, transparency can make both inflation and the output gap more stable.

However, once the central bank announces its output-gap target to all firms, inflation can become very sensitive to the central bank's target. The increased volatility of expectations in the face of additional information is a standard cost of transparency (Geraats 2002). Any noise in the central bank's cost-shock signal will now have a greater impact on inflation. If expectations and inflation react strongly to the central bank's announced output-gap target, and therefore to any noise in the central bank's estimate of the cost shock, inflation could become more volatile. In addition, because the central bank reacts more strongly to its signal on demand shocks, any noise in that signal will have a bigger impact on the output gap.

Walsh (2006) discussed the effects of transparency (as measured by P) on the optimal responses of policy to cost and demand shocks. In the present model, for example, $\delta_3 = -0.95$ when $P = 0$; the central bank does not fully offset expected demand shocks because the movements in x^I needed to do so lead to excessive fluctuations in inflation. When $P = 1$, the optimal value of δ_3 is -1, and expected demand shocks are fully offset. Thus, incentive effects are present but small.

Let $\delta^*(P)$ denote the policy coefficients optimized for a given P. For example, $\delta^*(1)$ would denote the policy rule optimized for complete transparency, and $\delta^*(0)$ is the policy rule optimized for the case of no announcements. The importance of accounting for changes in the optimal policy rule as the degree of transparency varies is illustrated in table 1. A switch from a regime with no announcements to one of full transparency increases loss as measured by (7) if the policy rule remains fixed at $\delta^*(0)$. Given the structure of the model, transparency has no effect on the variance of the output gap as long as the policy rule remains unchanged. With policy fixed at $\delta^*(0)$, however, transparency results in greater inflation rate volatility, and this accounts for the rise in loss. Inflation volatility rises because the additional information contained in x_t^T makes firms' expectations about x_t and $\bar{\pi}_t^*$ more volatile. The optimal policy rule, $\delta^*(1)$, involves a smaller (in absolute value) response to the central bank's signal on cost shocks, $\mid \delta_2^*(1) \mid = 0.5205 < 0.5964 = \mid \delta_2^*(0) \mid$, and this tempers the volatility of private-sector expectations. Inflation volatility still rises with $P = 1$ and $\delta = \delta^*(1)$, but this is compensated by the fall in output-gap volatility as the central bank reacts less to cost shocks and fully stabilizes the output gap from expected demand shocks.

Table 1. Effects of Policy Rule

		Loss	σ_π^2	σ_x^2
$P = 0$	$\delta^*(0)$	7.78	0.70	0.54
$P = 1$	$\delta^*(0)$	8.16	0.76	0.54
$P = 1$	$\delta^*(1)$	7.60	0.74	0.48

Table 2. Effects of Policy Rule: $\rho_s = 0.8$

		Loss	σ_π^2	σ_x^2
$P = 0$	$\delta^*(0)$	11.04	0.66	1.10
$P = 1$	$\delta^*(0)$	11.53	0.74	1.10
$P = 1$	$\delta^*(1)$	11.13	0.72	1.06

As a consequence, loss declines with full transparency as long as the central bank correctly optimizes its policy rule to reflect the new level of transparency. Note, however, that even though loss is reduced under transparency (as long as policy also adjusts), inflation is more volatile than it was without any announcements.

When disturbances are serially correlated, information that alters agents' expectations about current aggregate shocks will also affect their forecasts of future values of the disturbances and future inflation. This generates additional effects on inflation since current inflation depends on expected future inflation.[15] Table 2 illustrates how persistence in the aggregate cost shock affects outcomes under the extreme cases of no announcements and complete announcements. In contrast to the baseline case with $\rho_s = 0$, loss is lower when the output-gap target is not announced.

In contrast, adding persistence to the demand shock makes transparency superior to opaqueness. In fact, when both aggregate shocks are persistent as in table 3, based on $\rho_s = \rho_v = 0.8$, loss is reduced when the central bank announces its output-gap target even if the policy rule is held fixed at $\delta^*(0)$. Transparency allows the central bank to completely insulate the output gap and inflation from demand shocks. Doing so is particularly important when demand shocks are serially correlated; otherwise, a demand shock affects the output gap and inflation directly as well as by altering expected future inflation.

The results reported in tables 1–3 illustrate the importance of allowing the policy rule to vary optimally when the degree of

[15]From (11), the vector a_1 depends on the matrix C giving the effects of Z_{t-1} on Z_t, and $a_{i,2}$ and $a_{u,2}$ depend on a_1 (and so therefore on C). See the appendix for details.

Table 3. Effects of Policy Rule: $\rho_s = \rho_v = 0.8$

		Loss	σ_π^2	σ_x^2
$P = 0$	$\delta^*(0)$	11.28	0.74	1.07
$P = 1$	$\delta^*(0)$	11.22	0.73	1.07
$P = 1$	$\delta^*(1)$	11.13	0.73	1.05

transparency changes. They show, too, how the value of transparency can be affected by the persistence in the aggregate shocks. Finally, tables 2 and 3 reveal that demand and cost shocks can have asymmetric effects on the desirability of transparency. Persistence in the cost shock lowers the value of transparency; persistence in demand shocks raises it.

4.2 The Optimal Degree of Transparency

In this section, the optimal degree of partial transparency is investigated. Reported outcomes for different degrees of transparency are always evaluated using the policy rule coefficients that are optimal for the particular value of P.[16]

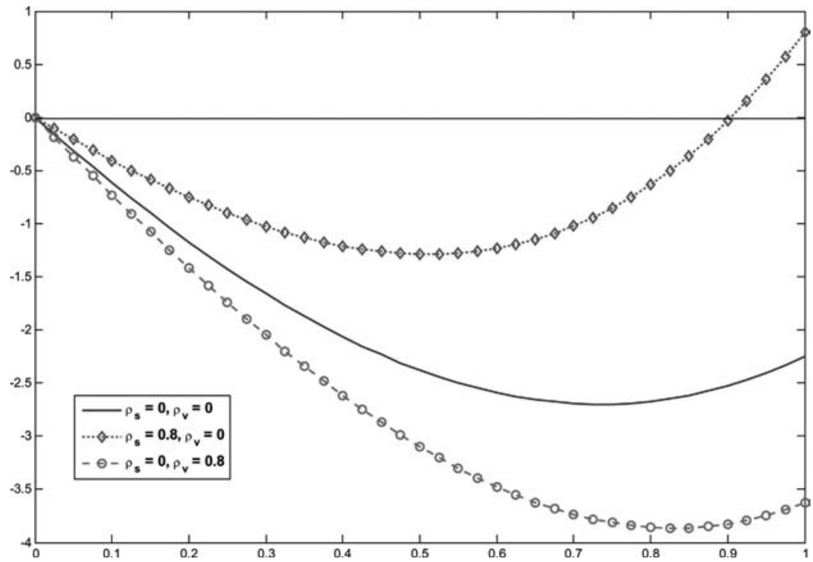
The solid line in figure 1 shows the percentage change in loss relative to the case of no announcement (i.e., the case of $P = 0$) as a function of P for the baseline parameter values. While loss is lower with complete transparency ($P = 1$) than it is in the absence of any announcements, the optimum occurs when $P = 0.725$. That is, it is optimal to be fairly transparent but not completely transparent.

Also shown in figure 1 is loss as a function of P when the disturbances are serially correlated. The case of a serially correlated demand shock ($\rho_v = 0.8$) is shown by the dashed line with circles in the figure. The optimal degree of transparency increases (the optimal P increases from 0.725 to 0.825) when demand shocks are persistent. In contrast, as shown by the dotted line with diamonds, introducing serial correlation in the cost shock ($\rho_s = 0.8$) decreases the optimal degree of transparency (the optimal P decreases from 0.725 to 0.5).

The reason for these differing effects on optimal transparency can be see from figure 2, which plots the variances of inflation and

[16] That is, outcomes for each P are always evaluated using the policy $\delta^*(P)$.

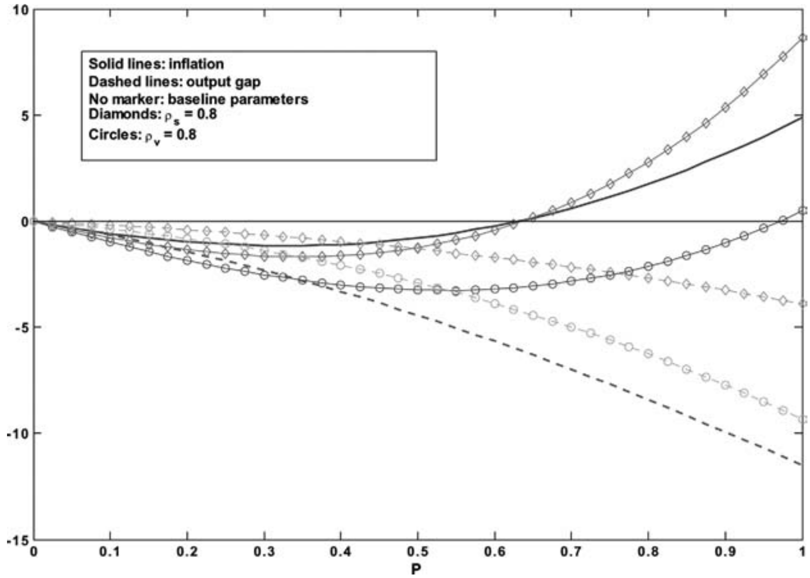
Figure 1. Effects of Transparency on Loss (Percentage Change Relative to $P = 0$)



the output gap as a function of P for the baseline parameters (no markers), $\rho_s = 0.8$ (indicated by diamonds), and $\rho_v = 0.8$ (indicated by circles). Consider first the case of a serially correlated cost shock. By increasing transparency, the central bank provides firms with information that can be useful in forecasting the current aggregate cost shock. When $\rho_s \neq 0$, this information is also useful for forecasting future s_{t+i} and therefore future inflation. As expectations fluctuate in response to the greater information provided with announcements, current inflation becomes more volatile. As indicated by the figure, inflation becomes significantly more variable as $P \to 1$ when $\rho_s = 0.8$. This places a limit on how transparent the central bank wants to be.

Now consider the situation when the demand shock is serially correlated. Transparency allows the central bank to more fully neutralize the impacts of demand shocks. When these shocks are serially correlated, it becomes more important to offset them since the impact on current inflation depends on the present discounted value of any current and future demand shock that is not offset by policy.

Figure 2. Effects of Transparency on Variances (Percentage Change Relative to $P = 0$)



As shown in figure 2, the variance of the output gap is reduced considerably relative to the $P = 0$ case, as $P \to 1$ when $\rho_v = 0.8$, while the variance of inflation is similar when $P = 0$ and $P = 1$.

4.3 The Effects of Central Bank Noise

Morris and Shin (2002) suggested that more-accurate central bank information could reduce welfare by making private expectations too sensitive to the noise in the information. In the present model (and consistent with Svensson 2006), reductions in the variances of the noise in the central bank's signals about the aggregate shocks always reduce loss. However, more-accurate central bank signals can have ambiguous effects on the optimal degree of transparency.

Table 4 shows how the optimal degree of transparency varies with the noise in the central bank's signals, holding constant the variance of the true aggregate shock. The upper half of the table shows that increased noise in the central bank's signal on the cost shock decreases optimal transparency. As $\sigma^2_{\phi,cb}$ increases, the central

Table 4. Optimal Transparency as Function of Noise Variances

	$\boldsymbol{\sigma^2_{\phi,\mathrm{cb}}}$					
	0	.2	.4	.6	.8	1
$\sigma^2_{\psi,cb} = 0.2$	1.0	0.93	0.40	0.20	0.10	0.03
$\sigma^2_{\psi,cb} = 0.4$	1.0	1.00	0.73	0.48	0.33	0.23
	$\boldsymbol{\sigma_{\psi,\mathrm{cb}}}$					
	0	.2	.4	.6	.8	1
$\sigma^2_{\phi,cb} = 0.2$	0.58	0.93	1.0	1.0	1.0	1.0
$\sigma^2_{\phi,cb} = 0.4$	0.15	0.40	0.73	1.0	1.0	1.0

bank's ability to engage in active stabilization is reduced. A less transparent regime limits the volatility of inflation expectations by reducing the public information provided by the central bank. This effect is stronger when the central bank has a more-accurate signal on demand disturbances in that the optimal P is lower for any given $\sigma^2_{\phi,cb} > 0$. A lower $\sigma^2_{\psi,cb}$ implies that the central bank is less concerned with limiting the impact on expectations of its demand forecast errors since these errors are smaller. Being less transparent reduces the effects on inflation of noise in the central bank's signal on cost disturbances.

The effects of altering the informational content of the central bank's signal on the demand disturbances are quite different. The bottom half of table 4 shows that optimal transparency increases when the central bank's signal on demand shocks contains more noise (i.e, when $\sigma^2_{\psi,cb}$ increases). Recall that in the absence of transparency, central bank errors in forecasting demand spill over to affect inflation. As these errors become larger, it is optimal to become more transparenct to limit their impact on inflation. This effect is stronger when the noise in the central bank's cost signal is reduced from the baseline case of $\sigma^2_{\phi,cb} = 0.4$ to a value of 0.2. With better information on cost shocks, the central bank engages in more-active stabilization. The gains to reducing private-sector confusion about the central bank's information rise, leading to an increase in the optimal degree of transparency for any given value of $\sigma^2_{\psi,cb}$ until transparency is complete. Thus, consistent with the results on serial correlation, the impact of noise on optimal transparency differs depending on the source.

5. Summary

In this paper, I have investigated the role of economic transparency when private information is diverse and the central bank provides public information either implicitly, by setting its policy instrument, or explicitly, by making announcements about its short-run targets. In contrast to earlier work that interpreted transparency as a reduction in the central bank's control error, I model transparency as the extent to which announcements are disseminated among the public. Being transparent is not an all-or-nothing proposition. Partial announcements provide one means of investigating how widely central banks should disseminate information about their targets. Under full transparency, the central bank's announced target reaches all firms.

By announcing its short-run output-gap target (equivalently, its short-run inflation target), the central bank reveals information about its internal forecast of demand and cost shocks. This provides more-accurate public information to price-setting firms, but it also makes private-sector decisions more sensitive to the central bank's forecast errors. As a result, inflation may become more volatile when the central bank announces its short-run target.

The degree of optimal transparency is affected differently by demand and cost disturbances. When the central bank's forecasts of cost disturbances improve, or such disturbances become less persistent, optimal transparency increases. In contrast, when the central bank's forecasts of demand disturbances improve, or such disturbances become less persistent, optimal transparency decreases.

To determine the optimal extent to which information should be made public, I employed a standard quadratic loss function. As Hellwig (2004) demonstrates, this can be misleading and will tend to undervalue the gains from transparency. The reason is based on the underlying distortion that makes inflation costly in New Keynesian models. These costs are due to the increase in price dispersion across firms that inflation generates. When firms have private information, this introduces a new source of price dispersion and exacerbates the welfare costs of inflation. By providing information that is common to all firms, the central bank can reduce the extent of price dispersion. This represents a welfare gain. In terms of the model of partial announcements, employing an explicit welfare criterion is likely to increase the optimal degree of transparency.

Appendix

The pricing decision of an informed firm satisfies

$$\pi^*_{j,t} = (1-\omega)E^j_t\bar{\pi}^*_t + (1-\omega\beta)\kappa E^j_t x_t + (1-\omega\beta)s_{jt} + \left(\frac{\omega\beta}{1-\omega}\right)E^j_t\pi_{t+1}, \tag{12}$$

where expectations are with respect to the information set $\{Z_{t-1}, \zeta_{j,t}\}$. Assume the equilibrium strategy for an informed firm is

$$\pi^*_{j,t} = a_{i,1}Z_{t-1} + a_{i,2}\zeta_{j,t}. \tag{13}$$

The pricing decision of an uninformed firm satisfies

$$\pi^*_{h,t} = (1-\omega)E^h_t\bar{\pi}^*_t + (1-\omega\beta)\kappa E^h_t x_t + (1-\omega\beta)s_{ht} + \left(\frac{\omega\beta}{1-\omega}\right)E^h_t\pi_{t+1}, \tag{14}$$

where expectations are with respect to the information set $\{Z_{t-1}, W\zeta_{h,t}\}$. Assume the equilibrium strategy for an uninformed firm is

$$\pi^*_{h,t} = a_{u,1}Z_{t-1} + a_{u,2}W\zeta_{h,t}. \tag{15}$$

Note that while $a_{i,2}$ in (13) is 1×4, $a_{u,2}$ in (15) is 1×3.

The strategies (13) and (15) will be used by all adjusting firms in forming expectations about $\bar{\pi}^*_t$, since

$$\bar{\pi}^*_t = P\int \pi^*_{j,t}dj + (1-P)\int \pi^*_{h,t}dh$$
$$= \alpha_1 Z_{t-1} + \alpha_2\zeta_t,$$

where

$$\alpha_1 = Pa_{i,1} + (1-P)a_{u,1}$$
$$\alpha_2 = Pa_{i,2} + (1-P)a_{u,2}W.$$

Hence, for firms that observe x_t^T,

$$E_t^j \bar{\pi}_t^* = \alpha_1 Z_{t-1} + \alpha_2 E_t^j \zeta_t = \alpha_1 Z_{t-1} + \alpha_2 LH\zeta_{j,t},$$

while for firms that do not observe x_t^T,

$$E_t^h \bar{\pi}_t^* = \alpha_1 Z_{t-1} + \alpha_2 E_t^h \zeta_t = \alpha_1 Z_{t-1} + \alpha_2 LGW\zeta_{h,t}.$$

Actual inflation will be

$$\pi_t = (1-\omega)\bar{\pi}_t^* = (1-\omega)(\alpha_1 Z_{t-1} + \alpha_2 \zeta_t). \tag{16}$$

Equation (16) implies that next-period inflation satisfies

$$\pi_{t+1} = (1-\omega)\bar{\pi}_{t+1}^* = (1-\omega)(\alpha_1 Z_t + \alpha_2 \zeta_{t+1}),$$

and so for informed firms,

$$\begin{aligned} E_t^j \pi_{t+1} &= (1-\omega)\alpha_1 E_t^j Z_t \\ &= (1-\omega)\alpha_1 (CZ_{t-1} + DH\zeta_{j,t}), \end{aligned}$$

where (10) and $E_t^j \Omega_t = H\zeta_{j,t}$ have been used. Similarly, for uninformed firms,

$$\begin{aligned} E_t^h \pi_{t+1} &= (1-\omega)\alpha_1 E_t^h Z_t \\ &= (1-\omega)\alpha_1 (CZ_{t-1} + DGW\zeta_{h,t}). \end{aligned}$$

Firms must also forecast the output gap. Since $x_t = e_3 Z_t$, where $e_3 = [0\ \ 0\ \ 1]$, $E_t^j x_t = e_3(CZ_{t-1} + DH\zeta_{j,t})$ and $E_t^h x_t = e_3(CZ_{t-1} + DGW\zeta_{h,t})$.

Substituting the expressions for $E_t^j\bar{\pi}_t$, $E_t^j x_t$, and $E_t^j \pi_{t+1}$ into the price equation for informed firms (equation (12)),

$$\pi^*_{j,t} = (1-\omega)(\alpha_1 Z_{t-1} + \alpha_2 LH\zeta_{j,t}) + (1-\omega\beta)\kappa e_3(CZ_{t-1} + DH\zeta_{j,t}) + (1-\omega\beta)(e_1 CZ_{t-1} + \bar{e}_1\zeta_{j,t}) + \omega\beta\alpha_1(CZ_{t-1} + DH\zeta_{j,t}),$$

where $e_1 = [1\ 0\ 0]$. and $\bar{e}_1 = [1\ 0\ 0\ 0]$.[17]

Equating coefficients with those in (13),

$$a_{i,1} = (1-\omega)\alpha_1 + (1-\omega\beta)[\kappa e_3 + e_1]C + \omega\beta\alpha_1 C, \tag{17}$$

and

$$a_{i,2}[I_4 - (1-\omega)PLH] - (1-P)(1-\omega)a_{u,2}WLH = (1-\omega\beta)[\kappa e_3 DH + \bar{e}_1] + \omega\beta\alpha_1 DH. \tag{18}$$

Turning to the uninformed firms, substituting the expressions for $E_t^h\bar{\pi}_t$, $E_t^h x_t$, and $E_t^h \pi_{t+1}$ into the price equation for informed firms (equation (14)) yields

$$\pi^*_{h,t} = (1-\omega)[\alpha_1 Z_{t-1} + \alpha_2 LGW\zeta_{h,t}] + (1-\omega\beta)\kappa e_3 \times (CZ_{t-1} + DGW\zeta_{h,t}) + (1-\omega\beta)(e_1 CZ_{t-1} + e_1 W\zeta_{h,t}) + \omega\beta\alpha_1(CZ_{t-1} + DGW\zeta_{h,t}).$$

Equating coefficients with (15),

$$a_{u,1} = (1-\omega)\alpha_1 + (1-\omega\beta)[\kappa e_3 + e_1]C + \omega\beta\alpha_1 C, \tag{19}$$

and

$$a_{u,2}W[I_4 - (1-\omega)(1-P)LGW] - (1-\omega)Pa_{i,2}LGW = (1-\omega\beta)[\kappa e_3 DG + e_1]W + \omega\beta\alpha_1 DGW. \tag{20}$$

Notice that the right-hand sides of (17) and (19) are the same. Therefore,

$$a_1 \equiv a_{i,1} = a_{u,1} = \alpha_1. \tag{21}$$

[17]So $e_1 CZ_{t-1} + \bar{e}_1\zeta_{j,t} = s_t + \phi_{j,t} = s_{j,t}$.

Taking the P-weighted average of (17) and (19) and solving for a_1,

$$a_1 = \left(\frac{1-\omega\beta}{\omega}\right)[\kappa e_3 + e_1]C(I_3 - \beta C)^{-1}. \tag{22}$$

Given a_1, (18) and (20) can be solved for $a_{i,2}$ and $a_{u,2}$ (recall that $a_{i,2}$ is 1×4, while $a_{u,2}$ is 1×3). Define

$$\bar{a} = [a_{i,2}, a_{u,2}W]$$

as a 1×8 vector of the unknown coefficients whose last element is equal to zero. Then

$$\bar{a} = (1-\omega\beta)\begin{bmatrix}\kappa e_3 DH + \bar{e}_1 & [\kappa e_3 DG + e_1]W\end{bmatrix}\begin{bmatrix}A_{11} & A_{21}\\ A_{12} & A_{22}\end{bmatrix}^{-1}$$
$$+\,\omega\beta\alpha_1\begin{bmatrix}DH & DGW\end{bmatrix}\begin{bmatrix}A_{11} & A_{21}\\ A_{12} & A_{22}\end{bmatrix}^{-1},$$

where

$$A_{11} = [I_4 - (1-\omega)PLH],$$
$$A_{21} = -(1-P)(1-\omega)LH,$$
$$A_{12} = -(1-\omega)PLGW,$$

and

$$A_{22} = [I_4 - (1-\omega)(1-P)LGW].$$

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The Mystique of Central Bank Speak*

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Despite the recent trend toward greater transparency of monetary policy, in many respects mystique still prevails in central bank speak. This paper shows that the resulting perception of ambiguity could be desirable. Under the plausible assumption of imperfect common knowledge about the degree of central bank transparency, economic outcomes are affected by both the actual and perceived degree of transparency. It is shown that actual transparency is beneficial, while it may be useful to create the perception of opacity. The optimal communication strategy for the central bank is to provide clarity about the inflation target and to communicate information about the output target and supply shocks with perceived ambiguity. In this respect, the central bank benefits from sustaining transparency misperceptions, which helps to explain the mystique of central bank speak.

JEL Codes: E52, E58, D82.

Since I've become a central banker, I've learned to mumble with great incoherence. If I seem unduly clear to you, you must have misunderstood what I said.

(Alan Greenspan, as quoted in the *Wall Street Journal*, September 22, 1987)

*I thank two anonymous referees; Jim Bullard; Alex Cukierman; Seppo Honkapohja; participants at the EEA Annual Congress in Vienna, August 24–28, 2006; and seminar participants at the Federal Reserve Bank of New York, the Federal Reserve Bank of St. Louis, the Tinbergen Institute at Erasmus University Rotterdam, and the University of Manchester for useful comments. Part of this paper was written while I was visiting Tel Aviv University and the Federal Reserve Bank of St. Louis, both of which I thank for their hospitality. I am also very grateful to the Oesterreichische Nationalbank for giving me the 2006 Klaus Liebscher Award for this paper. Any views expressed in this paper are my own. Author contact: Faculty of Economics, University of Cambridge, Cambridge, CB3 9DD, United Kingdom; e-mail: Petra.Geraats@econ.cam.ac.uk.

1. Introduction

Central banks have long been associated with secrecy. Even the recent trend toward greater transparency of monetary policy has not dispelled the mystique with which central bankers often speak. This paper provides an economic explanation for the role of oblique communication. Under the plausible assumption that there is imperfect common knowledge about the degree of transparency, economic outcomes are determined by both actual and perceived transparency. It is shown that it may be beneficial to combine actual transparency with perceived opacity. The optimal communication strategy for the central bank is to provide clarity about the inflation target but to provide information with perceived ambiguity about the output-gap target and supply shocks. Thus, the central bank benefits from sustaining transparency misperceptions, which helps to explain why transparency of monetary policy has not eliminated the mystique of central bank speak.

Intuitively, transparency is beneficial, as it reduces private-sector uncertainty. However, transparency can only be achieved through central bank communications that may upset market expectations. Since markets respond strongest to signals that are perceived to be clear, market volatility could be muted by creating a perception of ambiguity.

For both the central bank's inflation target and output target, transparency is shown to be optimal because it reduces erratic responses of market expectations. In addition, it is beneficial to create the perception of transparency regarding the inflation target (e.g., by publishing an explicit numeric target) because it aligns private-sector inflation expectations with the central bank's target. However, it is desirable to create the perception of ambiguity about the output-gap target since it makes it easier to reach the target without upsetting inflation expectations. Similarly, for supply shocks it is useful to combine maximum actual transparency with minimal perceived transparency.

In practice, many central banks have a quantitative inflation target, whereas opacity prevails for output (gap) targets (e.g., Geraats 2006). Furthermore, central bankers tend to be notorious for their "mumbling," as is illustrated by the introductory quote. Alan Greenspan, the former Chairman of the Board of Governors of the

Federal Reserve System, even used the term "constructive ambiguity" to describe his style of communication. This paper establishes that the perception of ambiguity could indeed be a constructive way to achieve transparency because it reduces volatility of market expectations.

This paper builds on two different strands of the transparency literature. There are several papers that model monetary uncertainty faced by the public by making a parameter in the central bank's objective function stochastic, completely abstracting from any communication of information (e.g., Sørensen 1991; Eijffinger, Hoeberichts, and Schaling 2000; Beetsma and Jensen 2003). Such monetary uncertainty directly increases the variability of economic outcomes, although it could also have indirect effects such as lower average inflation.[1] This "monetary uncertainty" literature provides an important argument in favor of transparency—namely, that it reduces private-sector uncertainty and economic volatility.

A second strand of the transparency literature explicitly models information transmission and incorporates the static effect that the information has on the formation of private-sector inflation expectations (e.g., Cukierman 2001; Hahn 2004).[2] In this "information approach," transparency could be detrimental because it leads to greater fluctuations in private-sector expectations and increases economic volatility. In a similar vein, Morris and Shin (2002) find that transparency could generate greater variability when agents disregard private information and rely on a sufficiently noisy public signal to coordinate their actions. A more comprehensive review of the transparency literature is provided in the survey by Geraats (2002).

Other interesting insights on central bank mystique are provided by Goodfriend (1986), who reviews the Federal Reserve's defense of secrecy in response to a Freedom of Information Act suit, including

[1] Sørensen (1991) provides an interesting example. However, it should be noted that many of the other indirect effects reported in this strand of the literature (including those in Eijffinger, Hoeberichts, and Schaling 2000) are spurious due to a biased specification of stochastic relative preferences (Geraats 2004).

[2] A third strand of the literature focuses on the dynamic effect of transparency on reputation (e.g., Faust and Svensson 2001; Jensen 2002; Geraats 2005). In this "reputation approach," transparency about central bank preferences reduces beneficial reputation effects, whereas transparency about economic shocks strengthens them.

the argument that disclosure of information could be prone to misinterpretation and cause inappropriate market reaction. In addition, Winkler (2002) discusses central bank communication and proposes to view transparency in terms of openness, clarity, honesty, and common understanding.

The present paper synthesizes the monetary uncertainty and information approaches. It allows for stochastic central bank preferences, and it features public signals that convey information about those preferences but could also generate undesirable market reactions.

The main innovation of this paper is that it relaxes the ubiquitous assumption of perfect common knowledge about the degree of transparency. This assumption requires perceived and actual stochastic distributions to be identical, which precludes an analysis of the role of transparency (mis)perceptions. Furthermore, in practice it is very difficult for the private sector to know how transparent the central bank actually is because the public cannot observe how much information the central bank withholds. Even if the private sector manages to perfectly predict monetary policy decisions, this need not imply complete transparency, since the forecasts may have been accurate despite asymmetric information about variables relevant for (future) policy decisions. So, it seems more realistic to allow for transparency misperceptions.

This paper deviates from the perfect-common-knowledge assumption by introducing asymmetric information about the degree of transparency. This allows for a discrepancy between actual transparency and private-sector perceptions of it. The result is that both the practice and perceptions of transparency matter for economic outcomes. It is shown that the drawbacks of transparency emphasized by the information approach stem not from the actual reduction of information asymmetries but from private-sector responses induced by transparency perceptions. So, it may be beneficial for perceived transparency to be less than actual transparency. To be precise, although it is best to have perfect actual and perceived transparency about the inflation target, for the output target and supply shocks it is desirable for the central bank to combine actual transparency with perceived opacity.

The remainder of the paper is organized as follows. The baseline model is presented in section 2. First, section 2.1 analyzes the case with perfect common knowledge about the degree of transparency about the central bank's inflation and output targets. Subsequently, section 2.2 introduces imperfect common knowledge and investigates the role of transparency perceptions. It is shown in section 3 that the main conclusion of the paper—namely, that transparency misperceptions could be optimal—is robust to several extensions of the model, including different objective functions (section 3.1), transparency about supply shocks (section 3.2), and a New Keynesian Phillips curve (section 3.3). Two additional transparency issues are discussed in section 4. In particular, a more comprehensive theoretical measure of transparency is proposed (section 4.1), and various arguments related to monetary mystique are considered (section 4.2). Finally, section 5 concludes that there is an economic rationale for central bank communications that generate perceived opacity and sustain transparency misperceptions.

2. Model

The central bank has the objective function

$$U = -\frac{1}{2}\alpha(\pi - \theta)^2 - \frac{1}{2}(1 - \alpha)(y - \kappa)^2, \tag{1}$$

where π denotes inflation, y the output gap, θ the central bank's inflation target, κ the central bank's output-gap target, and α the relative weight on inflation stabilization ($0 < \alpha < 1$). The inflation target θ and output-gap target κ are allowed to be stochastic with $\theta \sim N(\bar{\theta}, \sigma_\theta^2)$ and $\kappa \sim N(\bar{\kappa}, \sigma_\kappa^2)$, and θ and κ independent. The assumption of stochastic shocks to central bank objectives is widespread in the transparency literature, starting with the seminal paper by Cukierman and Meltzer (1986). In addition, the monetary uncertainty approach relies on such preference shocks.[3] Nevertheless, the main result of the present paper also holds for deterministic central bank targets (see section 3.1).

[3]The reputation approach also hinges on uncertainty about central bank preferences (e.g., Faust and Svensson 2001 assume shocks to the central bank's output target).

The economy is described by the expectations-augmented Phillips curve

$$\pi = \pi^e + y + s, \tag{2}$$

where π^e denotes the inflation expectations of the private sector and s is a supply shock, which is assumed to be i.i.d. white noise with variance σ_s^2. For analytical convenience, the slope of the Phillips curve is normalized to one, but this does not affect any of the qualitative conclusions below. For simplicity, it is assumed that the central bank directly controls the output gap y.[4] It would be straightforward to extend the model with an aggregate demand equation that relates the output gap to an interest rate controlled by the central bank, but this would merely clutter the analytical expressions without affecting any of the qualitative results. Furthermore, the key findings of the model also hold for a New Keynesian Phillips curve with persistent supply shocks (see section 3.3).

There are two important information asymmetries between the central bank and the private sector. First, the private sector does not observe the central bank's inflation target θ and output-gap target κ. Instead, it receives the public signals

$$\xi_\theta = \theta + \varepsilon \tag{3}$$

$$\xi_\kappa = \kappa + \eta, \tag{4}$$

where ε and η are i.i.d. white noise, $\varepsilon \sim N(0, \sigma_\varepsilon^2)$, and $\eta \sim N(0, \sigma_\eta^2)$. The noise ε and η stems from the difficulty the private sector has interpreting the central bank's fuzzy communication. When $\sigma_\varepsilon^2 = \sigma_\eta^2 = 0$, the signals ξ_θ and ξ_κ communicate θ and κ without any noise, so the information asymmetry is eliminated and there is perfect transparency about the central bank's targets.

The accuracy of the signals ξ_θ and ξ_κ is described by

$$\tau_\theta = \frac{\sigma_\theta^2}{\sigma_\theta^2 + \sigma_\varepsilon^2} \quad \text{and} \quad \tau_\kappa = \frac{\sigma_\kappa^2}{\sigma_\kappa^2 + \sigma_\eta^2}, \tag{5}$$

[4] Alternatively, one could assume a neomonetarist transmission mechanism in which the central bank controls inflation π and faces the Lucas supply equation $y = \pi - \pi^e - s$, but this leads to the same analytical results as for the Keynesian transmission mechanism in the model.

respectively, where $0 \leq \tau_\theta, \tau_\kappa \leq 1$. This measure of the *actual* degree of transparency follows Faust and Svensson (2002), who consider an announcement about a monetary control error. When the signals are completely accurate ($\sigma_\varepsilon^2 = \sigma_\eta^2 = 0$), there is perfect transparency ($\tau_\theta = \tau_\kappa = 1$) about the central bank's targets, which is defined as a situation of symmetric information between the central bank and the private sector. A shortcoming of the transparency measure in (5) is that a constant target ($\sigma_\theta^2 = 0$, $\sigma_\kappa^2 = 0$) implies minimal transparency ($\tau_\theta = 0$, $\tau_\kappa = 0$) regardless of the informativeness of the signal (ξ_θ, ξ_κ). This drawback disappears when private-sector perceptions are allowed to deviate from the actual stochastic distributions.[5]

The second information asymmetry is about the degrees of transparency τ_θ and τ_κ. The public is unsure how transparent the central bank really is. In particular, the public does not know the actual stochastic distributions of θ, κ, ε, and η. Instead, the public uses the perceived (or prior) distributions $\theta \sim N(\bar{\theta}, \tilde{\sigma}_\theta^2)$, $\kappa \sim N(\bar{\kappa}, \tilde{\sigma}_\kappa^2)$, $\varepsilon \sim N(0, \tilde{\sigma}_\varepsilon^2)$, and $\eta \sim N(0, \tilde{\sigma}_\eta^2)$. As a result, the *perceived* degrees of transparency are given by

$$\tilde{\tau}_\theta = \frac{\tilde{\sigma}_\theta^2}{\tilde{\sigma}_\theta^2 + \tilde{\sigma}_\varepsilon^2} \quad \text{and} \quad \tilde{\tau}_\kappa = \frac{\tilde{\sigma}_\kappa^2}{\tilde{\sigma}_\kappa^2 + \tilde{\sigma}_\eta^2}, \tag{6}$$

where $0 \leq \tilde{\tau}_\theta$, $\tilde{\tau}_\kappa \leq 1$. This (Bayesian) transparency measure does not depend on the actual variances σ_θ^2 and σ_κ^2, so it also applies when the central bank's targets θ and κ are deterministic. Furthermore, it describes transparency from the public's perspective, which makes it more relevant to understanding the behavior of the private sector.

The timing of events is as follows. First, the inflation target θ and output-gap target κ are realized but only observed by the central bank. Subsequently, the private sector receives the public signals ξ_θ and ξ_κ, which are used to rationally form private-sector inflation expectations π^e. Then, the supply shock s is realized and observed by the central bank. Finally, the central bank sets the output gap

[5]The transparency measure in (5) also has the peculiar feature that it is increasing in monetary uncertainty (σ_θ^2, σ_κ^2). This correctly reflects the relative accuracy of the signal (ξ_θ, ξ_κ), but it is an odd implication for a transparency measure. A more general measure of transparency that does not suffer from this shortcoming is presented in section 4.1.

y, and the level of inflation π is realized. This timing implies that monetary policy is conducted under discretion.

The central bank maximizes the expected value of its objective (1) with respect to y subject to the Phillips curve (2) and given private-sector inflation expectations π^e. This yields the optimal output gap

$$y = \alpha(\theta - \pi^e - s) + (1 - \alpha)\kappa. \tag{7}$$

The output gap is increasing in the central bank's inflation target θ and output-gap target κ as the central bank pursues expansionary policy to attempt to reach the targets. In addition, higher private-sector inflation expectations π^e cause the central bank to reduce the output gap to achieve price stability, and the same holds for a higher supply shock s. Substituting (7) into (2) produces the level of inflation

$$\pi = \alpha\theta + (1 - \alpha)(\pi^e + \kappa + s). \tag{8}$$

This gives rise to the standard result that inflation is increasing in the inflation target θ, the output-gap target κ, private-sector inflation expectations π^e, and the supply shock s.

To fully understand the role of the two information asymmetries in the formation of the private sector's inflation expectations, we assume in section 2.1 that the private sector only has asymmetric information about the central bank's inflation target θ and output-gap target κ, but has perfect common knowledge about the actual degrees of central bank transparency τ_θ and τ_κ. Then, in section 2.2, the assumption of asymmetric information about the degree of transparency is added and the role of transparency (mis)perceptions is analyzed.

2.1 Perfect Common Knowledge

The private sector has rational expectations, so it uses all available information, including the public signals ξ_θ and ξ_κ, to form its inflation expectations π^e. Taking expectations of (8) and solving for π^e gives

$$\pi^e = \mathrm{E}[\pi|\xi_\theta, \xi_\kappa] = \mathrm{E}[\theta|\xi_\theta] + \frac{1-\alpha}{\alpha}\mathrm{E}[\kappa|\xi_\kappa], \tag{9}$$

using the fact that ξ_κ is uninformative about θ and ξ_θ is uninformative about κ. Private-sector inflation expectations depend on the private sector's expectations of the central bank's inflation target θ and output-gap target κ, which it attempts to infer from the public signals ξ_θ and ξ_κ. Using (3), (4), and (5),[6]

$$\mathrm{E}[\theta|\xi_\theta] = \bar{\theta} + \frac{\sigma_\theta^2}{\sigma_\theta^2 + \sigma_\varepsilon^2}(\xi_\theta - \bar{\theta}) = (1-\tau_\theta)\bar{\theta} + \tau_\theta \xi_\theta \tag{10}$$

$$\mathrm{E}[\kappa|\xi_\kappa] = \bar{\kappa} + \frac{\sigma_\kappa^2}{\sigma_\kappa^2 + \sigma_\eta^2}(\xi_\kappa - \bar{\kappa}) = (1-\tau_\kappa)\bar{\kappa} + \tau_\kappa \xi_\kappa. \tag{11}$$

The private sector faces a signal extraction problem, and its expectation of θ (κ) equals a weighted average of its prior belief $\bar{\theta}$ ($\bar{\kappa}$) and the public signal ξ_θ (ξ_κ). For a higher degree of transparency τ_θ (τ_κ), the public signal ξ_θ (ξ_κ) is relatively more informative, so the private sector attaches greater weight to it. In the case of perfect transparency, $\tau_\theta = \tau_\kappa = 1$ and $\sigma_\varepsilon^2 = \sigma_\eta^2 = 0$, so the inflation target and output-gap target are perfectly inferred: $\mathrm{E}[\theta|\xi_\theta] = \xi_\theta = \theta$ and $\mathrm{E}[\kappa|\xi_\kappa] = \xi_\kappa = \kappa$. In the case of complete opacity ($\tau_\theta = \tau_\kappa = 0$), the private sector rationally ignores the signals so that $\mathrm{E}[\theta|\xi_\theta] = \bar{\theta}$ and $\mathrm{E}[\kappa|\xi_\kappa] = \bar{\kappa}$. Substituting (10) and (11) into (9) and using (3) and (4) gives

$$\pi^e = \bar{\theta} + \tau_\theta(\theta - \bar{\theta}) + \tau_\theta \varepsilon + \frac{1-\alpha}{\alpha}[\bar{\kappa} + \tau_\kappa(\kappa - \bar{\kappa}) + \tau_\kappa \eta]. \tag{12}$$

The private sector's inflation expectations are determined by its prior expectations $\bar{\theta}$ and $\bar{\kappa}$ of the central bank's targets, the deviations of the central bank's targets from the private sector's priors, and the noise ε and η in the public signals. The latter shows how misinterpretation of monetary policy communications causes inappropriate market reaction. The variability of private-sector inflation expectations depends on the degrees of transparency. In particular,

$$\mathrm{Var}[\pi^e] = \tau_\theta \sigma_\theta^2 + \left(\frac{1-\alpha}{\alpha}\right)^2 \tau_\kappa \sigma_\kappa^2,$$

[6] This uses the fact that for two jointly normally distributed variables x and z, $\mathrm{E}[x|z] = \mathrm{E}[x] + \frac{\mathrm{Cov}\{x,z\}}{\mathrm{Var}[z]}(z - \mathrm{E}[z])$.

using the fact that (5) implies $\sigma_\varepsilon^2 = \frac{1-\tau_\theta}{\tau_\theta}\sigma_\theta^2$ and $\sigma_\eta^2 = \frac{1-\tau_\kappa}{\tau_\kappa}\sigma_\kappa^2$. This shows that inflation expectations π^e are most stable when the central bank is least transparent ($\tau_\theta = \tau_\kappa = 0$). Intuitively, the complete lack of transparency makes the public signal so noisy that the public no longer relies on it and only uses its prior expectations.[7]

Substituting (12) into (7) and using (2) gives the levels of the output gap y and inflation π:

$$y = \alpha[(1-\tau_\theta)(\theta-\bar{\theta}) - \tau_\theta\varepsilon] + (1-\alpha)[(1-\tau_\kappa)(\kappa-\bar{\kappa}) - \tau_\kappa\eta] - \alpha s \tag{13}$$

$$\pi = \bar{\theta} + (\alpha + (1-\alpha)\tau_\theta)(\theta-\bar{\theta}) + (1-\alpha)\tau_\theta\varepsilon + \frac{1-\alpha}{\alpha}[\bar{\kappa} + (\alpha + (1-\alpha)\tau_\kappa)(\kappa-\bar{\kappa}) + (1-\alpha)\tau_\kappa\eta] + (1-\alpha)s. \tag{14}$$

The output gap and inflation depend on the central bank's targets θ and κ, the private sector's priors $\bar{\theta}$ and $\bar{\kappa}$, the signal noise ε and η, and the supply shock s. Although the degrees of transparency τ_θ and τ_κ influence the output gap and inflation, they have no effect on the expected values $\mathrm{E}[y]$ and $\mathrm{E}[\pi]$. In the case of perfect transparency ($\tau_\theta = \tau_\kappa = 1$, so $\varepsilon = \eta = 0$), the expressions simplify to $y = -\alpha s$ and $\pi = \theta + (1-\alpha)(\kappa + \alpha s)/\alpha$, which gives the familiar rational expectations outcome that the targets θ and κ only affect inflation and do not influence output.

The variability of the output gap and inflation is given by

$$\mathrm{Var}[y] = \alpha^2(1-\tau_\theta)\sigma_\theta^2 + (1-\alpha)^2(1-\tau_\kappa)\sigma_\kappa^2 + \alpha^2\sigma_s^2$$

$$\mathrm{Var}[\pi] = [\alpha^2 + (1-\alpha^2)\tau_\theta]\sigma_\theta^2 + \frac{(1-\alpha)^2}{\alpha^2}[\alpha^2 + (1-\alpha^2)\tau_\kappa]\sigma_\kappa^2 + (1-\alpha)^2\sigma_s^2,$$

where (5) is used to substitute for σ_ε^2 and σ_η^2. This shows that the output gap is most stable when the central bank is perfectly transparent ($\tau_\theta = \tau_\kappa = 1$). The reason is that greater transparency

[7] This case in which private-sector expectations do not incorporate any communications resembles the monetary uncertainty literature mentioned in section 1. It features deterministic private-sector inflation expectations π^e, and the degree of monetary uncertainty is described by σ_θ^2 and σ_κ^2.

makes private-sector inflation expectations more sensitive to the central bank's targets. For a change in the inflation target, the stronger response of private-sector inflation expectations means that a smaller adjustment of the output gap is required to reach the inflation target. For a change in the output-gap target, the output gap is adjusted by less because the larger shift in inflation expectations hampers inflation stabilization.[8] However, inflation is most stable when the central bank is least transparent ($\tau_\theta = \tau_\kappa = 0$). This is due to the greater stability of private-sector inflation expectations.

To determine the optimal degrees of transparency, substitute (8) and (7) into (1), use (12), and rearrange to get

$$\begin{aligned} U &= -\frac{1}{2}\alpha(1-\alpha)(\pi^e - \theta + \kappa + s)^2 \qquad (15)\\ &= -\frac{1}{2}\frac{1-\alpha}{\alpha}[\alpha(\tau_\theta - 1)(\theta - \bar{\theta}) + \alpha\tau_\theta\varepsilon + \bar{\kappa} + (\alpha + (1-\alpha)\tau_\kappa)(\kappa - \bar{\kappa}) \\ &\quad + (1-\alpha)\tau_\kappa\eta + \alpha s]^2. \end{aligned}$$

When there is imperfect transparency about the inflation target ($\tau_\theta \neq 1$), the deviation between the actual target θ and the private sector's prior expectation $\bar{\theta}$ affects the level of U. The prior expectation $\bar{\kappa}$ also matters, unless there is perfect transparency about the output-gap target ($\tau_\kappa = 1$). So, the outcome is distorted when there is incomplete transparency.

Taking unconditional expectations of (15) and substituting for σ_ε^2 and σ_η^2 using (5) gives the ex ante expected central bank payoff

$$\mathrm{E}[U] = -\frac{1}{2}\frac{1-\alpha}{\alpha}\left[\alpha^2(1-\tau_\theta)\sigma_\theta^2 + \bar{\kappa}^2 + \left(\alpha^2 + (1-\alpha^2)\tau_\kappa\right)\sigma_\kappa^2 + \alpha^2\sigma_s^2\right].$$

As a result, it would be optimal to have maximum transparency about the inflation target ($\tau_\theta = 1$) and minimal transparency about the output-gap target ($\tau_\kappa = 0$). Although transparency about the inflation target increases the variance of inflation, this drawback is dominated by the benefits that transparency makes the output gap more stable and brings inflation closer to the inflation target. In

[8] For the neomonetarist transmission mechanism with a Lucas supply equation, the intuition is that greater transparency reduces inflation surprises, which makes the output gap more stable.

addition, opacity about the output-gap target makes the output gap more volatile, but this disadvantage is more than offset by the greater stability of inflation and the smaller deviation between the output gap and its target. The optimality of opacity about the output-gap target is similar in spirit to the result in the seminal paper by Cukierman and Meltzer (1986), where ambiguity about the output preference parameter allows the central bank to successfully stimulate output when it is most desirable. Cukierman and Meltzer (1986) assume that ambiguity is created through monetary control errors, whereas the present paper assumes perfect control over the monetary policy instrument but opacity caused by imperfect communications.

The following proposition summarizes the key results.

PROPOSITION 1. *When there is asymmetric information about the central bank's inflation target θ and output-gap target κ, and perfect common knowledge about the degree of central bank transparency τ_θ and τ_κ,*

(i) greater transparency (τ_θ and/or τ_κ) increases the variability of private-sector inflation expectations π^e and inflation π, but reduces the volatility of the output gap y; and

(ii) it is optimal to have maximum transparency about the inflation target ($\tau_\theta = 1$) and minimal transparency about the output target ($\tau_\kappa = 0$).

In section 2.2, the assumption of perfect common knowledge about the degree of transparency is relaxed, allowing for a difference between actual and perceived transparency.

2.2 Transparency Misperceptions

The assumption of perfect common knowledge about transparency has the critical drawback that private-sector perceptions are restricted to be determined by the actual volatilities σ_θ^2, σ_κ^2, σ_ε^2, and σ_η^2. This is problematic because it is hard for the private sector to establish how transparent the central bank actually is. For instance, what is the noise σ_η^2 associated with a central banker's speech? It could easily vary, which means that the public is unlikely to know the level of transparency τ. So, it is realistic to allow for imperfect common knowledge about the degree of transparency. This has the virtue that it decouples private-sector perceptions of uncertainty from actual stochastic volatility.[9]

In contrast to section 2.1, assume now that the private sector does not know the actual stochastic distribution of the central bank's inflation target θ and output-gap target κ, and the noise ε and η. Instead, it uses the perceived (or prior) distributions $\theta \sim N(\bar{\theta}, \tilde{\sigma}_\theta^2)$, $\kappa \sim N(\bar{\kappa}, \tilde{\sigma}_\kappa^2)$, $\varepsilon \sim N(0, \tilde{\sigma}_\varepsilon^2)$, and $\eta \sim N(0, \tilde{\sigma}_\eta^2)$. This gives rise to the perceived degrees of transparency $\tilde{\tau}_\theta$ and $\tilde{\tau}_\kappa$ in (6).

Transparency perceptions do not affect the central bank's optimization problem, so (7) and (8) continue to hold. In addition, the private sector still receives the public signals (3) and (4), which it uses to rationally form its inflation expectations $\pi^e = \widetilde{\mathrm{E}}[\pi|\xi]$, where $\widetilde{\mathrm{E}}[.]$ denotes the private-sector expectation based on the perceived distributions of θ, κ, ε, and η. But the signal-extraction process is affected by private-sector perceptions. To be precise, (10) and (11) are replaced by

$$\widetilde{\mathrm{E}}[\theta|\xi_\theta] = (1 - \tilde{\tau}_\theta)\bar{\theta} + \tilde{\tau}_\theta \xi_\theta \tag{16}$$

$$\widetilde{\mathrm{E}}[\kappa|\xi_\kappa] = (1 - \tilde{\tau}_\kappa)\bar{\kappa} + \tilde{\tau}_\kappa \xi_\kappa. \tag{17}$$

So, with imperfect common knowledge about the degree of transparency, it is the perceived transparency $\tilde{\tau}_\theta$ and $\tilde{\tau}_\kappa$ that matters for the updating of private-sector expectations. As a result, private-sector inflation expectations now equal

$$\pi^e = \bar{\theta} + \tilde{\tau}_\theta(\theta - \bar{\theta}) + \tilde{\tau}_\theta \varepsilon + \frac{1-\alpha}{\alpha}[\bar{\kappa} + \tilde{\tau}_\kappa(\kappa - \bar{\kappa}) + \tilde{\tau}_\kappa \eta]. \tag{18}$$

The variability of private-sector inflation expectations depends on the perceived degrees of transparency $\tilde{\tau}_\theta$ and $\tilde{\tau}_\kappa$. But now there are two measures of variability: $\widetilde{\mathrm{Var}}[.]$ is based on the perceived stochastic distribution of θ, κ, ε, and η, and measures private-sector

[9]In a perceptive contribution, Hahn (2004) aims to analyze transparency about the central bank's relative preference weight α independently of the stochastic distribution of α. However, the private sector's ex ante distribution and the actual distribution of α are assumed to be the same, so there is no effective separation.

uncertainty (ex ante); and Var[.] is based on the actual stochastic distribution of θ, κ, ε, and η, and measures average volatility (ex post).

The perceived variance of private-sector inflation expectations equals

$$\widetilde{\mathrm{Var}}[\pi^e] = \tilde{\tau}_\theta \tilde{\sigma}_\theta^2 + \left(\frac{1-\alpha}{\alpha}\right)^2 \tilde{\tau}_\kappa \tilde{\sigma}_\kappa^2,$$

using the fact that (6) implies $\tilde{\sigma}_\varepsilon^2 = \frac{1-\tilde{\tau}_\theta}{\tilde{\tau}_\theta}\tilde{\sigma}_\theta^2$ and $\tilde{\sigma}_\eta^2 = \frac{1-\tilde{\tau}_\kappa}{\tilde{\tau}_\kappa}\tilde{\sigma}_\kappa^2$. This shows that private-sector uncertainty about inflation expectations is smallest when the central bank is perceived to be least transparent ($\tilde{\tau}_\theta = \tilde{\tau}_\kappa = 0$). The reason is that the perceived lack of transparency makes the public signals ξ_θ and ξ_κ unreliable, so the private sector only uses its prior expectations $\bar{\theta}$ and $\bar{\kappa}$.

The actual variance of private-sector inflation expectations equals

$$\mathrm{Var}[\pi^e] = \frac{\tilde{\tau}_\theta^2}{\tau_\theta}\sigma_\theta^2 + \left(\frac{1-\alpha}{\alpha}\right)^2 \frac{\tilde{\tau}_\kappa^2}{\tau_\kappa}\sigma_\kappa^2,$$

using the fact that (5) implies $\sigma_\varepsilon^2 = \frac{1-\tau_\theta}{\tau_\theta}\sigma_\theta^2$ and $\sigma_\eta^2 = \frac{1-\tau_\kappa}{\tau_\kappa}\sigma_\kappa^2$. This shows that the volatility of private-sector inflation expectations is increasing in perceived transparency $\tilde{\tau}_\theta$ and $\tilde{\tau}_\kappa$, and decreasing in actual transparency τ_θ and τ_κ. Intuitively, lower perceived transparency causes the private sector to rely less on the noisy public signals (ξ_θ and ξ_κ), and greater actual transparency reduces the variance of the noise (σ_ε^2 and σ_η^2), both making inflation expectations π^e less volatile.

Substituting (18) into (7) and using (2) gives the levels of the output gap y and inflation π for transparency perceptions $\tilde{\tau}$:

$$y = \alpha[(1-\tilde{\tau}_\theta)(\theta-\bar{\theta}) - \tilde{\tau}_\theta\varepsilon] + (1-\alpha)[(1-\tilde{\tau}_\kappa)(\kappa-\bar{\kappa}) - \tilde{\tau}_\kappa\eta] - \alpha s \tag{19}$$

$$\pi = \bar{\theta} + (\alpha + (1-\alpha)\tilde{\tau}_\theta)(\theta-\bar{\theta}) + (1-\alpha)\tilde{\tau}_\theta\varepsilon + \frac{1-\alpha}{\alpha}[\bar{\kappa} + (\alpha+(1-\alpha)\tilde{\tau}_\kappa)(\kappa-\bar{\kappa}) + (1-\alpha)\tilde{\tau}_\kappa\eta] + (1-\alpha)s. \tag{20}$$

These expressions are identical to their counterparts under common knowledge, (13) and (14), except that the actual degrees of transparency τ_θ and τ_κ are replaced by the perceived degrees of transparency $\tilde{\tau}_\theta$ and $\tilde{\tau}_\kappa$. The same holds for $\widetilde{\mathrm{Var}}[y]$ and $\widetilde{\mathrm{Var}}[\pi]$ when σ_θ^2 and σ_κ^2 are also replaced by $\tilde{\sigma}_\theta^2$ and $\tilde{\sigma}_\kappa^2$, so the perceived variances only depend on private-sector perceptions. The actual variance is equal to

$$\mathrm{Var}[y] = \alpha^2\left(1 - 2\tilde{\tau}_\theta + \frac{\tilde{\tau}_\theta^2}{\tau_\theta}\right)\sigma_\theta^2 + (1-\alpha)^2\left(1 - 2\tilde{\tau}_\kappa + \frac{\tilde{\tau}_\kappa^2}{\tau_\kappa}\right)\sigma_\kappa^2 + \alpha^2\sigma_s^2$$

$$\mathrm{Var}[\pi] = \left[\alpha^2 + 2\alpha(1-\alpha)\tilde{\tau}_\theta + (1-\alpha)^2\frac{\tilde{\tau}_\theta^2}{\tau_\theta}\right]\sigma_\theta^2 + \frac{(1-\alpha)^2}{\alpha^2} \times \left[\alpha^2 + 2\alpha(1-\alpha)\tilde{\tau}_\kappa + (1-\alpha)^2\frac{\tilde{\tau}_\kappa^2}{\tau_\kappa}\right]\sigma_\kappa^2 + (1-\alpha)^2\sigma_s^2,$$

where (5) is used to substitute for σ_ε^2 and σ_η^2. The variability of the output gap and inflation depends on both the perceived and actual degrees of transparency. In the special case in which $\tilde{\tau}_\theta = \tau_\theta$ and $\tilde{\tau}_\kappa = \tau_\kappa$, the common-knowledge results in section 2.1 are obtained. With imperfect common knowledge, the volatility of the output gap is decreasing in actual transparency τ_θ and τ_κ, and is minimized for $\tilde{\tau}_\theta = \tau_\theta = 1$ and $\tilde{\tau}_\kappa = \tau_\kappa = 1$.[10] The variability of inflation is also decreasing in actual transparency τ_θ and τ_κ, but increasing in perceived transparency $\tilde{\tau}_\theta$ and $\tilde{\tau}_\kappa$. Intuitively, greater transparency corresponds to fewer inflation surprises and therefore more output-gap stability, whereas lower perceived and higher actual transparency reduces the volatility of private-sector expectations and thereby the variance of inflation.

To derive the optimal degrees of actual and perceived transparency, substitute (18) into (15) and rearrange to get

$$U = -\frac{1}{2}\frac{1-\alpha}{\alpha}[\alpha(\tilde{\tau}_\theta - 1)(\theta - \bar{\theta}) + \alpha\tilde{\tau}_\theta\varepsilon + \bar{\kappa} + (\alpha + (1-\alpha)\tilde{\tau}_\kappa)(\kappa - \bar{\kappa}) + (1-\alpha)\tilde{\tau}_\kappa\eta + \alpha s]^2. \tag{21}$$

This is identical to the expression under common knowledge, except that τ_θ and τ_κ are replaced by $\tilde{\tau}_\theta$ and $\tilde{\tau}_\kappa$, respectively. It shows that

[10] Formally, these results follow from differentiating Var[y] with respect to τ_θ, τ_κ, $\tilde{\tau}_\theta$, and $\tilde{\tau}_\kappa$.

in the presence of transparency misperceptions, it is the lack of perceived transparency that causes the prior expectations $\bar{\theta}$ and $\bar{\kappa}$ to exert their influence on the outcome, regardless of the stochastic distribution of the central bank targets.

Taking expectations using the distributions perceived by the private sector yields

$$\widetilde{\mathrm{E}}[U] = -\frac{1}{2}\frac{1-\alpha}{\alpha}\left[\alpha^2(1-\tilde{\tau}_\theta)\tilde{\sigma}_\theta^2 + \bar{\kappa}^2 + (\alpha^2 + (1-\alpha^2)\tilde{\tau}_\kappa)\tilde{\sigma}_\kappa^2 + \alpha^2\tilde{\sigma}_s^2\right].$$

This reflects the ex ante expectation based on private-sector perceptions. It is the same as the expression for $\mathrm{E}[U]$ under common knowledge after replacing τ with $\tilde{\tau}$ and σ^2 with $\tilde{\sigma}^2$.

Taking unconditional expectations based on the actual distributions and substituting for σ_ε^2 and σ_η^2 using (5) yields

$$\mathrm{E}[U] = -\frac{1}{2}\frac{1-\alpha}{\alpha}\left[\alpha^2\left(1 - 2\tilde{\tau}_\theta + \frac{\tilde{\tau}_\theta^2}{\tau_\theta}\right)\sigma_\theta^2 + \bar{\kappa}^2 \right.$$
$$\left. + \left(\alpha^2 + 2\alpha(1-\alpha)\tilde{\tau}_\kappa + (1-\alpha)^2\frac{\tilde{\tau}_\kappa^2}{\tau_\kappa}\right)\sigma_\kappa^2 + \alpha^2\sigma_s^2\right].$$

This reflects the central bank's ex ante expectation, and it corresponds to the average ex post experience. It shows that $\mathrm{E}[U]$ is increasing in the actual degrees of transparency τ_θ and τ_κ, so that perfect transparency is optimal ($\tau_\theta = \tau_\kappa = 1$). In addition, $\mathrm{E}[U]$ is maximized for $\tilde{\tau}_\theta = \tau_\theta$ and $\tilde{\tau}_\kappa = 0$.[11] So, it is best to have complete perceived and actual transparency about the inflation target ($\tilde{\tau}_\theta = \tau_\theta = 1$) but maximum actual transparency ($\tau_\kappa = 1$) and minimal perceived transparency ($\tilde{\tau}_\kappa = 0$) about the output-gap target. Intuitively, it is desirable to have actual transparency about the central bank's targets because it avoids erratic reactions of private-sector expectations. Furthermore, it is beneficial to have perceived transparency about the inflation target so that private-sector inflation expectations are more responsive and become more closely aligned with the inflation target. However, perceived transparency

[11]Formally, $\partial\mathrm{E}[U]/\partial\tilde{\tau}_\theta = -\alpha(1-\alpha)\frac{\tilde{\tau}_\theta - \tau_\theta}{\tau_\theta}\sigma_\theta^2$ and $\partial^2\mathrm{E}[U]/\partial\tilde{\tau}_\theta^2 < 0$ imply that $\tilde{\tau}_\theta = \tau_\theta$ is optimal, and $\partial\mathrm{E}[U]/\partial\tilde{\tau}_\kappa = -\frac{(1-\alpha)^2}{\alpha}(\alpha + (1-\alpha)\frac{\tilde{\tau}_\kappa}{\tau_\kappa})\sigma_\kappa^2 < 0$ implies the corner solution $\tilde{\tau}_\kappa = 0$.

about the output-gap target is detrimental because the response of private-sector inflation expectations hampers the achievement of the inflation and output-gap targets.

This shows that the optimal communication strategy is different for the central bank's inflation and output-gap targets. It is best to be transparent and unambiguously clear about the inflation target. But for the output-gap target, it is desirable to provide information with perceived ambiguity.

The following proposition summarizes the results.

PROPOSITION 2. *When there is asymmetric information about the central bank's inflation target* θ *and output-gap target* κ*, and about the degree of central bank transparency* τ_θ *and* τ_κ*,*

(i) greater actual transparency (τ_θ *and/or* τ_κ*) reduces the variability of private-sector inflation expectations* π^e*, inflation* π*, and the output gap* y*;*

(ii) greater perceived transparency ($\tilde{\tau}_\theta$ *and/or* $\tilde{\tau}_\kappa$*) increases the volatility of private-sector inflation expectations* π^e *and inflation* π*, whereas the output gap is most stable in the absence of transparency misperceptions (*$\tilde{\tau}_\theta = \tau_\theta$ *and* $\tilde{\tau}_\kappa = \tau_\kappa$*); and*

(iii) it is optimal to have maximum actual and perceived transparency about the inflation target ($\tau_\theta = \tilde{\tau}_\theta = 1$*) and maximum actual transparency but minimal perceived transparency about the output-gap target (*$\tau_\kappa = 1$*,* $\tilde{\tau}_\kappa = 0$*).*

A comparison with proposition 1 reveals that the detrimental effects of transparency under common knowledge—namely, greater inflation volatility and the optimality of opacity about the output-gap target—are not due to the actual degree of transparency but to the private sector's perceptions of it. The fact that the public is actually better informed is beneficial, but the stronger response of private-sector expectations driven by greater perceived transparency leads to undesirable inflation volatility and makes it more difficult for the central bank to reach its inflation and output-gap targets.

3. Extensions

It is important to assess the robustness of the results above, so several extensions are analyzed in this section. In particular, it is shown that transparency misperceptions could also be optimal for different objective functions, including "conservative" central banks and deterministic central bank targets (section 3.1), for transparency about supply shocks (section 3.2), and for a New Keynesian Phillips curve (section 3.3).

3.1 Objective Functions

Propositions 1(i) and 2(ii) show that transparency (perceptions) could have different effects on inflation and output-gap variability, which may give the impression that the desirability of transparency depends on the weight attached to inflation versus output-gap stabilization. To explore this issue, suppose that the central bank's objective remains (1) but that social welfare is given by

$$W = -\frac{1}{2}\beta(\pi - \theta)^2 - \frac{1}{2}(1-\beta)(y-\kappa)^2, \tag{22}$$

where $0 < \beta < 1$. So, monetary policy has been delegated to a central bank with a different relative preference weight. For instance, $\alpha > \beta$ would amount to a "conservative" central bank that is more concerned about inflation stabilization than society (Rogoff 1985). Interestingly, the degrees of transparency given in propositions 1(ii) and 2(iii) that are optimal for the central bank are also socially optimal, regardless of the weight β. More precisely, both $\mathrm{E}[U]$ and $\mathrm{E}[W]$ are maximized for $\tau_\theta = 1$ and $\tau_\kappa = 0$ under common knowledge, and for $\tilde{\tau}_\theta = \tau_\theta = \tau_\kappa = 1$ and $\tilde{\tau}_\kappa = 0$ with transparency misperceptions.[12] The reason that β is immaterial is that social welfare is not determined by $\mathrm{Var}[y]$ and $\mathrm{Var}[\pi]$ but by $\mathrm{E}[(\pi-\theta)^2]$ and $\mathrm{E}[(y-\kappa)^2]$. The latter are always proportional when the central bank behaves optimally according to (7) and (8), so transparency affects them in the same way.

[12] To see this, substitute (7) and (8) into (22) and rearrange to get $W = -\frac{1}{2}(\beta(1-\alpha)^2 + (1-\beta)\alpha^2)(\pi^e - \theta + \kappa + s)^2$. This is directly proportional to (15) so that $\mathrm{E}[W]$ is maximized for the same degrees of transparency as $\mathrm{E}[U]$.

Suppose now that monetary policy is still delegated to a central bank that maximizes (1) but that the social welfare function equals

$$W = -\frac{1}{2}\beta(\pi - \bar{\theta})^2 - \frac{1}{2}(1-\beta)(y - \bar{\kappa})^2. \tag{23}$$

So, again, the central bank attaches a different weight to inflation stabilization. In addition, although the targets of the central bank (θ and κ) and society ($\bar{\theta}$ and $\bar{\kappa}$) are the same on average, they typically differ due to idiosyncratic shocks ($\theta \neq \bar{\theta}$ and $\kappa \neq \bar{\kappa}$). This variation on the basic model is analyzed in the appendix, section A.1. With perfect common knowledge, the degree of transparency that is socially optimal now depends on β. To be precise, $\tau_\theta = \tau_\kappa = 1$ is socially optimal for $\alpha^2 > \beta$, and $\tau_\theta = \tau_\kappa = 0$ for $\alpha^2 < \beta$. In other words, if the central bank is sufficiently conservative, the social optimum is transparency. Intuitively, if society cares a lot about output-gap stabilization, the benefit of greater output-gap stability under transparency outweighs the drawback of more inflation variability. This result is similar to Hahn (2004), who considers transparency about the central bank's relative preference weight α.

With imperfect common knowledge, perfect actual transparency about the central bank's targets ($\tau_\theta = \tau_\kappa = 1$) is socially optimal regardless of the value of β. The reason is that transparency avoids erratic movements of market expectations. Regarding perceived transparency, if the central bank is not conservative ($\alpha \leq \beta$), society benefits from complete perceived opacity ($\tilde{\tau}_\theta = \tilde{\tau}_\kappa = 0$). Furthermore, for any other β, the degree of perceived transparency in the social optimum is strictly positive but remains less than the degree of actual transparency ($0 < \tilde{\tau}_\theta < \tau_\theta$ and $0 < \tilde{\tau}_\kappa < \tau_\kappa$). Intuitively, the perception of opacity reduces the response of market expectations to noise in the signal and therefore limits volatility.

Another issue is whether the conclusions depend on the assumption that the central bank's inflation and output-gap targets follow a normal distribution. In particular, the expressions for $\mathrm{E}[U]$ in section 2 give the impression that the degrees of actual and perceived transparency τ and $\tilde{\tau}$ are immaterial when the targets θ and κ are deterministic ($\sigma_\theta^2 = \sigma_\kappa^2 = 0$). The case of constant central bank targets is more closely examined in the appendix, section A.2. This reveals that it is optimal to have complete perceived opacity about both targets ($\tilde{\tau}_\theta = \tilde{\tau}_\kappa = 0$) but maximum actual transparency in the sense of minimally noisy signals ($\sigma_\varepsilon^2 = \sigma_\eta^2 = 0$). Intuitively, noisy signals lead to inflation and output-gap variability, but this effect is muted when the signals are perceived to be opaque so that the private sector pays less attention to them. So, again, it is desirable to have maximum actual transparency but to sustain transparency misperceptions such that perceived opacity exceeds actual opacity.

3.2 Transparency about Supply Shocks

Another interesting extension is to consider transparency about the supply shock s. In particular, suppose that the private sector receives a public signal of the supply shock before it forms its inflation expectations π^e. This is analyzed in the appendix, section A.3. In the case of perfect common knowledge, greater transparency τ_s about the supply shock s increases the volatility of both the output gap and inflation. Intuitively, greater transparency about the supply shock makes private-sector inflation expectations π^e more sensitive to the supply shock s, so the central bank increases the output-gap response to partially offset the increased volatility of inflation. Not surprisingly, minimal transparency about supply shocks ($\tau_s = 0$) is optimal. This result is consistent with Cukierman (2001), who compares limited ($\tau_s = 0$) and full ($\tau_s = 1$) transparency about the supply shock s in a model with a neomonetarist transmission mechanism.

With imperfect common knowledge about the degree of transparency τ_s, the variance of the output gap y and inflation π are both minimized for minimal perceived transparency ($\tilde{\tau}_s = 0$) and maximum actual transparency ($\tau_s = 1$). The intuition behind this result is familiar. Minimal perceived transparency mutes the response of private-sector expectations π^e to the supply shock s, which contributes to greater stability of the output gap and inflation. In addition, maximum actual transparency reduces the noise of the public signal, which makes inflation expectations more stable and thereby generates less volatility in the output gap and inflation. Not surprisingly, it is (socially) optimal to have minimal perceived and maximum actual transparency about supply shocks ($\tilde{\tau}_s = 0$ and $\tau_s = 1$).

So, the most effective communication strategy for supply shocks is to provide all the relevant information but to downplay its relevance. Perhaps this could explain why some central banks (e.g., the European Central Bank) stress that the quarterly macroeconomic forecasts they publish are staff forecasts that come without any endorsement by the monetary policymakers.

3.3 New Keynesian Phillips Curve

Finally, it is important to discuss to what extent the results extend to a New Keynesian Phillips curve. The baseline model assumes the expectations-augmented Phillips curve

$$\pi = \widetilde{\mathrm{E}}[\pi|\xi] + y + s,$$

where inflation expectations incorporate information from the public signal ξ about shocks affecting (current) inflation. With the New Keynesian Phillips curve

$$\pi_t = \widetilde{\mathrm{E}}_t[\pi_{t+1}|\xi_t] + y_t + s_t, \tag{24}$$

inflation expectations incorporate information from ξ_t about shocks affecting future inflation. If the shocks are (perceived to be) i.i.d., the signal ξ_t is (considered) uninformative about future shocks, and the (perceived) degree of transparency is immaterial. But for the more plausible case in which the shocks are (perceived to be) persistent, ξ_t is (considered) informative about both the current and the future shocks affecting inflation, so the effect on inflation expectations is similar for the expectations-augmented Phillips curve and the New Keynesian Phillips curve.

This is formally shown in the appendix, section A.4, for transparency about supply shocks when the central bank targets are deterministic.[13] In particular, the optimal (actual and perceived) transparency about supply shocks s_t is derived analytically for the New Keynesian Phillips curve (24) in an infinite-horizon model with discretionary monetary policy and commitment to a communication

[13] Allowing for asymmetric information about the central bank targets would greatly complicate the analysis with a New Keynesian Phillips curve. Even for the simple two-period model by Jensen (2002), no closed-form solution exists, and the optimal degree of transparency has to be computed numerically.

technology with a particular degree of (actual and perceived) transparency.[14] For i.i.d. supply shocks, transparency about the supply shock s_t does not affect economic outcomes, because information about current supply shocks has no effect on forward-looking inflation expectations. But for persistent supply shocks, the effect of (actual and perceived) transparency about supply shocks is qualitatively the same as for the model with the expectations-augmented Phillips curve. In the case of perfect common knowledge about the degree of transparency, greater transparency about the supply shock s_t increases the variability of inflation π_t and the output gap y_t, so minimal transparency is optimal. In the presence of transparency misperceptions, greater actual and smaller perceived transparency about the supply shock s_t reduce the variability of inflation π_t and the output gap y_t, so it is optimal to have maximum actual transparency but minimal perceived transparency. These results for the New Keynesian Phillips curve (24) are exactly the same as for the model with the expectations-augmented Phillips curve (2) in section 3.2. So, as long as shocks (are perceived to) have some persistence, the findings of the present paper remain relevant for a New Keynesian Phillips curve.

All these extensions of the baseline model show that the key findings of section 2 are robust: when the assumption of perfect common knowledge is relaxed, actual transparency is beneficial, and it is desirable to have a perceived degree of transparency that is no greater than the actual degree of transparency ($\tilde{\tau} \leq \tau$).[15]

4. Discussion

This section discusses two remaining issues. First, it addresses the limitation of τ as a measure of transparency and presents a more comprehensive alternative (section 4.1). In addition, various explanations for central bank mystique are discussed (section 4.2).

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[14] In practice, communication commitments could stem from formal accountability requirements. For instance, many central banks are required to publish quarterly inflation reports and provide parliamentary testimony.

[15] Another extension would be to incorporate the reputation approach. Since reputation effects are based on the updating of private-sector inflation expectations, they would depend only on perceived transparency. So, actual transparency would remain desirable, and transparency perceptions would again play a key role.

4.1 Transparency Measures

Since the transparency measure in (5) suffers from some drawbacks, it is useful to reconsider it. Although τ describes the relative accuracy of the signal ξ, it is less suitable as a measure of central bank transparency because it is increasing in monetary uncertainty (σ_θ^2, σ_κ^2). In the literature, transparency typically refers to the absence of information asymmetries (e.g., Geraats 2002). So, transparency is decreasing in the extent to which the private sector faces asymmetric information. However, an increase in opacity due to greater variability of the central bank's targets has the awkward implication that it leads to a higher value of τ. This shows that (5) is not a good indicator of the degree of transparency.

Instead, it is useful to construct a more fundamental measure that is directly based on the definition of transparency. Focusing on the inflation target θ, the private sector has the prior $\bar{\theta}$, and symmetric information amounts to $\theta = \bar{\theta}$. The difference between θ and $\bar{\theta}$ gives an indication of the degree of asymmetric information. So, ex ante opacity can be described by $\mathrm{E}[(\theta - \bar{\theta})^2] = \sigma_\theta^2$, which is the monetary uncertainty measure used in one strand of the literature.

However, the private sector is able to use the public signal ξ_θ to update its prior $\bar{\theta}$, which leads to the posterior $\mathrm{E}[\theta|\xi_\theta]$ in (10). Taking into account the information conveyed by the signal, the appropriate measure of opacity becomes

$$\mathrm{E}[(\theta - \mathrm{E}[\theta|\xi_\theta])^2] = (1 - \tau_\theta)\sigma_\theta^2$$

after substituting (10), (3), and using (5) to substitute for σ_ε^2. This shows that opacity about θ is increasing in the amount of initial monetary uncertainty σ_θ^2 and decreasing in the relative accuracy τ_θ of the signal ξ_θ.

Taking the inverse of opacity and substituting (5) leads to the transparency measure

$$\gamma_\theta = \frac{1}{(1 - \tau_\theta)\sigma_\theta^2} = \frac{1}{\sigma_\theta^2} + \frac{1}{\sigma_\varepsilon^2}.$$

This measure of (actual) transparency depends positively on the relative accuracy of the signal τ_θ and negatively on monetary uncertainty σ_θ^2. It has the intuitive property that transparency about

θ could be enhanced in two independent ways: (i) reduce the initial uncertainty (σ_θ^2) or (ii) reduce the noisiness of the signal (σ_ε^2). So, γ_θ has the desirable property that greater monetary uncertainty decreases transparency, which is in contrast to τ_θ.

Nevertheless, γ_θ still has the drawbacks that it depends on the actual stochastic distributions and implies infinite transparency if θ is deterministic ($\sigma_\theta^2 = 0$). These problems can be overcome by the following analogous measure of perceived transparency:

$$\tilde{\gamma}_\theta = \frac{1}{(1-\tilde{\tau}_\theta)\tilde{\sigma}_\theta^2} = \frac{1}{\tilde{\sigma}_\theta^2} + \frac{1}{\tilde{\sigma}_\varepsilon^2}.$$

If the private sector believes the target is deterministic ($\tilde{\sigma}_\theta^2 = 0$) and therefore known ($\theta = \bar{\theta}$), or if the private sector thinks that the public signal ξ_θ is completely accurate and has no noise ($\tilde{\sigma}_\varepsilon^2 = 0$), then the private sector has the perception of symmetric information about the inflation target θ, and perceived transparency $\tilde{\gamma}_\theta$ is infinite. On the other hand, complete perceived opacity ($\tilde{\gamma}_\theta = 0$) requires both an infinitely diffuse prior ($\tilde{\sigma}_\theta^2 \to \infty$) and the perception of an infinitely noisy signal ($\tilde{\sigma}_\varepsilon^2 \to \infty$).

The transparency measures γ_κ, $\tilde{\gamma}_\kappa$, γ_s, and $\tilde{\gamma}_s$ can be defined in a similar way. Although γ and $\tilde{\gamma}$ are better measures of the degree of asymmetric information, the economic effects of transparency are more easily understood in terms of the relative accuracy of the signal (τ, $\tilde{\tau}$) and the extent of monetary uncertainty (σ_θ^2, σ_κ^2, $\tilde{\sigma}_\theta^2$, $\tilde{\sigma}_\kappa^2$). The reason is that the relative signal accuracy need not have the same effect as initial monetary uncertainty. In particular, suppose there is common knowledge about all the variance parameters σ^2 and thereby about τ. Then, greater opacity through higher monetary uncertainty σ_θ^2, σ_κ^2, and σ_s^2 is always detrimental because it increases the variance of output and inflation, $\mathrm{Var}[y]$ and $\mathrm{Var}[\pi]$, and reduces $\mathrm{E}[U]$.[16] In contrast, greater opacity through a lower relative signal accuracy τ_κ or τ_s is beneficial and actually increases $\mathrm{E}[U]$.

Nevertheless, one of the main findings of the paper—namely, that actual transparency is beneficial in the presence of private-sector misperceptions—not only holds for the measure τ but also

[16]This holds not only ceteris paribus (i.e., for a constant τ_θ, τ_κ, and τ_s) but also for the total effects of σ_θ^2, σ_κ^2, and σ_s^2 on $\mathrm{Var}[y]$, $\mathrm{Var}[\pi]$, and $\mathrm{E}[U]$.

for the more general measure γ. To be precise, a decrease in initial monetary uncertainty (σ_θ^2, σ_κ^2, σ_s^2) and in signal noise (σ_ε^2, σ_η^2, σ_υ^2) are both beneficial because of a reduction in Var[y] and Var[π] and an increase in E[U].[17] As a result, the conclusion about the desirability of actual transparency remains robust even when a more comprehensive transparency measure is used.

4.2 Central Bank Mystique

Despite all the emphasis on transparency of monetary policy nowadays, central bankers still often speak with a remarkable lack of clarity. Although it is difficult to characterize "central bank speak," one insider described it as follows:

> *[Fed speak] is a language in which it is possible to speak, without ever saying anything.*
>
> (Mike Moskow, president of the Federal Reserve Bank of Chicago, December 7, 2002)

This paper shows that a central bank may try to give this impression of transparency while creating the perception of opacity. This could be achieved by avoiding the publication of precise, quantitative information and instead resorting to qualitative statements. For example, a numeric inflation target is likely to contribute to a high degree of perceived (and actual) transparency, whereas speeches that provide ambiguous perspectives could lower transparency perceptions.

It is worthwhile to note that the conclusions of this paper regarding the desirability of perceived opacity are independent of the public's prior expectation of the central bank's output-gap target, $\bar{\kappa}$. In particular, the results also hold for $\bar{\kappa} = 0$, in which case there is no average inflation bias, so the central bank has no systematic incentive to misrepresent its information. In that case, commitment to a truthful communication technology is perfectly credible. To the extent that this is not possible, there may be central bank "cheap talk" such that communication of central bank private information is only credible when it is imprecise (Stein 1989).

[17] This refers to the total effect, which is straightforward (though tedious) to compute by differentiating Var[y], Var[π], and E[U] after substituting for τ.

In addition, there may be institutional reasons for central banks to be vague. For example, a central bank without an explicit legal primary objective of price stability, such as the Federal Reserve, could be more reluctant to adopt a numeric inflation target because it may give the impression that it is neglecting its other objectives.

There could also be other reasons for oblique communications by central bankers. For instance, evasiveness could be used to limit accountability or hide incompetence. In addition, secretive central bankers receive more media attention, as their every word is scrutinized. Last but not least, vague communications could reflect the tremendous uncertainty faced by central bankers, which is often difficult to explicate.

The paper shows that under certain circumstances maximum perceived opacity is optimal. In principle, there are two ways to achieve this. The central bank could give the impression that the public signal ξ is infinitely noisy, so that $\tilde{\tau} = 0$. Alternatively, the central bank could remain silent and not communicate at all, so that $\xi \in \{\varnothing\}$ and $\pi^e = \mathrm{E}[\pi]$. In the latter case, the actual and perceived degrees of transparency always coincide: $\tau = \tilde{\tau} = 0$. In practice, few central bankers prefer to remain silent but, rather, engage in oblique speak. This still gives them the benefits of perceived opacity while allowing them to communicate relevant information to the private sector and achieve greater actual transparency.[18]

In practice, there are likely to be some feasibility constraints on the extent of transparency (e.g., Cukierman 2006). In particular, it may not be possible to achieve complete opacity or perfect transparency. Suppose that there are binding constraints on the degree of (actual and perceived) transparency such that $\tau_{MIN} \leq \tau \leq \tau_{MAX}$ and $\tilde{\tau}_{MIN} \leq \tilde{\tau} \leq \tilde{\tau}_{MAX}$. Then, an optimum of maximum actual transparency ($\tau = 1$) and minimal perceived transparency ($\tilde{\tau} = 0$) would not be achievable. In that case, the constrained optimum is maximum possible perceived opacity, $\tilde{\tau} = \tilde{\tau}_{MIN}$, and maximum attainable actual transparency, $\tau = \tau_{MAX}$.

[18] Another reason for not remaining completely silent is that most central banks face accountability requirements, such as testimony before parliament or the publication of inflation reports.

A key finding of the paper is that it tends to be desirable to have less perceived than actual transparency ($\tilde{\tau} < \tau$). The only exception is the inflation target θ, for which $\tilde{\tau}_\theta = \tau_\theta$ is preferred by the central bank but not necessarily by society. An important practical consideration is the extent to which it is possible to sustain systematic deviations between actual and perceived transparency. If all the parameters of the model were stable, it would be possible for the private sector to learn the degree of transparency τ over time.[19] For instance, inflation reports with consistently detailed information are likely to facilitate learning about the central bank's transparency τ. However, when the accuracy of communications is variable so that σ_ε^2, σ_η^2, and σ_υ^2 are unstable, τ_θ, τ_κ, and τ_s can never be learned.

As a result, it may be impossible to learn the degree of transparency, which is especially relevant for verbal communications such as speeches and testimonies. Their informativeness could easily vary from one occasion to another. So, there is no constant degree of transparency to be learned, and the private sector is left in limbo about how much weight to attach to a particular central bank communication.

Adding to potential ambiguity is the fact that speeches by central bankers are used for two purposes—not only to convey news (e.g., about the economic outlook) but also to educate the public (e.g., about the monetary policy strategy or the monetary transmission process). The choice of educational topics and the way in which they are explained could be deliberate.[20] So, financial market analysts are likely to scrutinize speeches to look for clues about (changes in) central bankers' perceptions. Since there is typically ambiguity about whether prima facie educational content also contains some new policy-relevant views, it is difficult to assess the precise informativeness of a central banker's speech.

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[19]To see this, note that s and υ follow (ex post) from (2) and (25), so that σ_s^2, σ_υ^2, and τ_s could be learned over time. In addition, y, ξ_θ, and ξ_κ could be used to estimate $\text{Var}[\xi_\theta]$, $\text{Cov}\{y, \xi_\theta\}$, $\text{Var}[\xi_\kappa]$, and $\text{Cov}\{y, \xi_\kappa\}$, from which σ_θ^2, σ_ε^2, σ_κ^2, and σ_η^2 can be deduced. So, τ_θ and τ_κ would also be learnable.

[20]For instance, the speech on monetary policy and wage growth by Governor Svein Gjedrem of the Norwegian central bank in June 2002, which emphasized a positive empirical relation between interest rates and the growth in labor costs, was followed by an increase in the policy rate of 50 basis points in July 2002 to counter high wage growth.

In contrast to the fixed format of inflation reports and written policy statements, verbal communications tend to provide greater flexibility to convey information with a degree of transparency τ that is unknown to the private sector. Thus, speeches provide an important communication tool that is well suited to the dissemination of information with sustained transparency misperceptions.

An interesting finding of the present paper is that it could be beneficial to inhibit private-sector learning about the degree of transparency τ. Whenever $\tilde{\tau} = \tau$ is not optimal, it is actually desirable to have imperfect transparency about the actual degree of transparency. Central banks could exploit flexible communication tools such as speeches to hamper learning about τ and maintain advantageous transparency misperceptions.

Empirical evidence for the importance of speeches is provided by Reinhart and Sack (2006) for the Federal Reserve. Although speeches by members of the Federal Open Market Committee (FOMC) tend to have a very small average impact on market interest rates, their collective effect is sizable and second only to that of FOMC policy statements. This indicates that speeches are a major component of central bank communication.

Although it could be desirable to communicate with a sustained discrepancy between actual and perceived transparency, central bankers may not be equally skilled at it. Perhaps this is where part of the "art" of central banking comes in. A "maestro" like Alan Greenspan managed to effectively guide financial markets by means of statements that appeared to be open to multiple interpretations. He was (in)famous for his Delphic utterances.[21] The fact that his statements were perceived to be rife with ambiguity was constructive and prevented financial markets from reacting too strongly. In contrast, central bankers that speak with clarity appear to be more prone to criticism. For instance, the directness of the

[21] For example, Greenspan's befuddling speech to the Economic Club of New York on June 20, 1995, was summarized by the headline "Greenspan Hints Fed May Cut Interest Rates" in the *Washington Post* but by the headline "Doubts Voiced by Greenspan on a Rate Cut" in the *New York Times*.

first president of the European Central Bank, Wim Duisenberg, was often considered a liability.[22] Instead, central bankers tend to nurture speaking in guarded language that fosters transparency misperceptions, as is illustrated by Greenspan's quote at the beginning of this paper.

5. Conclusion

Central banks are transparent in many respects nowadays, but there is still considerable ambiguity in their communication. This paper shows that arcane statements by central bankers may serve an important purpose. They create the perception of opacity and make markets more cautious in their response to central bank communications, which reduces the volatility of private-sector expectations.

The paper models this mechanism by relaxing the strong assumption of perfect common knowledge about the degree of central bank transparency. In practice, there is considerable disagreement among researchers and market participants about how transparent central banks are. In addition, it would be difficult to verify the degree of transparency. So, it appears realistic to allow the actual and perceived degrees of transparency to differ from each other. This has the virtue that asymmetric information can be modeled regardless of the actual variability of parameters, thereby decoupling ex ante uncertainty and ex post volatility.

Moreover, the analysis of transparency perceptions of the private sector gives a better understanding of some of the disadvantages of transparency suggested in the literature. Although transparency is likely to reduce private-sector uncertainty, information disclosed by the central bank could alter private-sector expectations and give rise to greater economic volatility. However, this drawback appears to be entirely due to transparency perceptions. In particular, the paper shows that actual transparency is beneficial because it reduces the noisiness of communication, but perceived transparency

[22]To give an illustration, in response to a question about further interest rate cuts at a press conference after a cut of 50 basis points (on April 8, 1999), Duisenberg bluntly answered, "You be sure: this is it."

could be more problematic, as it makes markets more sensitive to (potentially noisy) information. This provides an economic rationale for transparent central bank communications that sustain transparency misperceptions. So, transparency about the degree of transparency may not be desirable. In particular, central banks may find it beneficial to disclose information under a veil of perceived ambiguity.

The paper shows that the central bank's optimal communication strategy is to be crystal clear about the inflation target but to be informative about the output-gap target and supply shocks through statements that are perceived to be opaque. In that respect, central bankers should speak, but with mystique.

Appendix

This appendix analyzes four extensions to the basic model that are discussed in section 3.

A.1 Alternative Social Welfare Function

This section computes the optimal degrees of transparency when the social welfare function equals (23). Substituting (7), (8), and (18) into (23) gives

$$\begin{aligned}
W &= -\frac{1}{2}\beta\{\alpha\theta + (1-\alpha)(\pi^e + \kappa + s) - \bar{\theta}\}^2 \\
&\quad - \frac{1}{2}(1-\beta)\{\alpha(\theta - \pi^e - s) + (1-\alpha)\kappa - \bar{\kappa}\}^2 \\
&= -\frac{1}{2}\beta\Big\{(\alpha + (1-\alpha)\tilde{\tau}_\theta)(\theta - \bar{\theta}) + (1-\alpha)\tilde{\tau}_\theta\varepsilon \\
&\quad + \frac{1-\alpha}{\alpha}[\bar{\kappa} + (\alpha + (1-\alpha)\tilde{\tau}_\kappa)(\kappa - \bar{\kappa}) + (1-\alpha)\tilde{\tau}_\kappa\eta + \alpha s]\Big\}^2 \\
&\quad - \frac{1}{2}(1-\beta)\{\alpha(1-\tilde{\tau}_\theta)(\theta - \bar{\theta}) - \alpha\tilde{\tau}_\theta\varepsilon + (1-\alpha)(1-\tilde{\tau}_\kappa)(\kappa - \bar{\kappa}) \\
&\quad - (1-\alpha)\tilde{\tau}_\kappa\eta - \bar{\kappa} - \alpha s\}^2.
\end{aligned}$$

Taking expectations and substituting for σ_ε^2 and σ_η^2 using (5) gives

$$\begin{aligned}
\mathrm{E}[W] = &-\frac{1}{2}\beta\left\{\left(\alpha^2 + 2\alpha(1-\alpha)\tilde{\tau}_\theta + (1-\alpha)^2\frac{\tilde{\tau}_\theta^2}{\tau_\theta}\right)\sigma_\theta^2 + \frac{(1-\alpha)^2}{\alpha^2}\right.\\
&\left.\times\left[\bar{\kappa}^2 + \left(\alpha^2 + 2\alpha(1-\alpha)\tilde{\tau}_\kappa + (1-\alpha)^2\frac{\tilde{\tau}_\kappa^2}{\tau_\kappa}\right)\sigma_\kappa^2 + \alpha^2\sigma_s^2\right]\right\}\\
&-\frac{1}{2}(1-\beta)\left\{\alpha^2\left(1 - 2\tilde{\tau}_\theta + \frac{\tilde{\tau}_\theta^2}{\tau_\theta}\right)\sigma_\theta^2 + (1-\alpha)^2\right.\\
&\left.\times\left(1 - 2\tilde{\tau}_\kappa + \frac{\tilde{\tau}_\kappa^2}{\tau_\kappa}\right)\sigma_\kappa^2 + \bar{\kappa}^2 + \alpha^2\sigma_s^2\right\}.
\end{aligned}$$

Since $\mathrm{E}[W]$ is increasing in τ_θ and τ_κ, it is socially optimal to have perfect actual transparency about the central bank's targets ($\tau_\theta = \tau_\kappa = 1$). Concerning perceived transparency, the first-order conditions $\partial\mathrm{E}[W]/d\tilde{\tau}_\theta = 0$ and $\partial\mathrm{E}[W]/d\tilde{\tau}_\kappa = 0$ yield

$$\begin{aligned}
\tilde{\tau}_\theta &= \frac{\alpha(\alpha-\beta)}{\beta(1-\alpha)+\alpha(\alpha-\beta)}\tau_\theta\\
\tilde{\tau}_\kappa &= \frac{\alpha(\alpha-\beta)}{\beta(1-\alpha)+\alpha(\alpha-\beta)}\tau_\kappa,
\end{aligned}$$

respectively. For $\alpha \geq \beta$, these are the socially optimal degrees of perceived transparency, since $\partial^2\mathrm{E}[W]/\partial\tilde{\tau}_\theta^2 < 0$ and $\partial^2\mathrm{E}[W]/\partial\tilde{\tau}_\kappa^2 < 0$. But for $\alpha < \beta$, the social optimum is the corner solution $\tilde{\tau}_\theta = \tilde{\tau}_\kappa = 0$. So, if the central bank is not conservative, society benefits from complete perceived opacity. Regardless of the value of β, in the social optimum the degree of perceived transparency is strictly less than the degree of actual transparency ($\tilde{\tau}_\theta < \tau_\theta$ and $\tilde{\tau}_\kappa < \tau_\kappa$).

In the case of common knowledge about the degree of transparency ($\tilde{\tau}_\theta = \tau_\theta$ and $\tilde{\tau}_\kappa = \tau_\kappa$),

$$\begin{aligned}
\mathrm{E}[W] = &-\frac{1}{2}\beta\left\{(\alpha^2 + (1-\alpha^2)\tau_\theta)\sigma_\theta^2 + \frac{(1-\alpha)^2}{\alpha^2}\right.\\
&\left.\times\left[\bar{\kappa}^2 + (\alpha^2 + (1-\alpha^2)\tau_\kappa)\sigma_\kappa^2 + \alpha^2\sigma_s^2\right]\right\} - \frac{1}{2}(1-\beta)\\
&\times\left\{\alpha^2(1-\tau_\theta)\sigma_\theta^2 + \bar{\kappa}^2 + (1-\alpha)^2(1-\tau_\kappa)\sigma_\kappa^2 + \alpha^2\sigma_s^2\right\}.
\end{aligned}$$

Differentiating yields

$$\frac{\partial \mathrm{E}[W]}{\partial \tau_\theta} = -\frac{1}{2}[\beta(1-\alpha^2) - (1-\beta)\alpha^2]\sigma_\theta^2 = -\frac{1}{2}(\beta - \alpha^2)\sigma_\theta^2$$

$$\frac{\partial \mathrm{E}[W]}{\partial \tau_\kappa} = -\frac{1}{2}\left[\beta\frac{(1-\alpha)^2}{\alpha^2}(1-\alpha^2) - (1-\beta)(1-\alpha)^2\right]\sigma_\kappa^2$$

$$= -\frac{1}{2}\left[\frac{\beta}{\alpha^2} - 1\right](1-\alpha)^2\sigma_\kappa^2.$$

Note that $\partial \mathrm{E}[W]/\partial \tau_\theta = \partial \mathrm{E}[W]/\partial \tau_\kappa = 0$ for $\beta = \alpha^2$, and $\mathrm{sgn}(\partial \mathrm{E}[W]/\partial \tau_\theta) = \mathrm{sgn}(\partial \mathrm{E}[W]/\partial \tau_\kappa) = \mathrm{sgn}(\alpha^2 - \beta)$. Hence, $\tau_\theta = \tau_\kappa = 1$ is socially optimal for $\alpha^2 > \beta$, and $\tau_\theta = \tau_\kappa = 0$ is socially optimal for $\alpha^2 < \beta$. So, if society attaches a sufficiently low weight to inflation stabilization or the central bank is sufficiently conservative, the social optimum is to have transparency about the central bank's targets.

The following statements summarize the results for the social welfare function (23):

- With perfect common knowledge about the degrees of transparency τ_θ and τ_κ, it is socially optimal to have maximum transparency about the central bank targets ($\tau_\theta = \tau_\kappa = 1$) for $\alpha^2 > \beta$ and minimal transparency ($\tau_\theta = \tau_\kappa = 0$) for $\alpha^2 < \beta$.
- With transparency misperceptions, it is socially optimal to have maximum actual transparency about the central bank's targets ($\tau_\theta = \tau_\kappa = 1$) regardless of α and β, some perceived opacity ($0 < \tilde{\tau}_\theta, \tilde{\tau}_\kappa < 1$) for $\alpha > \beta$, and maximum perceived opacity ($\tilde{\tau}_\theta = \tilde{\tau}_\kappa = 0$) for $\alpha \leq \beta$.

A.2 Constant Central Bank Targets

This section examines optimal transparency (mis)perceptions when the central bank's inflation target θ and output-gap target κ are constant. More precisely, the actual distributions of θ and κ are degenerate, but the private sector still faces asymmetric information about these targets and has the perceived (or prior) distributions $\theta \sim N(\bar{\theta}, \tilde{\sigma}_\theta^2)$, $\kappa \sim N(\bar{\kappa}, \tilde{\sigma}_\kappa^2)$. The optimal output gap and inflation still satisfy (7) and (8). In addition, private-sector expectations are again given by (16), (17), and (18).[23] The difference with the model in section 2.2 is that the actual values of θ and κ are now deterministic, so $\theta = \bar{\theta}$, $\kappa = \bar{\kappa}$, and $\sigma_\theta^2 = \sigma_\kappa^2 = 0$. As a result, the actual variance of inflation expectations equals

$$\mathrm{Var}[\pi^e] = \tilde{\tau}_\theta^2 \sigma_\varepsilon^2 + \left(\frac{1-\alpha}{\alpha}\right)^2 \tilde{\tau}_\kappa^2 \sigma_\eta^2.$$

This shows that the volatility of inflation expectations is increasing in perceived transparency $\tilde{\tau}_\theta$ and $\tilde{\tau}_\kappa$, and in the noise variances σ_ε^2 and σ_η^2, so that it is essentially decreasing in actual transparency about θ and κ.

The levels of the output gap and inflation are still given by (19) and (20), but their actual variances now equal

$$\mathrm{Var}[y] = \alpha^2 \tilde{\tau}_\theta^2 \sigma_\varepsilon^2 + (1-\alpha)^2 \tilde{\tau}_\kappa^2 \sigma_\eta^2 + \alpha^2 \sigma_s^2$$
$$\mathrm{Var}[\pi] = (1-\alpha)^2 \tilde{\tau}_\theta^2 \sigma_\varepsilon^2 + \frac{(1-\alpha)^2}{\alpha^2}(1-\alpha)^2 \tilde{\tau}_\kappa^2 \sigma_\eta^2 + (1-\alpha)^2 \sigma_s^2.$$

So, the variability of the output gap and inflation are both increasing in perceived transparency $\tilde{\tau}_\theta$ and $\tilde{\tau}_\kappa$, and in the noise variances σ_ε^2 and σ_η^2. As a result, the output gap and inflation are more stable when there is greater perceived opacity about the inflation and output-gap targets, and greater transparency in the communications ξ_θ and ξ_κ.

Regarding welfare effects, (21) still holds, and taking unconditional expectations based on actual distributions yields

$$\mathrm{E}[U] = -\frac{1}{2}\frac{1-\alpha}{\alpha}\left[\alpha^2 \tilde{\tau}_\theta^2 \sigma_\varepsilon^2 + \bar{\kappa}^2 + (1-\alpha)^2 \tilde{\tau}_\kappa^2 \sigma_\eta^2 + \alpha^2 \sigma_s^2\right].$$

Clearly, the best outcome is obtained for maximum perceived opacity ($\tilde{\tau}_\theta = \tilde{\tau}_\kappa = 0$) and maximum actual transparency ($\sigma_\varepsilon^2 = \sigma_\eta^2 = 0$). So, again, it is optimal to have transparency misperceptions.

[23] Note that if the perceived distributions were not normal, (16) and (17) would still be the best linear predictors.

The same conclusion holds for the social welfare functions in (22) and (23). Concerning the latter, expected social welfare now equals

$$\mathrm{E}[W] = -\frac{1}{2}[(\beta(1-\alpha)^2 + (1-\beta)\alpha^2)] \times \left\{ \tilde{\tau}_\theta^2 \sigma_\varepsilon^2 + \frac{1}{\alpha^2}\bar{\kappa}^2 + \frac{(1-\alpha)^2}{\alpha^2}\tilde{\tau}_\kappa^2 \sigma_\eta^2 + \sigma_s^2 \right\}.$$

So, again, minimal perceived transparency ($\tilde{\tau}_\theta = \tilde{\tau}_\kappa = 0$) and maximum actual transparency ($\sigma_\varepsilon^2 = \sigma_\eta^2 = 0$) is optimal.

As a result, the conclusion that it is desirable to have transparency misperceptions does not depend on the assumption that the central bank targets θ and κ are stochastic, and it even holds when these targets are actually deterministic.

A.3 Transparency about Supply Shocks

This section analyzes the effect of transparency about the supply shock s, where $s \sim N(0, \sigma_s^2)$. In the model of section 2, transparency about the supply shock s is immaterial because s is only realized after the private sector has formed its inflation expectations π^e. Now suppose that the private sector receives a public signal ξ_s of the supply shock before it forms its inflation expectations π^e:

$$\xi_s = s + \upsilon, \tag{25}$$

where υ is i.i.d. white noise with $\upsilon \sim N(0, \sigma_\upsilon^2)$. Then, the actual degree of transparency about supply shocks is given by

$$\tau_s = \frac{\sigma_s^2}{\sigma_s^2 + \sigma_\upsilon^2}. \tag{26}$$

Similarly, the perceived degree of transparency about supply shocks is given by

$$\tilde{\tau}_s = \frac{\tilde{\sigma}_s^2}{\tilde{\sigma}_s^2 + \tilde{\sigma}_\upsilon^2}, \tag{27}$$

where $\tilde{\sigma}_s^2$ and $\tilde{\sigma}_\upsilon^2$ are the private-sector perceptions of the (prior) variance of s and υ, respectively.

Note that the optimal degrees of transparency about the inflation target θ and output-gap target κ in section 2 are independent of the variability of the supply shock s. The reason is that σ_θ^2, σ_κ^2, and σ_s^2 enter separably in $\mathrm{E}[U]$, and θ, κ, and s are independent. Similarly, the optimal degree of transparency about the supply shock is independent of the variability of the inflation and output-gap targets. For simplicity, assume that the inflation target and output-gap target are deterministic and known to the private sector, so $\theta = \bar{\theta}$ and $\kappa = \bar{\kappa}$ with $\sigma_\theta^2 = \tilde{\sigma}_\theta^2 = \sigma_\kappa^2 = \tilde{\sigma}_\kappa^2 = 0$, which implies perfect (actual and perceived) transparency about the central bank's preferences. But now the private sector faces imperfect information about the supply shock s when it forms its inflation expectations. The central bank still maximizes (1) subject to (2) given π^e, which yields (7) and (8).

The results for imperfect common knowledge about the degree of transparency of supply shocks are derived first. Perfect common knowledge amounts to the special case in which there are no transparency misperceptions ($\tilde{\tau}_s = \tau_s$). Taking expectations of (8) and solving for π^e gives

$$\pi^e = \widetilde{\mathrm{E}}[\pi|\xi_s] = \bar{\theta} + \frac{1-\alpha}{\alpha}(\bar{\kappa} + \widetilde{\mathrm{E}}[s|\xi_s]).$$

Using (25) and (27),

$$\widetilde{\mathrm{E}}[s|\xi_s] = \frac{\tilde{\sigma}_s^2}{\tilde{\sigma}_s^2 + \tilde{\sigma}_\upsilon^2}\xi_s = \tilde{\tau}_s \xi_s.$$

Substituting into π^e and using (25) gives

$$\pi^e = \bar{\theta} + \frac{1-\alpha}{\alpha}(\bar{\kappa} + \tilde{\tau}_s s + \tilde{\tau}_s \upsilon). \tag{28}$$

Substituting this into (7) and (8) yields

$$\begin{aligned} y &= -(\alpha + (1-\alpha)\tilde{\tau}_s)s - (1-\alpha)\tilde{\tau}_s \upsilon \\ \pi &= \bar{\theta} + \frac{1-\alpha}{\alpha}[\bar{\kappa} + (\alpha + (1-\alpha)\tilde{\tau}_s)s + (1-\alpha)\tilde{\tau}_s \upsilon]. \end{aligned}$$

The variance of the output gap and inflation depend on the degree of transparency:

$$\mathrm{Var}[y] = \left[\alpha^2 + 2\alpha(1-\alpha)\tilde{\tau}_s + (1-\alpha)^2 \frac{\tilde{\tau}_s^2}{\tau_s}\right]\sigma_s^2$$

$$\mathrm{Var}[\pi] = \frac{(1-\alpha)^2}{\alpha^2}\left[\alpha^2 + 2\alpha(1-\alpha)\tilde{\tau}_s + (1-\alpha)^2 \frac{\tilde{\tau}_s^2}{\tau_s}\right]\sigma_s^2,$$

using the fact that (26) implies $\sigma_v^2 = \frac{1-\tau_s}{\tau_s}\sigma_s^2$. This shows that the variance of the output gap and inflation are decreasing in actual transparency τ_s and increasing in perceived transparency $\tilde{\tau}_s$.

Not surprisingly, perceived transparency about supply shocks is harmful, whereas actual transparency is beneficial. Formally, substitute (28) into (15) to get

$$U = -\frac{1}{2}\frac{1-\alpha}{\alpha}[\bar{\kappa} + (\alpha + (1-\alpha)\tilde{\tau}_s)s + (1-\alpha)\tilde{\tau}_s v]^2.$$

Taking unconditional expectations and substituting $\sigma_\varepsilon^2 = \frac{1-\tau_s}{\tau_s}\sigma_s^2$ gives the ex ante expected central bank payoff

$$\mathrm{E}[U] = -\frac{1}{2}\frac{1-\alpha}{\alpha}\left[\bar{\kappa}^2 + \left(\alpha^2 + 2\alpha(1-\alpha)\tilde{\tau}_s + (1-\alpha)^2\frac{\tilde{\tau}_s^2}{\tau_s}\right)\sigma_s^2\right].$$

As a result, for supply shocks it is optimal for the central bank to have maximum actual transparency ($\tau_s = 1$) and minimal perceived transparency ($\tilde{\tau}_s = 0$). Formally, this follows from $\partial \mathrm{E}[U]/\partial\tau_s > 0$ and $\partial \mathrm{E}[U]/\partial\tilde{\tau}_s < 0$.

The results under common knowledge are obtained by imposing the restriction that $\tilde{\tau}_s = \tau_s$. The variance of the output gap and inflation are equal to

$$\mathrm{Var}[y] = [\alpha^2 + (1-\alpha^2)\tau_s]\sigma_s^2$$

$$\mathrm{Var}[\pi] = \frac{(1-\alpha)^2}{\alpha^2}[\alpha^2 + (1-\alpha^2)\tau_s]\sigma_s^2.$$

This shows that greater transparency about the supply shock s increases the volatility of both the output gap and inflation.

This implies that transparency about supply shocks is detrimental. Formally,

$$\mathrm{E}[U] = -\frac{1}{2}\frac{1-\alpha}{\alpha}[\bar{\kappa}^2 + (\alpha^2 + (1-\alpha^2)\tau_s)\sigma_s^2].$$

Clearly, minimal transparency about supply shocks ($\tau_s = 0$) is optimal for the central bank. It is also socially optimal for the social welfare functions (22) and (23).

The following statements summarize the results concerning transparency about supply shocks s:

- With perfect common knowledge about the degree of transparency τ_s, greater transparency τ_s increases the variability of inflation π and the output gap y, and minimal transparency ($\tau_s = 0$) is optimal for the central bank and society.
- With transparency misperceptions, greater actual transparency τ_s and smaller perceived transparency $\tilde{\tau}_s$ reduce the variability of inflation π and the output gap y, and it is optimal for the central bank and society to have maximum actual transparency ($\tau_s = 1$) but minimal perceived transparency ($\tilde{\tau}_s = 0$).

A.4 Transparency about Supply Shocks with New Keynesian Phillips Curve

This section analyzes the effect of transparency about the supply shock s for an infinite-horizon model in which the central bank maximizes the expected value of

$$\bar{U} = (1-\delta)\sum_{t=1}^{\infty}\delta^{i-1}U_t,$$

where δ is the subjective intertemporal discount factor ($0 < \delta < 1$), and the objective function U_t is still given by (1). The central bank targets θ and κ are assumed to be deterministic and known to the private sector, just like in section A.3 of this appendix. But the expectations-augmented Phillips curve (2) is now replaced by the New Keynesian Phillips curve (24):

$$\pi_t = \widetilde{\mathrm{E}}_t[\pi_{t+1}|\xi_t] + y_t + s_t,$$

where $\widetilde{\mathrm{E}}_t[.]$ denotes the expectation of the private sector at the beginning of period t based on the stochastic distributions perceived by the private sector and (implicitly) conditional on all variables observed in periods $t-k$ for $k \in \{1, 2, \ldots\}$. The supply shock s_t is allowed to be persistent:

$$s_t = \rho s_{t-1} + \zeta_t, \tag{29}$$

where $0 \leq \rho < 1$ and ζ_t is i.i.d. white noise with $\zeta_t \sim N(0, \sigma_\zeta^2)$. So, $\mathrm{Var}[s_t] = \sigma_s^2 = \frac{1}{1-\rho^2}\sigma_\zeta^2$. The private sector observes a public signal ξ_t of the innovation ζ_t to the supply shock s_t:

$$\xi_t = \zeta_t + \upsilon_t, \tag{30}$$

where υ_t is i.i.d. white noise with $\upsilon_t \sim N(0, \sigma_\upsilon^2)$. So, $\mathrm{Var}[\xi_t] = \sigma_\zeta^2 + \sigma_\upsilon^2$. The degree of transparency about the supply shock innovation equals

$$\tau_\zeta = \frac{\sigma_\zeta^2}{\sigma_\zeta^2 + \sigma_\upsilon^2}. \tag{31}$$

Similarly, the perceived degree of transparency about the supply shock innovation is given by

$$\tilde{\tau}_\zeta = \frac{\tilde{\sigma}_\zeta^2}{\tilde{\sigma}_\zeta^2 + \tilde{\sigma}_\upsilon^2}, \tag{32}$$

where $\tilde{\sigma}_\zeta^2$ and $\tilde{\sigma}_\upsilon^2$ are the private-sector perceptions of the (prior) variance of ζ and υ, respectively.

The timing of events is as follows. At the beginning of each period, the private sector observes the public signal ξ_t of the innovation ζ_t to the supply shock s_t, and it forms its inflation expectations $\widetilde{\mathrm{E}}_t[\pi_{t+1}|\xi_t]$. Then, the supply shock innovation ζ_t, and thereby s_t, is realized. Finally, the central bank sets the output gap y_t, and the level of inflation π_t is realized. Monetary policy is still conducted under pure discretion. For simplicity, it is assumed that the central bank commits to a communication technology with a particular degree of (actual and perceived) transparency.

The private sector faces imperfect information about the supply shock s_t when it forms its inflation expectations. The information set available to the private sector when it forms $\widetilde{\mathrm{E}}_t[\pi_{t+1}|\xi_t]$ includes the public signal ξ_t and the history of the output gap y_{t-k}, inflation π_{t-k}, and supply shocks s_{t-k}, for $k \in \{1, 2, \ldots\}$. Note that the supply shock s_t can always be inferred by the private sector at the end of period t from y_t, π_t, and $\widetilde{\mathrm{E}}_t[\pi_{t+1}|\xi_t]$ using the Phillips curve (24), even if the private sector cannot directly observe s_t.

In every period, the central bank faces the same infinite-horizon problem, but with a different state variable $\widetilde{\mathrm{E}}_t[\pi_{t+1}|\xi_t]$. Since the current policy decision y_t has no effect on future outcomes, the central bank simply sets y_t to maximize U_t every period subject to (24) and given $\widetilde{\mathrm{E}}_t[\pi_{t+1}|\xi_t]$.[24] This yields the optimal levels of the output gap and inflation under discretion:

$$y_t = \alpha(\theta - \widetilde{\mathrm{E}}_t[\pi_{t+1}|\xi_t] - s_t) + (1-\alpha)\kappa \tag{33}$$

$$\pi_t = \alpha\theta + (1-\alpha)(\widetilde{\mathrm{E}}_t[\pi_{t+1}|\xi_t] + \kappa + s_t). \tag{34}$$

These are similar to (7) and (8) in the baseline model.

Recursive substitution of (34) yields

$$\pi_t = \alpha \sum_{i=0}^{k} (1-\alpha)^i \theta + (1-\alpha)^{k+1} \widetilde{\mathrm{E}}_t[\pi_{t+k+1}|\xi_t] + (1-\alpha) \sum_{i=0}^{k} (1-\alpha)^i \kappa$$
$$+ (1-\alpha) \sum_{i=1}^{k} (1-\alpha)^i \widetilde{\mathrm{E}}_t[s_{t+i}|\xi_t] + (1-\alpha) s_t.$$

Taking the limit $\lim_{k\to\infty} \pi_t$, inflation reduces to

$$\pi_t = \theta + \frac{1-\alpha}{\alpha}\kappa + \frac{(1-\alpha)\rho}{1-(1-\alpha)\rho} s_{t-1} + (1-\alpha)\frac{1-(1-\alpha)\rho(1-\tilde{\tau}_\zeta)}{1-(1-\alpha)\rho}\zeta_t$$
$$+ \frac{(1-\alpha)^2\rho}{1-(1-\alpha)\rho}\tilde{\tau}_\zeta \upsilon_t, \tag{35}$$

[24]This no longer holds when there is asymmetric information about the central bank targets θ and/or κ. In that case, there is generally no closed-form solution for the output gap y_t and inflation π_t, and the optimal degree of transparency has to be computed numerically, as in the two-period model by Jensen (2002).

using (29), $\widetilde{\mathrm{E}}_t[s_{t+i}|\xi_t] = \rho^{i+1}s_{t-1} + \rho^i\widetilde{\mathrm{E}}_t[\zeta_t|\xi_t]$, (30), and $\widetilde{\mathrm{E}}_t[\zeta_t|\xi_t] = \frac{\tilde{\sigma}_\zeta^2}{\tilde{\sigma}_\zeta^2+\tilde{\sigma}_\upsilon^2}\xi_t = \tilde{\tau}_\zeta(\zeta_t + \upsilon_t)$. So, private-sector inflation expectations equal

$$\widetilde{\mathrm{E}}_t[\pi_{t+1}|\xi_t] = \theta + \frac{1-\alpha}{\alpha}\kappa + \frac{(1-\alpha)\rho}{1-(1-\alpha)\rho}[\rho s_{t-1} + \tilde{\tau}_\zeta(\zeta_t + \upsilon_t)]. \quad (36)$$

Substitute this into (33), use (29), and simplify to get

$$\begin{aligned} y_t = &-\frac{\alpha\rho}{1-(1-\alpha)\rho}s_{t-1} - \alpha\frac{1-(1-\alpha)\rho(1-\tilde{\tau}_\zeta)}{1-(1-\alpha)\rho}\zeta_t \\ &- \frac{\alpha(1-\alpha)\rho}{1-(1-\alpha)\rho}\tilde{\tau}_\zeta\upsilon_t. \end{aligned} \quad (37)$$

The variance of inflation and the output gap are equal to

$$\begin{aligned} \mathrm{Var}[\pi_t] = &\frac{(1-\alpha)^2}{(1-(1-\alpha)\rho)^2}\left[\frac{1}{1-\rho^2} - 2(1-\alpha)\rho(1-\tilde{\tau}_\zeta)\right. \\ &\left. + (1-\alpha)^2\rho^2\left(1-2\tilde{\tau}_\zeta + \frac{\tilde{\tau}_\zeta^2}{\tau_\zeta}\right)\right]\sigma_\zeta^2 \\ \mathrm{Var}[y_t] = &\frac{\alpha^2}{(1-(1-\alpha)\rho)^2}\left[\frac{1}{1-\rho^2} - 2(1-\alpha)\rho(1-\tilde{\tau}_\zeta)\right. \\ &\left. + (1-\alpha)^2\rho^2\left(1-2\tilde{\tau}_\zeta + \frac{\tilde{\tau}_\zeta^2}{\tau_\zeta}\right)\right]\sigma_\zeta^2, \end{aligned}$$

using the fact that (29) and (31) imply $\mathrm{Var}[s_t] = \frac{1}{1-\rho^2}\sigma_\zeta^2$ and $\sigma_\upsilon^2 = \frac{1-\tau_\zeta}{\tau_\zeta}\sigma_\zeta^2$. In the special case in which the supply shock s_t is i.i.d. ($\rho = 0$), the variance of inflation and the output gap do not depend on the (actual and perceived) degree of transparency (τ_ζ and $\tilde{\tau}_\zeta$). But, when the supply shock is persistent ($\rho \neq 0$), differentiating with respect to τ_ζ and $\tilde{\tau}_\zeta$ gives

$$\begin{aligned} \frac{\partial\mathrm{Var}[\pi_t]}{\partial\tau_\zeta} &= -\frac{(1-\alpha)^4\rho^2}{(1-(1-\alpha)\rho)^2}\frac{\tilde{\tau}_\zeta^2}{\tau_\zeta^2}\sigma_\zeta^2 < 0 \\ \frac{\partial\mathrm{Var}[\pi_t]}{\partial\tilde{\tau}_\zeta} &= \frac{2(1-\alpha)^3\rho}{(1-(1-\alpha)\rho)^2}\left[1-(1-\alpha)\rho + (1-\alpha)\rho\frac{\tilde{\tau}_\zeta}{\tau_\zeta}\right]\sigma_\zeta^2 > 0. \end{aligned}$$

Similarly, $\partial \text{Var}[y_t]/\partial \tau_\zeta < 0$ and $\partial \text{Var}[y_t]/\partial \tilde{\tau}_\zeta > 0$. So, $\text{Var}[\pi_t]$ and $\text{Var}[y_t]$ are minimized for maximum actual transparency, $\tau_\zeta = 1$, and minimal perceived transparency, $\tilde{\tau}_\zeta = 0$.

Not surprisingly, for persistent supply shocks, actual transparency about supply shocks is beneficial, whereas perceived transparency is harmful. Formally, substituting (34) and (33) into (1) yields

$$U_t = -\frac{1}{2}\alpha(1-\alpha)(\widetilde{\text{E}}_t[\pi_{t+1}|\xi_t] - \theta + \kappa + s_t)^2 \tag{38}$$

similar to (15). Substituting (36) and taking unconditional expectations,

$$\begin{aligned} \text{E}[U_t] = &-\frac{1}{2}\alpha(1-\alpha)\Bigg[\frac{1}{\alpha^2}\kappa^2 + \frac{\rho^2}{(1-(1-\alpha)\rho)^2}\text{E}[s_{t-1}^2] \\ &+ \frac{(1-(1-\alpha)\rho(1-\tilde{\tau}_\zeta))^2}{(1-(1-\alpha)\rho)^2}\sigma_\zeta^2 + \frac{(1-\alpha)^2\rho^2\tilde{\tau}_\zeta^2}{(1-(1-\alpha)\rho)^2}\sigma_\upsilon^2\Bigg] \\ = &-\frac{1}{2}\alpha(1-\alpha)\Bigg[\frac{1}{\alpha^2}\kappa^2 \\ &+ \frac{\frac{1}{1-\rho^2} - 2(1-\alpha)\rho(1-\tilde{\tau}_\zeta) + (1-\alpha)^2\rho^2\left(1 - 2\tilde{\tau}_\zeta + \frac{\tilde{\tau}_\zeta^2}{\tau_\zeta}\right)}{(1-(1-\alpha)\rho)^2}\sigma_\zeta^2\Bigg], \end{aligned}$$

again using $\text{E}[s_{t-1}^2] = \text{Var}[s_t] = \frac{1}{1-\rho^2}\sigma_\zeta^2$ and $\sigma_\upsilon^2 = \frac{1-\tau_\zeta}{\tau_\zeta}\sigma_\zeta^2$. This shows that for i.i.d. supply shocks ($\rho = 0$), the degree of actual and perceived transparency τ_ζ and $\tilde{\tau}_\zeta$ is immaterial. For persistent supply shocks ($\rho \neq 0$), the optimal degrees of actual and perceived transparency follow from differentiating with respect to τ_ζ and $\tilde{\tau}_\zeta$, respectively:

$$\begin{aligned} \frac{\partial \text{E}[U_t]}{\partial \tau_\zeta} &= \frac{1}{2}\frac{\alpha(1-\alpha)^3\rho^2}{(1-(1-\alpha)\rho)^2}\frac{\tilde{\tau}_\zeta^2}{\tau_\zeta^2}\sigma_\zeta^2 > 0 \\ \frac{\partial \text{E}[U_t]}{\partial \tilde{\tau}_\zeta} &= -\frac{\alpha(1-\alpha)^2\rho}{(1-(1-\alpha)\rho)^2}\left[1-(1-\alpha)\rho + (1-\alpha)\rho\frac{\tilde{\tau}_\zeta}{\tau_\zeta}\right]\sigma_\zeta^2 < 0. \end{aligned}$$

As a result, it is optimal to have maximum actual transparency ($\tau_\zeta = 1$) and minimal perceived transparency ($\tilde{\tau}_\zeta = 0$).

The special case of perfect common knowledge about the degree of transparency follows from imposing the restriction that $\tilde{\tau}_\zeta = \tau_\zeta$. This yields

$$\begin{aligned}\text{Var}[\pi_t] &= \frac{(1-\alpha)^2}{(1-(1-\alpha)\rho)^2} \\ &\quad \times \left[\frac{1}{1-\rho^2} - (1-\alpha)\rho(2-(1-\alpha)\rho)(1-\tau_\zeta)\right]\sigma_\zeta^2 \\ \text{Var}[y_t] &= \frac{\alpha^2}{(1-(1-\alpha)\rho)^2} \\ &\quad \times \left[\frac{1}{1-\rho^2} - (1-\alpha)\rho(2-(1-\alpha)\rho)(1-\tau_\zeta)\right]\sigma_\zeta^2.\end{aligned}$$

In the special case in which the supply shock s_t is i.i.d. ($\rho = 0$), the variance of inflation and the output gap are again independent of the degree of transparency τ_ζ. However, for persistent supply shocks ($\rho \neq 0$), the variance of inflation and the output gap are both increasing in actual transparency, so $\text{Var}[\pi_t]$ and $\text{Var}[y_t]$ are minimized for $\tau_\zeta = 0$.

It is straightforward to see that transparency about supply shocks is detrimental under perfect common knowledge ($\tilde{\tau}_s = \tau_s$). Formally,

$$\begin{aligned}\text{E}[U_t] &= -\frac{1}{2}\alpha(1-\alpha) \\ &\quad \times \left[\frac{1}{\alpha^2}\kappa^2 + \frac{\frac{1}{1-\rho^2} - (1-\alpha)\rho(2-(1-\alpha)\rho)(1-\tau_\zeta)}{(1-(1-\alpha)\rho)^2}\sigma_\zeta^2\right].\end{aligned}$$

Again, the degree of transparency τ_ζ is immaterial when the supply shock is i.i.d. ($\rho = 0$). For persistent supply shocks ($\rho \neq 0$), $\partial\text{E}[U_t]/\partial\tau_\zeta < 0$, so minimal transparency about supply shocks ($\tau_\zeta = 0$) is optimal in the absence of transparency misperceptions.

The following statements summarize the results concerning transparency about supply shocks s_t with a New Keynesian Phillips curve:

- In the special case in which the supply shocks s_t are i.i.d. ($\rho = 0$), the degree of actual transparency τ_ζ and perceived transparency $\tilde{\tau}_\zeta$ have no effect on the variance of inflation π_t and the output gap y_t, and no effect on expected utility $\mathrm{E}[U_t]$.

- For persistent supply shocks ($\rho \neq 0$) and perfect common knowledge about the degree of transparency τ_ζ, greater transparency τ_ζ increases the variability of inflation π_t and the output gap y_t, and minimal transparency ($\tau_\zeta = 0$) is optimal.
- For persistent supply shocks ($\rho \neq 0$) and transparency misperceptions, greater actual transparency τ_ζ and smaller perceived transparency $\tilde{\tau}_\zeta$ reduce the variability of inflation π_t and the output gap y_t, and it is optimal to have maximum actual transparency ($\tau_\zeta = 1$) but minimal perceived transparency ($\tilde{\tau}_\zeta = 0$).

Clearly, when there is some persistence in the supply shock s_t, the qualitative results for the New Keynesian Phillips curve (24) are exactly the same as for the expectations-augmented Phillips curve (2) in the baseline model.

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Imperfect Common Knowledge in First-Generation Models of Currency Crises*

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First-generation models assume that the level of reserves of a central bank is common knowledge among arbitrageurs, and therefore the timing of the attack on the currency can be correctly anticipated. The collapse of the peg thus leads to no discrete change in the exchange rate. We relax the assumption of perfect information and introduce uncertainty about the willingness of a central bank to defend the peg. In this new setting, there is a unique equilibrium at which the fixed exchange rate is abandoned. The lack of common knowledge will lead to a discrete devaluation once the peg finally collapses.

JEL Codes: D82, E58, F31.

1. Introduction

Traditionally, exchange rates have been explained by macroeconomic fundamentals. However, there seem to be significant deviations from them. The need to understand these unexplained movements has drawn attention to the basic assumptions of the standard models,

*This paper is based on my 2003–04 dissertation at the London School of Economics. I am deeply indebted to Hyun Song Shin for precious advice. I am grateful to Miguel Artola for valuable and encouraging comments on an earlier draft. Also, I thank Kosuke Aoki, Markus K. Brunnermeier, Antoine Faure-Grimaud, Charles Goodhart, Bernardo Guimarães, Nobuhiro Kiyotaki, Ivan Pastine, José Scheinkman, Dimitri Vayanos, and participants at the FMG PhD seminar, the Finance Workshop at Princeton University, the IX Jornadas de Economía Internacional, the Econometric Society World Congress 2005, and the XIII Foro de Finanzas. I am thankful to the Bank of Spain for financial support and to the Economic and Social Research Council for its support under research grant RES-156-25-0026. E-mail: G.Minguez-Afonso@lse.ac.uk.

such as the homogeneity of market consumers or the irrelevance of private information.

First-generation models of currency crises assume that consumers are perfectly informed about macroeconomic fundamentals. The original model is due to Krugman (1979), who drew on the work of Salant and Henderson (1978) on the study of attacks on a government-controlled price of gold.[1] Krugman (1979) presents an economy in which the level of the central bank's foreign reserves is common knowledge among consumers. In this setting, market participants know not only the level of reserves but also that the other agents know it too. There is perfect transmission of information, and speculators can precisely coordinate the attack on the currency. The model concludes that the attack is therefore accurately predictable and implies zero devaluation. However, during currency crises, large discrete devaluations are normally observed.

In this paper, we incorporate the information structure presented in Abreu and Brunnermeier (2003)[2] to introduce uncertainty about the willingness of the central bank to defend the peg in first-generation models of currency crises. The application of Abreu and Brunnermeier's dynamic model to currency crises presents several advantages over the original setting. Firstly, it provides a reasonable explanation for the assumption that the asset's market price remains constant until the time when the bubble bursts. In our setting, the exchange rate does remain invariable until the peg collapses, and the cumulative selling pressure will not affect the fixed exchange rate until it exceeds a certain threshold and the central bank can no longer maintain the peg. Secondly, it gives a sound interpretation to the exogenous price paths, which in our model can be intuitively identified with the fixed exchange rate. Thirdly, in Abreu and Brunnermeier's model it is necessary to introduce a final condition that guarantees the burst of the asset bubble even if no arbitrageur sells his shares. In our model, the central bank will be ultimately

[1] For a review on the currency crises literature, see Flood and Marion (1999).

[2] Abreu and Brunnermeier (2003) consider an economy in which arbitrageurs learn sequentially, but in random order, that the market price has departed from fundamentals. They assumed this information structure to argue the existence and persistence of asset bubbles despite the presence of rational agents in the economy.

forced to abandon the peg when the foreign reserves are exhausted (even if no speculator attacks the currency).

We consider an economy with a fixed exchange rate regime and a persistent deficit that reduces the central bank's reserves. In this setting, we suppose a continuum of arbitrageurs who, one by one, cannot affect the exchange rate. They can choose between local and foreign currency. We assume that holding local currency generates higher returns, although there is a risk of devaluation. Arbitrageurs take their investment decisions by evaluating the trade-off between these higher profits and the fear of capital losses. At some random time, they become sequentially aware that the shadow price has exceeded the peg,[3] and they have to decide between canceling and maintaining their positions. Arbitrageurs notice the mispricing in random order, and they do not know if other arbitrageurs are also aware of it. They would prefer to hold local currency for as long as possible, since it produces higher profits, but they would not want to wait for too long because of the capital losses caused by devaluation.

We suppose that arbitrageurs have financial constraints that limit their individual maximum positions and their impact on the exchange rate. To force the exchange rate off the peg, it will be necessary to coordinate the attack on the currency. Arbitrageurs face a synchronization problem and, at the same time, a competition dilemma: only a fraction of them can leave the market before the peg collapses, because as soon as a large-enough number of arbitrageurs sell out local currency, the central bank will be forced to abandon the fixed exchange rate regime, and those who still hold local currency at that time will suffer a capital loss.

We prove that there exists a unique equilibrium in which, for moderate heterogeneity among arbitrageurs, the peg is abandoned after enough arbitrageurs have held overvalued currency for some period of time τ^* since they noticed that the fixed exchange rate lies below the shadow price. Arbitrageurs will hold a maximum long position in local currency until they fear the attack is imminent. At that time, they will sell out, causing the fall of the peg. For extreme

[3]The shadow price is the exchange rate that would prevail in the market if the peg were abandoned. This concept was originally developed by Flood and Garber (1984).

levels of dispersion of opinion among them, the fixed exchange rate regime collapses when the central bank's foreign reserves are completely exhausted. In either case, the abandonment of the peg implies a discrete devaluation of the currency. In the former, we will prove that arbitrageurs optimally hold overvalued currency for some time $\tau^* > 0$. (For their setting, Abreu and Brunnermeier (2003) state: "After becoming aware of the bubble, they [arbitrageurs] ... optimally choose to ride the bubble over some interval.") Hence, the attack will take place strictly after the shadow price exceeds the peg, causing a jump in the exchange rate. In the latter, the central bank will defend the peg until the reserves are exhausted. This will necessarily occur some time after the shadow price exceeds the peg, which will imply a discrete change in the exchange rate. In this paper we derive a first-generation model of currency crises with imperfect information, which explains the discrete jump in the exchange rate generally observed in the transition from a fixed to a floating exchange rate regime.

This paper is related to the recent literature on currency crises that incorporates private information to accommodate discrete devaluations. Guimarães (2006) introduces uncertainty in a first-generation model by assuming that agents do not know whether they would be able to escape the devaluation. He argues that there is a unique equilibrium in which agents delay their decisions to attack the currency due to these market frictions. A different approach is presented in Pastine (2002). He incorporates a forward-looking rational policymaker that dislikes speculative attacks and is capable of choosing the timing of the move to a floating exchange rate regime. Pastine (2002) shows that the monetary authority has an incentive to introduce uncertainty into the speculators' decisions in order to avoid predictable attacks on the currency. In this model, the standard perfectly predictable attack is replaced by an extended period of speculation that gradually places increasing pressure on the policymaker.

Broner (2006) relaxes the assumption of perfect information and includes a new type of investor: the uninformed consumer. The ratio between informed and uninformed consumers is fixed exogenously and determines the resulting equilibria. He concludes that if the fraction of informed consumers is high enough, market agents face a situation similar to the lack of private information. However, when the private information is high, the model arrives at a large set of equilibria, characterized by possible discrete devaluations, which differ on the informed consumers' propensity to attack the currency. In Broner's model, the threshold level of the central bank's reserves—and, therefore, the exact time when the peg is attacked—is still common knowledge among informed consumers. In a competitive environment, though, rational agents may not be willing to reveal what they know to other participants.

In independent work, Rochon (2006)[4] applies Abreu and Brunnermeier's structure to currency crises. She considers an economy with a fixed exchange rate regime in which a negative shock triggers a gradual depletion of the central bank's foreign reserves. The similarities between Rochon (2006) and our work lie in the application of Abreu and Brunnermeier's information structure to currency crises. However, our paper differs from Rochon (2006) in several ways. We consider a different setting; we assume a first-generation model, as described in Krugman (1979), in which a government runs a persistent deficit that will gradually reduce the central bank's foreign reserves. Rochon (2006) defines a model in which the central bank is committed to defend the fixed exchange rate regime, but it is not forced to finance an expansionary monetary policy. Also, we suppose that rational agents have imperfect information about the shadow price, while in Rochon (2006) the key variable is the level of reserves. From there on, the specification and focus of the model, the derivation of the unique equilibrium, and the timing of the attack are clearly different.

The paper is organized in the following order. Section 2 analyzes the Krugman model. We explain Abreu and Brunnermeier's model in section 3. Section 4 illustrates the generalization of the traditional first-generation model of currency crises. We relax the assumption of perfect information and define the new setting. Section 5 studies the resulting unique equilibrium. We derive the timing of the attack and analyze the determinants of the period of time τ^* during which arbitrageurs optimally hold overvalued domestic currency. Finally, we present our conclusions in section 6.

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[4]I am thankful to Fernando Broner for bringing this paper to my attention at the International Economics Seminar (London School of Economics, December 2004).

2. The Krugman Model

The original model of speculative attacks on fixed exchange rates is due to Krugman (1979). He considered an economy with a fixed exchange rate regime where the government runs a budget deficit that will gradually reduce the central bank's reserves. The model concludes that the peg will be abandoned before the reserves are completely exhausted. At that time, there will be a speculative attack that eliminates the lasting foreign exchange reserves and leads to the abandonment of the fixed exchange rate.

In this model, the central bank faces two different tasks. First, it must satisfy the financial needs of the government, and second, it has to maintain a fixed exchange rate. The central bank finances the deficit by issuing government debt and defends the peg through direct intervention in the foreign exchange rate market. In this economy, the asset side of the central bank's balance sheet at time t is made up of domestic credit (D_t) and the value in domestic currency of the international reserves (R_t). The balance sheet's liability side consists of the domestic currency in circulation, the money supply (M_t^s). Hence:

$$M_t^s = D_t + R_t.$$

The budget deficit grows at a constant rate μ $(\mu > 0)$:

$$\mu = \frac{\dot{D}_t}{D_t}.$$

Also assume that the purchasing parity holds:

$$S_t = \frac{P_t}{P_t^*},$$

where, at time t, P_t is the domestic price level, S_t is the exchange rate of domestic currency for foreign, and P_t^* is the foreign price level. We can fix $P_t^* = 1$, and therefore the exchange rate can be identified with the domestic price level $(P_t = S_t)$.

In this model it is supposed that money is only created through the deficit. As long as the central bank is committed to defend the peg, it will print money to finance the deficit. This will tend to raise the money supply and hence affect the domestic prices and the exchange rate. Domestic prices will begin to increase, bringing about an incipient depreciation of the currency. To maintain the exchange rate fixed, the authorities will reduce the foreign reserves to purchase the domestic currency, and foreign reserves will fall as domestic assets continually rise. Ultimately, if the budget is in deficit, pegging the rate becomes impossible, no matter how large the initial reserves were.

However, the model concludes that the attack comes *before* the stock of foreign reserves would have been exhausted in the absence of speculation. Why? In Krugman's model, consumers can correctly anticipate the exhaustion of the reserves, they can only choose between domestic and foreign money, and it is also supposed that foreigners do not hold domestic money. Then, the assumption of perfect foresight implies that speculators, anticipating an abandonment of the peg, will attack the exchange rate to acquire the central bank's reserves and to avoid a capital loss.

To determine the timing of the crisis, we introduce the following definition.

DEFINITION 1 *(Krugman and Obstfeld 2003). The shadow floating exchange rate or shadow price at time t (S_t) is the exchange rate that would prevail at time t if the central bank held no foreign reserves and allowed the currency to float but continued to allow the domestic credit to grow over time.*

In appendix 1, we derive an expression for the shadow floating exchange rate. To simplify the analysis, it is convenient to express all magnitudes in logarithms.[5] We present logarithmic versions of the previous equations and describe the monetary equilibrium by the Cagan equation. Then, the logarithm of shadow price is given by

$$s_t = \gamma + \mu \times t,$$

where γ and μ are constants, and μ is the rate of growth of the budget deficit. The time of the attack on the currency T is

[5]We use the standard notation in which an uppercase letter represents a variable in levels and a lowercase one its logarithm: $s_t = ln(S_t)$. From now on, exchange rates will be expressed in logarithms. To simplify the reasoning, we will still refer to them as fixed exchange rate and shadow price, where, to be precise, it should say fixed *log*-exchange rate and *log*-shadow price.

defined as the date on which the shadow price reaches the peg ($s_t = \overline{s}$):

$$T = \frac{\overline{s} - \gamma}{\mu}.$$

In the Krugman model, the level of the central bank's foreign reserves is common knowledge among consumers. Thus, the timing of the attack is accurately predictable, and the transition from a fixed to a floating exchange rate regime occurs without discrete jumps in the exchange rate.

3. The Abreu and Brunnermeier Model

Abreu and Brunnermeier (2003) present a model in which an asset bubble can survive despite the presence of rational arbitrageurs. They consider an information structure where rational arbitrageurs become sequentially aware that an asset's market price has departed from fundamentals and do not know if other arbitrageurs have already noticed the mispricing. The model concludes that if the arbitrageurs' opinions are sufficiently dispersed, the asset bubble bursts for exogenous reasons when it reaches its maximum size. And in the case of moderate levels of dispersion of opinion, Abreu and Brunnermeier (2003) prove that endogenous selling pressure advances the bubble collapse. They demonstrate that these equilibria are unique. Also, the model shows how news events can have a disproportionate impact on market prices, since they allow agents to synchronize their exit strategies.

This model considers two types of agents: behavioral traders (influenced by fads, fashions, overconfidence, etc.) and rational arbitrageurs. Initially the stock price p_t grows at the risk-free interest rate r ($p_t = e^{rt}$) and rational arbitrageurs are fully invested in the market. At $t = 0$, the price starts growing at a faster rate g ($g > r$). Behavioral traders believe that the stock price p_t will grow at a rate g in perpetuity. Hence, whenever the stock price falls below $p_t = e^{gt}$, they are willing to buy any quantity of shares (up to their aggregate absorption capacity κ). Then, at some random time t_0 (exponentially distributed on $[0, \infty)$), rational arbitrageurs become (in random order) sequentially aware that the price is too high. However, the price continues to grow at a rate $g > r$ and, hence, only a fraction $(1 - \beta(\cdot))$ of the price is explained by the fundamentals, where $\beta(\cdot)$ represents the "bubble component." Rational agents understand that the market will eventually collapse but still prefer to ride the bubble as it generates higher returns.

In Abreu and Brunnermeier's model, the bubble collapses as soon as the cumulative selling pressure exceeds some threshold κ (the absorption capacity of the behavioral traders) or ultimately at $t = t_0 + \overline{\tau}$ when it reaches its maximum size $(\overline{\beta})$. It is assumed that arbitrageurs, one by one, have limited impact on the price, because of the financial constraints they face. Consequently, large movements in prices require a coordinated attack. They consider that in each instant t, from $t = t_0$ until $t = t_0 + \eta$, a mass of $1/\eta$ arbitrageurs becomes aware of the mispricing, where η can be understood as a measure of the dispersion of opinion among agents concerning the timing of the bubble. Since t_0 is random, the arbitrageurs do not know how many other rational arbitrageurs have noticed the mispricing, because they will only become aware of the selling pressure when the bubble finally bursts. Rational arbitrageurs face temporal miscoordination. Then, an arbitrageur who becomes aware of this mispricing at time t_i has the following posterior cumulative distribution for the date (t_0) on which the price departed from its fundamental value, with support $[t_i - \eta, t_i]$:

$$\Phi(t_0|t_i) = \frac{e^{\lambda\eta} - e^{\lambda(t_i - t_0)}}{e^{\lambda\eta} - 1}.$$

Therefore, from $t = t_0 + \eta\kappa$ onward, the mispricing is known to enough arbitrageurs to correct it. Nevertheless, they do not attempt to, since as soon as they coordinate, the selling pressure will burst the bubble. However, there is also a competitive component in the model: only a fraction κ of the arbitrageurs will be able to sell out before the bubble collapses (because it bursts the moment the selling pressure surpasses κ). Thus, arbitrageurs also have an incentive to leave the market.

In this setting, each arbitrageur can sell all or part of his stock of shares until a certain limit due to some financial constraints. It is possible to buy back shares and to exit and reenter the market multiple times. The strategy of an agent who became aware of the bubble at time t_i is defined as the selling pressure at time t: $\sigma(\cdot, t_i) =$

$[0, t_i + \overline{\tau}] \mapsto [0, 1]$. The action space is normalized to be the continuum between $[0, 1]$, where 0 indicates a maximum long position and 1 a maximum short position. Then, the aggregate selling pressure of all agents at time $t \geq t_0$ is given by $s(t, t_0) = \int_{t_0}^{min\{t,\ t_0+\eta\}} \sigma(t, t_i) dt_i$, and therefore the bursting time can be expressed as

$$T^*(t_0) = \inf\{t | s(t, t_0) \geq \kappa \text{ or } t = t_0 + \overline{\tau}\}.$$

Given this information structure, arbitrageur t_i's beliefs about the date on which the bubble bursts are described by

$$\Pi(t_0 | t_i) = \int_{T^*(t_0) < t} d\Phi(t_0 | t_i).$$

In their analysis, Abreu and Brunnermeier (2003) focus on trigger strategies in which an agent, who sells out at t, continues to attack the bubble at all times thereafter. In this case, solving the optimization problem of the arbitrageur who notices the bubble at time t_i and sells out at time t yields the following condition.

LEMMA 1 *(Abreu and Brunnermeier 2003) (sellout condition). If arbitrageur t_i's subjective hazard rate is smaller than the "cost-benefit ratio," i.e.,*

$$h(t | t_i) < \frac{g - r}{\beta(t - T^{*-1}(t))},$$

trader t_i will choose to hold the maximum long position at t. Conversely, if $h(t|t_i) > \frac{g-r}{\beta(t-T^{*-1}(t))}$, trader t_i will trade to the maximum short position.

With this condition, $h(t|t_i) = \frac{\pi(t|t_i)}{1-\Pi(t|t_i)}$ is the hazard rate that the bubble will burst at time t, $\Pi(t|t_i)$ represents arbitrageur t_i's beliefs about the bursting date, and $\pi(t|t_i)$ denotes the associated conditional density. Abreu and Brunnermeier (2003) conclude that an arbitrageur who becomes aware of the mispricing at time t_i will hold a maximum long position until his subjective hazard rate becomes larger than the cost-benefit ratio. That is, arbitrageur t_i will ride the bubble until his subjective probability that the bubble will burst in the next trading round is high enough. At that time, arbitrageur t_i will trade to the maximum short position to get out of the market.

They consider two different scenarios. When arbitrageurs' opinions are sufficiently dispersed, Abreu and Brunnermeier (2003) prove that the selling pressure does not affect the time when the bubble collapses, because each arbitrageur optimally rides the bubble for so long that, at the end of the horizon ($t = t_0 + \overline{\tau}$), there is not enough pressure to burst the bubble (less than κ will have sold out). They show that there is a unique equilibrium at which the bubble bursts for exogenous reasons at $t = t_0 + \overline{\tau}$. A different conclusion is reached when a moderate level of heterogeneity is assumed. In this case, they demonstrate that there is a unique and symmetric equilibrium in which each arbitrageur sells his shares τ^* periods after becoming aware of the mispricing. The bubble bursts at $t = t_0 + \eta\kappa + \tau^*$ ($< t_0 + \overline{\tau}$, given small values for η).

The model assumes an information structure based on the lack of common knowledge (when an arbitrageur becomes aware of the mispricing, that arbitrageur does not know if others know) and derives that these equilibria are unique. However, in typical applications, the symmetry information game has multiple equilibria. Abreu and Brunnermeier (2003) argue that the fact that arbitrageurs are competitive (since at most a fraction of them can leave the market prior to the crash) leads to a unique equilibrium even under symmetric information.

4. Imperfect Common Knowledge

This section presents a first-generation model of currency crises in which the traditional assumption of perfect information is relaxed. We introduce the new setting, and we derive the sellout condition that determines the moment when an arbitrageur fears the abandonment of the peg and prefers to attack the currency.

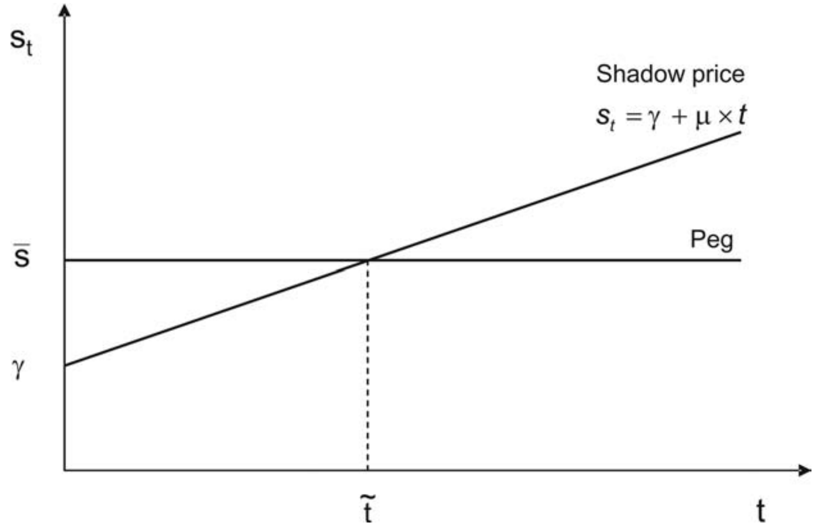
Consider an economy similar to the one described in Krugman (1979) and summarized in section 2. In this setting, the level of the central bank's foreign reserves is common knowledge among arbitrageurs and, therefore, the peg is attacked whenever it leads to no discrete change in the price level, i.e., as soon as the shadow price reaches the fixed exchange rate ($s_t = \overline{s}$). In our model, we incorporate the information structure presented in Abreu and Brunnermeier

(2003) (and reviewed in section 3) to introduce uncertainty about the willingness of the central bank to defend the peg. We consider that the level of reserves is no longer common knowledge among arbitrageurs, and in this paper we analyze the consequences of this uncertainty on the abandonment of the fixed exchange rate.

4.1 The Model

The following process is assumed in our setting. The central bank establishes the fixed exchange rate at a certain level $\overline{s}$ as depicted in figure 1. We denote (the logarithm of) the shadow price by s_t.[6]

Figure 1. Fixed Exchange Rate ($\overline{s}$) and Shadow Price (s_t)



Note: We represent a fixed exchange rate regime in which the central bank finances a persistent deficit and maintains the exchange rate fixed at a certain level ($\overline{s}$). We plot the random time $t = \widetilde{t}$, when (the logarithm of) the shadow price (s_t) reaches the peg ($\overline{s}$).

[6]In appendix 1, we prove that the logarithm of the shadow price is a linear function of time ($s_t = \gamma + \mu \times t$) or, equivalently, that the shadow price grows exponentially.

We assume that $\widetilde{t}$ is exponentially distributed on $[0, \infty)$ with cumulative distribution function $\mathrm{F}(\widetilde{t}) = 1 - e^{-\lambda \widetilde{t}}$ $(\lambda > 0, \widetilde{t} \geq 0)$. Prior to $t = \widetilde{t}$, the peg lies above the shadow price s_t $(\overline{s} > s_t)$, and the fixed exchange rate cannot collapse, since arbitrageurs would only attack the peg if it was profitable for them. If before $t = \widetilde{t}$ the peg is abandoned, the currency would immediately revaluate to reach the shadow price (the local currency would be worth more while arbitrageurs hold short positions in domestic currency). Hence, anticipating this capital loss, arbitrageurs will not attack the currency, and therefore no speculative attack will occur before $t = \widetilde{t}$. From $t = \widetilde{t}$ onward, the shadow price exceeds the fixed exchange rate $(\overline{s} < s_t)$, and the peg might be attacked.

4.1.1 Agents and Actions

In our model, there is only one type of agent: the rational arbitrageurs. We assume a continuum of arbitrageurs, with mass equal to one, who one by one cannot affect the exchange rate because of some financial constraints that limit their maximum market positions. In currency crises, however, it may seem more realistic to consider that only a few relevant institutions actively participate in currency markets and that information might be clustered. This assumption would not modify the intuition of our results. Brunnermeier and Morgan (2004) prove that the equilibrium delay in such games always exceeds equilibrium delay in the game with a continuum of agents and no information clustering (i.e., in the Abreu and Brunnermeier model). Hence, defining a finite number of arbitrageurs and allowing for information clustering increases the optimal waiting time τ^*, and therefore it delays longer the attack on the fixed exchange rate regime, causing a larger discrete devaluation of the home currency.

Let us denote by arbitrageur i the agent who, at time t_i, receives a signal indicating that the shadow price exceeds the fixed exchange rate. Arbitrageur i may take one of two actions—hold local currency or buy foreign currency. Investing in domestic currency generates a return equal to r, while the foreign investment yields r^*. We impose the following condition.

Assumption 1. *$r > r^*$.*

We consider that the local currency pays an interest rate r higher than the foreign currency ($r > r^*$) to guarantee that, initially, arbitrageurs invest in domestic currency. Hence, in our economy, rational arbitrageurs originally prefer to invest in domestic currency because of the higher profits, but they understand that the exchange rate will be attacked and the peg eventually abandoned. Therefore, the only decision is when to exit. Selling too early leads to less profitable outcomes, but if they wait too long and they do not leave the market before the fixed exchange rate collapses, they will incur capital losses associated with the devaluation.

An individual arbitrageur is limited in the amount of currency he can buy or sell. As in Abreu and Brunnermeier (2003), we can normalize the action space to lie between $[0, 1]$ and define the strategy of arbitrageur i by his selling pressure at time t: $\sigma(\cdot, t_i) = [0, t_i + \overline{\tau}] \mapsto [0, 1]$. A selling pressure equal to 0 ($\sigma(t, t_i) = 0$) indicates a maximum long position in local currency, and a value equal to 1 ($\sigma(t, t_i) = 1$) implies that arbitrageur i has sold out all his holdings of domestic currency (maximum pressure). Let $s(t, \widetilde{t})$ denote the aggregate selling pressure of all arbitrageurs at time $t \geq \widetilde{t}$.

4.1.2 Collapse of the Peg

The fixed exchange rate can collapse for one of two reasons. It is abandoned at $t = \widetilde{t} + \tau^* + \eta\kappa$ when the aggregate selling pressure exceeds a certain threshold κ ($s(t, \widetilde{t}) \geq \kappa$) or ultimately at a final time when all foreign reserves are exhausted, say at $t = \widetilde{t} + \overline{\tau}$. Let us denote this collapsing date by $T^*(\widetilde{t}) = \widetilde{t} + \zeta$, where $\zeta = \tau^* + \eta\kappa$ if the abandonment of the peg is caused by arbitrageurs' selling pressure (endogenous collapse) and $\zeta = \overline{\tau}$ if it is due to the exhaustion of reserves (exogenous collapse). Since we have assumed that arbitrageurs have no market power, they will need to coordinate to force the abandonment of the peg. However, only a proportion $\kappa < 1$ of arbitrageurs can exit the market before the peg is abandoned. Therefore, arbitrageurs face both cooperation and competition.

4.1.3 Information Structure

To simplify the analysis, we assume that at the random time $t = \widetilde{t}$ when the shadow price reaches the peg, arbitrageurs begin to notice this mispricing. They become aware sequentially and in random order, and they do not know if they have noticed it early or late compared to others. They cannot know if they are the first or the last to know. Specifically, at each instant (between $\widetilde{t}$ and $\widetilde{t}+\eta$), a new mass $1/\eta$ of arbitrageurs receives a signal indicating that the shadow price exceeds the fixed exchange rate, where η is a measure of the dispersion of opinion among them. The timing of arbitrageur i's signal is uniformly distributed on $[\widetilde{t}, \widetilde{t}+\eta]$, but since $\widetilde{t}$ is exponentially distributed, each arbitrageur does not know how many others have received the signal before him. Arbitrageur i only knows that at $t = t_i + \eta$ all other arbitrageurs received their signals. Conditioning on $\widetilde{t} \in [t_i - \eta, t_i]$, arbitrageur i's posterior cumulative distribution function for the date $\widetilde{t}$ on which the shadow price reached the peg is $\Phi(\widetilde{t}|t_i) = \frac{e^{\lambda\eta} - e^{\lambda(t_i - \widetilde{t})}}{e^{\lambda\eta}-1}$. Then, arbitrageur i's posterior cumulative distribution function over the collapsing date $T^*(\widetilde{t})$ is

$$\Pi(T^*(\widetilde{t})|t_i) = \frac{e^{\lambda\eta} - e^{\lambda(t_i+\zeta-T^*(\widetilde{t}))}}{e^{\lambda\eta}-1},$$

given that $T^*(\widetilde{t}) \in [t_i + \zeta - \eta, t_i + \zeta]$.

4.1.4 Further Assumptions

We consider the following statements to simplify the analysis and the specification of our setting.

ASSUMPTION 2. *In equilibrium, an arbitrageur holds either a maximum long position or a maximum short position in local currency:* $\sigma(t, t_i) \in \{0, 1\}\ \forall\ t, t_i$.

We consider that an arbitrageur prefers to invest his whole budget in local currency, since it generates higher returns, until a certain time when he fears that the attack on the currency is imminent and decides to cancel his position by selling all his stock of domestic currency. Hence, his selling pressure is initially equal to zero (when he is fully invested in domestic currency) and equal to one once he sells out. The information structure considered in our model and assumption 2 implies the following result.

COROLLARY 1. *If arbitrageur* i *holds a maximum short position at time* t *in local currency* $(\sigma(t, t_i) = 1)$*, then at time* t *any arbitrageur* j $(\forall t_j \leq t_i)$ *has already sold out his stock of domestic currency* $(\sigma(t, t_j) = 1,\ \forall t_j \leq t_i)$*.*

We assume that once an arbitrageur sells his stock of domestic currency, any arbitrageur that became aware of the mispricing before him is already out of the market.

ASSUMPTION 3. *No reentry.*

To simplify the analysis, we suppose that once an arbitrageur gets out of the market, he will not enter again. Intuitively, an arbitrageur sells out when he believes that the attack is close. Then, even if he does not observe the attack during some period of time after leaving the market, he still will not know when the fixed exchange rate will collapse, but certainly it will happen sooner than he thought when he exited the market. Therefore, if he does not change his beliefs, he will not have an incentive to reenter the market.

4.1.5 The Sellout Condition

In our economy, an arbitrageur can choose between buying domestic or foreign currency. Initially, each arbitrageur is fully invested in local currency because of the higher returns $(r > r^*)$, but there is a risk of devaluation. Hence, each arbitrageur will sell exactly at the moment when the fear of the devaluation of the home currency offsets the excess of return derived from investing in local currency. Ideally, the arbitrageur would like to sell *just* before the exchange rate is abandoned and the domestic currency suffers devaluation or, equivalently, just before the appreciation of the foreign currency. In appendix 2, we define the size of the expected appreciation of the foreign currency perceived by arbitrageur i as $A_f^i(t - t_i) = \left| E\left[\frac{\frac{1}{S_t} - \frac{1}{\overline{S}}}{\frac{1}{\overline{S}}} \middle| t_i \right] \right| = 1 - E\left[\frac{\overline{S}}{S_t} | t_i \right] \geq 0$ $\left(\text{if } E\left[\frac{\overline{S}}{S_t} | t_i \right] \leq 1\right)$, and we present the optimization problem that yields the following sellout condition.

LEMMA 2 *(sellout condition). Arbitrageur* i *prefers to hold a maximum long position in local currency at time* t *if his hazard rate is* *smaller than the "greed-to-fear ratio," i.e., if*

$$h(t|t_i) < \frac{r - r^*}{1 - E\left[\frac{\overline{S}}{S_t}|t_i\right]} = \frac{r - r^*}{A_f^i(t - t_i)}.$$

He trades to a maximum short position in local currency, if $h(t|t_i) > \frac{r-r^*}{A_f^i(t-t_i)}$.

In our model, an arbitrageur who notices the mispricing at time $t = t_i$ compares his subjective hazard rate $(h(t|t_i))$ with the "greed-to-fear ratio" $\left(\frac{r-r^*}{A_f^i(t-t_i)}\right)$ and trades to a maximum short position as soon as he observes that the probability of devaluation given that the peg still holds is larger than the "greed-to-fear ratio."

5. Equilibrium

The exchange rate collapses as soon as the cumulative selling pressure exceeds a threshold κ or at a final date $t = \widetilde{t} + \overline{\tau}$ when all foreign reserves are exhausted. This statement implies that no fixed exchange rate regime in an economy with persistent deficit can survive in the long term. We will focus our analysis on the first scenario, in which the peg collapses for endogenous reasons.

5.1 Endogenous Collapse of the Peg

We have seen that arbitrageurs become aware of the mispricing in random order during an interval $[\widetilde{t}, \widetilde{t} + \eta]$, where $\widetilde{t}$ is exponentially distributed and represents the time when the shadow price reaches the peg. To simplify the analysis, we have supposed that $\widetilde{t}$ is also the moment when the first arbitrageur notices the mispricing. η is a measure of the heterogeneity of the arbitrageurs (a larger η corresponds to a wider dispersion of opinion among them). Since all arbitrageurs are ex ante identical, we restrict our attention to symmetric equilibria. Then, for moderate values of the parameter η, we will show that there exists a unique symmetric equilibrium in which the peg falls when the aggregate selling pressure surpasses a certain threshold (κ).

Consider the following backward reasoning. If at the final date $t = \widetilde{t} + \overline{\tau}$ the selling pressure has not exceeded the threshold κ, we have assumed that the exchange rate collapses because the central bank's foreign reserves are exhausted, and that this final condition is common knowledge among all arbitrageurs.[7] This induces arbitrageur i to sell out at τ_1 periods after he observes the mispricing ($t_i + \tau_1 < \widetilde{t} + \overline{\tau}$) in order to avoid a capital loss. Therefore, the currency will come under attack at $t = \widetilde{t} + \tau_1 + \eta\kappa < \widetilde{t} + \overline{\tau}$ (since we consider small values of the parameters η and κ). But if the peg is abandoned at $t = \widetilde{t} + \tau_1 + \eta\kappa$, arbitrageurs will sell out earlier, let us say $\tau_2 < \tau_1$ periods after they notice that the shadow price exceeds the peg. But given the new timing, arbitrageurs will choose to sell even earlier (τ_3) and so on. As the selling date advances, the cost of devaluation of the domestic currency (or the appreciation of the foreign currency) diminishes and, therefore, the benefit from holding local currency rises—that is, the "greed-to-fear ratio" increases as the selling date advances. In our setting, at each instant, an arbitrageur compares his hazard rate to his "greed-to-fear ratio." He will prefer to sell local currency until the time ($t = t_i + \tau^*$) when the "greed-to-fear ratio" equals the probability of the peg collapsing, given that it still holds (the equality defines the switching condition). This guarantees that arbitrageurs will have an incentive to hold "overvalued" local currency for some period of time after they become aware of the mispricing or, equivalently, that the decreasing sequence of periods converges to $\tau^* > 0$. This result is depicted in figure 2.

We can derive an expression for τ^* from previous results. We have assumed that, in equilibrium, an arbitrageur holds either a maximum long position or a maximum short position in local currency, depending on the relation between the probability of the peg collapsing and the profits derived from holding local currency.

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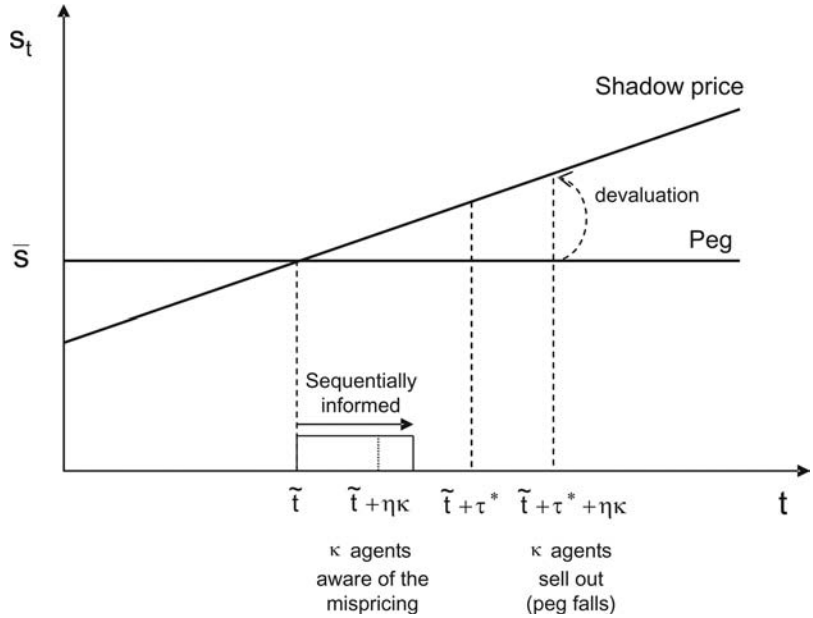
[7]Specifically, $\overline{\tau}$ is common knowledge among arbitrageurs but not $t = t_i + \overline{\tau}$, which will depend on the random time when each arbitrageur notices the mispricing. It is supposed that once an arbitrageur finds out that the shadow price has exceeded the peg, he knows that the central bank's foreign reserves will last *at most* $\overline{\tau}$ periods, and he also knows that all other arbitrageurs, who are aware of the mispricing, will know it too. But this arbitrageur does not know if he has learned this information early or late compared to the other arbitrageurs, and hence he does not know if the attack on the currency will happen before this final date.

Figure 2. Collapse of the Peg (Moderate Levels of Dispersion of Opinion)



Note: We plot (the logarithm of) the fixed exchange rate ($\overline{s}$), (the logarithm of) the shadow price (s_t), and relevant moments in time. At $t = \widetilde{t}$, the shadow price exceeds the peg and arbitrageurs become sequentially aware of it. At $t = \widetilde{t} + \eta\kappa$, enough arbitrageurs have noticed the mispricing, but they prefer to wait τ^* periods before selling out. At $t = \widetilde{t} + \tau^* + \eta\kappa$, the selling pressure surpasses the threshold κ and the peg is finally abandoned. There is a discrete devaluation of the exchange rate.

Hence, we can obtain τ^* from the time ($t = t_i + \tau^*$) when agent i will switch from maximum holding to maximum selling. This is given by

$$\tau^* = \frac{1}{\mu} \ln \left[\left(1 - \frac{r - r^*}{h} \right)^{-1} \right] - \tau',$$

where $r - r^*$ is the excess of return, $h = h(t|t_i)$ denotes the hazard rate (which we will prove remains constant over time), μ is a positive constant corresponding to the slope of the linear logarithm of the shadow price (s_t) that represents the rate of growth of the budget deficit, and τ' is indicative of the difference between the date t_i at which the arbitrageur receives the signal about the mispricing and the time when he believes the foreign currency begins appreciating.

We can summarize this result in proposition 1.

PROPOSITION 1. *There exists a unique symmetric equilibrium at which each arbitrageur sells out τ^* periods after becoming aware of the mispricing, where*

$$\tau^* = \frac{1}{\mu} \ln \left[\left(1 - \frac{r - r^*}{h} \right)^{-1} \right] - \tau'.$$

Thus, the fixed exchange rate will be abandoned at $t = \widetilde{t} + \tau^* + \eta\kappa$.

Proof. Arbitrageur i prefers to invest in local currency for as long as possible, since this strategy generates higher returns than buying foreign currency ($r > r^*$). But, at a certain moment in time ($t = t_i$), he learns that the shadow price exceeds the peg and that there exists a risk of devaluation. We have argued that he still prefers to hold domestic currency (for some period of time τ^*) until he fears that the attack on the currency is imminent and he decides to sell out. This occurs at $t = t_i + \tau^*$. Arbitrageur i sells whenever his "greed-to-fear ratio" equals his hazard rate, i.e., when $h(t|\widetilde{t}) = \frac{r - r^*}{A^i_f(t - t_i)}$. From this switching condition, we will derive the optimal waiting time τ^*, i.e., the period of time when an arbitrageur knows that he is holding overvalued currency.

We will organize the proof in three steps. In the first step, we demonstrate that the "greed-to-fear ratio" is decreasing in time. Step 2 shows why the hazard rate is constant in time. Finally, in step 3 we derive the expression for τ^* from the time when the hazard rate equals the "greed-to-fear ratio" and arbitrageur i changes from a maximum long position to a maximum short position in local currency.

STEP 1. *The "greed-to-fear ratio" decreases in time.*

Proof. The "greed-to-fear ratio" is defined as

$$\frac{r - r^*}{A^i_f(t - t_i)},$$

where $r-r^*$ is the excess of return derived from investing in domestic currency and $A^i_f(t-t_i)$ denotes the size of the expected appreciation of the foreign currency feared by agent i:

$$A^i_f(t - t_i) = \left| E\left[\frac{\frac{1}{S_t} - \frac{1}{\overline{S}}}{\frac{1}{\overline{S}}} \middle| t_i \right] \right| = 1 - E\left[\frac{\overline{S}}{S_t} \middle| t_i \right]$$

and

$$E\left[\frac{\overline{S}}{S_t} \middle| t_i \right] = \int_{t_i - \eta}^{t_i} e^{-\mu(t - \widetilde{t})} \phi(\widetilde{t}|t_i) d\widetilde{t} = k e^{-\mu(t - t_i)},$$

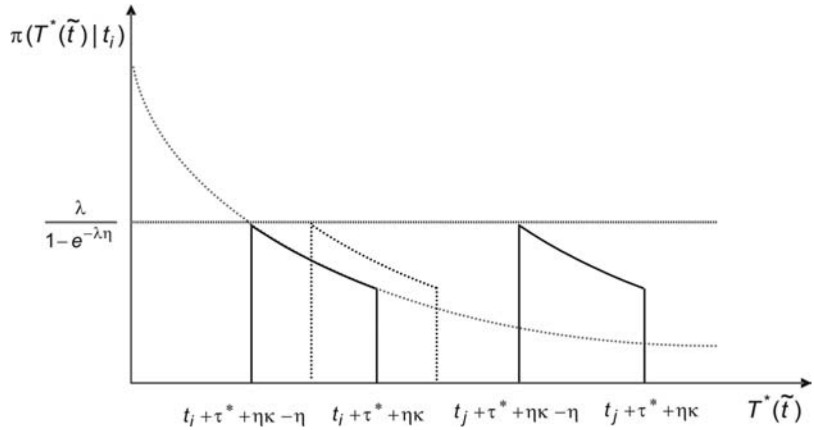
where $k = \frac{\lambda}{\lambda - \mu} \frac{e^{(\lambda - \mu)\eta} - 1}{e^{\lambda\eta} - 1}$, $k \in [0, 1]$ for $\lambda \geq \mu$. Hence, $A^i_f(t - t_i)$ is a strictly increasing and continuous function of the time elapsed since agent i received his signal indicating that the shadow price exceeded the peg.

Assumption 1 establishes that the excess of return $(r - r^*)$ is positive and constant in time. Therefore the "greed-to-fear ratio," $\frac{r - r^*}{A^i_f(t - t_i)}$, decreases in time. Intuitively, the further in time, the larger the possible appreciation of the foreign currency once the peg collapses, and therefore the smaller the benefits (in relative terms) that a rational agent obtains from holding local currency. Thus, the "greed-to-fear ratio" will decrease in time.

STEP 2. *The hazard rate is constant in time.*

Proof. The hazard rate is defined as $h(T^*(\widetilde{t})|t_i) = \frac{\pi(T^*(\widetilde{t})|t_i)}{1 - \Pi(T^*(\widetilde{t})|t_i)}$, where $\pi(T^*(\widetilde{t})|t_i)$ is the conditional density function and $\Pi(T^*(\widetilde{t})|t_i)$ is the conditional cumulative distribution function of the date on which the peg collapses. The hazard rate represents, at each time, the probability that the peg is abandoned, given that it has survived until $t = t_i$. We have considered that the timing of agent i's signal is uniformly distributed on $[\widetilde{t}, \widetilde{t} + \eta]$ and that $\widetilde{t}$ is exponentially distributed. Then, an arbitrageur who becomes aware that

Figure 3. Posterior Density Function for Arbitrageurs *i* and *j*



the shadow price exceeds the peg at $t = t_i$ has a posterior density function of the date on which the peg is abandoned, with support $[t_i + \tau^* + \eta\kappa - \eta, t_i + \tau^* + \eta\kappa]$, given by $\pi(T^*(\widetilde{t})|t_i) = \frac{\lambda e^{\lambda(t_i+\zeta-T^*(\widetilde{t}))}}{e^{\lambda\eta}-1} = \frac{\lambda e^{\lambda(t_i+\tau^*+\eta\kappa-T^*(\widetilde{t}))}}{e^{\lambda\eta}-1}$, where $\zeta = \tau^* + \eta\kappa$ if the peg collapses for endogenous reasons. This is depicted in figure 3.

At time $t = t_i$, arbitrageur i only knows if the peg has collapsed or not. But if the fixed-rate regime has not been attacked, arbitrageur i cannot know when it will happen, since he does not know if any other agent became aware of the mispricing before him. At any other time $t = t_j > t_i$, arbitrageur j faces an equivalent scenario (shifted from t_i to time t_j, but with no additional information); i.e., arbitrageurs cannot learn from the process (if the peg has not collapsed, they cannot know when the attack will take place). Therefore, the hazard rate, over the collapsing dates $t = t_i + \tau^*$, is constant in time and is given by the following expression:

$$h(t_i + \tau^*|t_i) = \frac{\lambda}{1 - e^{-\lambda\eta\kappa}} \equiv h.$$

STEP 3. *The optimal* τ^* *is given by* $\tau^* = \frac{1}{\mu} \ln \left[\left(1 - \frac{r-r^*}{h}\right)^{-1}\right] - \tau'$.

Proof. We have obtained that the "greed-to-fear ratio" is a decreasing function of time, while the hazard rate is constant. Therefore, we can derive τ^* from the time $t = t_i + \tau^*$ when arbitrageur i fears that the collapse of the peg is imminent and decides to sell out the local currency. We have proved that he will hold local currency during τ^* periods after becoming aware of the mispricing; i.e., arbitrageur i will hold a long position in local currency until $t = t_i + \tau^*$, when his "greed-to-fear ratio" equals his hazard rate:

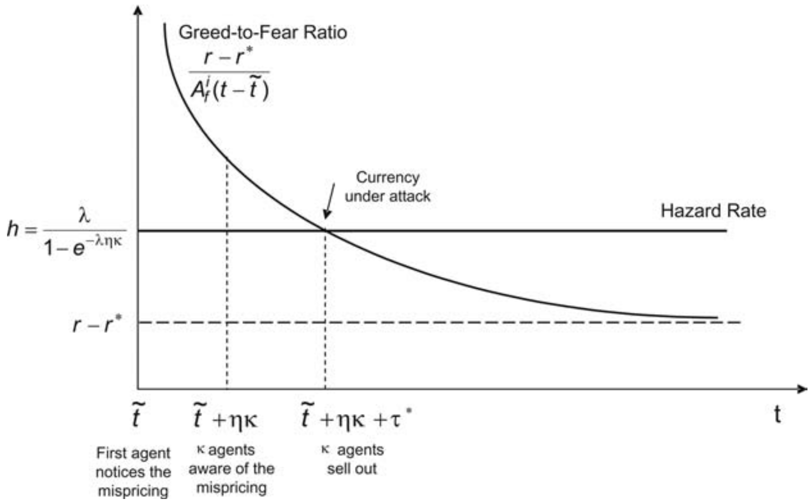
$$\underbrace{\frac{r-r^*}{A_f^i(t-t_i)}}_{\substack{Greed\text{-}to\text{-}Fear\\ Ratio}}\Bigg|_{t=t_i+\tau^*} = \underbrace{\frac{\lambda}{1-e^{-\lambda\eta\kappa}}}_{Hazard\ \ Rate} \Rightarrow \frac{r-r^*}{1-ke^{-\mu(t_i+\tau^*-t_i)}} = h \Rightarrow$$

$$\Rightarrow \tau^* = \frac{1}{\mu}\ln\left[\left(1-\frac{r-r^*}{h}\right)^{-1}\right] - \tau' \Rightarrow \tau^* = \frac{1}{\mu}\ln\left[\frac{h}{h-(r-r^*)}\right] - \tau',$$

where $\tau' = \frac{1}{\mu}\ln\frac{1}{k} \in [0,\infty)$. The optimal waiting time τ^* has two components. The first one defines the trade-off between the excess of return derived from investing in domestic currency and the capital loss borne by arbitrageur i if the fixed exchange rate is abandoned before he sells out. The second component τ' is due to the information structure and measures the period of time elapsed between the date $t = t_i$ at which arbitrageur i receives the signal and the time when he believes that the foreign currency starts appreciating. To simplify the reasoning, suppose that there is no delay; i.e., assume that at $t = t_i$ arbitrageur i receives the signal about the mispricing and believes that the shadow price has "just" reached the peg. In this case, $\tau' = 0$, and each arbitrageur waits $\tau^* = \frac{1}{\mu}\ln\left[\left(1-\frac{r-r^*}{h}\right)^{-1}\right]$ after receiving the signal. Then, he exits the market.

Figure 4 represents the decreasing "greed-to-fear ratio," the hazard rate, τ^*, and the time of the attack. It is interesting to note that if the hazard rate is larger than the excess of return ($h > r - r^*$), arbitrageurs wait a finite positive period of time ($\tau^* > 0$) before selling out. At some point in time, they believe that the attack on the fixed exchange rate is imminent and they cancel their positions in home currency. There is an endogenous collapse of the peg. However, if $h = r - r^*$, arbitrageurs sell overvalued currency after waiting for an infinite time ($\tau^* = \infty$) to elapse since receiving the signal.

Figure 4. Timing of the Attack



Note: An arbitrageur holds a maximum long position in local currency until he believes that the attack is imminent and he prefers to sell out—that is, when his "greed-to-fear ratio" equals his hazard rate. At $t = \tilde{t}+\tau^*+\eta\kappa$, *enough* arbitrageurs have sold out and the currency comes under attack.

Finally, if $h < r - r^*$, arbitrageurs never sell, i.e., if the probability that the peg collapses (given that it still holds) is lower than the excess of return derived from investing in domestic currency, then arbitrageurs do not fear a devaluation, and hence they never leave the market. In this case ($h \leq r - r^*$), the fixed exchange rate collapses for exogenous reasons when the central bank's foreign reserves are exhausted.

5.2 Determinants of τ^*

Excess of Return. The period of time τ^* during which arbitrageurs optimally hold overvalued local currency depends directly on the excess of return derived from investing in domestic currency. Increasing the spread between returns $(r - r^*)$ delays the attack on the peg, since a more attractive local currency will induce arbitrageurs to hold overvalued currency for a longer time. The size of the delay depends on

$$\frac{\partial \tau^*}{\partial (r - r^*)} = \frac{1}{\mu} \cdot \frac{1}{h - (r - r^*)}.$$

This suggests that rising returns will have a small impact on the delay of the attack if the probability of the peg collapsing (given that it still holds) and the slope of the (logarithm of the) shadow price are high.

Hazard Rate. τ^* is a decreasing function of the hazard rate ($\frac{\partial \tau^*}{\partial h} < 0$). The hazard rate represents the probability that the fixed exchange rate is abandoned, given that the peg is still in place. Assuming the information structure presented in this paper, the hazard rate remains constant over time[8] and equal to

$$h = \frac{\lambda}{1 - e^{-\lambda \eta \kappa}},$$

where λ characterizes the exponential distribution of $\widetilde{t}$ (the time when the shadow price exceeds the peg), η is a measure of the dispersion of opinion among agents, and κ defines the threshold level of cumulative selling pressure that triggers the attack on the currency.

A lower heterogeneity among market participants increases the hazard rate and advances the currency crises. In the limit, as η tends to zero (no private information), we converge to the Krugman setting in which the fundamentals are common knowledge and the peg is attacked as soon as the shadow price reaches the fixed exchange rate. In this case, $h \to \infty$ and $\tau^* = 0$. On the other extreme case where there is large dispersion of opinion among arbitrageurs, the hazard rate tends to zero and the peg is abandoned whenever the central bank's foreign reserves are exhausted.

Also, a higher threshold κ delays the crisis. If the central bank is determined to commit a larger proportion of its foreign reserves to defend the fixed exchange rate, the peg will survive longer.

Slope of the Shadow Price. The optimal time τ^* depends inversely on the slope of (the logarithm of) the shadow price μ ($\frac{\partial \tau^*}{\partial \mu} < 0$). μ can be seen as the speed of depletion of the central

[8] This is proved in subsection 5.1.

bank's foreign reserves. This suggests that a steeper (logarithm of the) shadow price implies a faster rate of exhaustion of reserves and, ultimately, that the central bank's reserves will be exhausted earlier. Hence, a higher slope reduces τ^* and advances the attack on the fixed exchange rate.

μ also represents the rate of growth of the government's budget deficit. Then, the faster the level of the government's expenditure, the shorter arbitrageurs will be willing to hold the overvalued local currency, hence advancing the attack on the currency.

Our analysis suggests that in a first-generation model in which a government runs a persistent deficit, which grows at a constant rate μ, raising the spread between returns to make the local currency more attractive, committing more foreign reserves to defend the peg, and inducing dispersion of opinion among arbitrageurs will delay the attack on the currency. However, since the expansionary monetary policy makes a fixed exchange rate ultimately unsustainable, these policy instruments would only increase the size of the devaluation whenever it occurs. The only effective means would be to reduce the rate of growth of the budget deficit (μ). This would delay the speculative attack on the fixed exchange rate and diminish the size of the devaluation when the peg finally collapses.

6. Conclusion

In this paper, we relax the traditional assumption of perfect information in first-generation models of currency crises. We consider an economy similar to the one described in Krugman (1979) and, to introduce uncertainty about the willingness of a central bank to defend the peg, we incorporate the information structure presented in Abreu and Brunnermeier (2003).

At a random time, the shadow price exceeds the fixed exchange rate and sequentially, but in random order, arbitrageurs become aware of this mispricing. They understand that the currency will be attacked and the peg eventually abandoned, but still prefer to hold local currency during some period of time (τ^*) after they notice the mispricing, since we have assumed that holding domestic currency generates higher returns. We derive an expression for τ^*. The optimal period of time τ^* is the same for all arbitrageurs, and it is independent from the time when each arbitrageur notices the mispricing. Increasing the excess of return $(r - r^*)$ obtained from investing in domestic currency, reducing the hazard rate or diminishing the level of persistent deficit, would increase the period of time when arbitrageurs prefer to hold overvalued local currency and therefore would delay the attack on the currency.

In our model, arbitrageurs sequentially know that the peg lies below the shadow price, but they do not know if other arbitrageurs have already noticed it; i.e., macroeconomic fundamentals are no longer common knowledge among market participants. Therefore, arbitrageurs in this economy face a synchronization problem. However, they do not have incentives to coordinate, since as soon as they do, the peg collapses. There is also a competitive component in our model: only a fraction κ of arbitrageurs can leave the market before the fixed exchange rate is abandoned. Consequently, in our setting, the currency does not come under attack the moment the shadow price exceeds the peg, as in Krugman's model, but at a later time when a large-enough mass of arbitrageurs has waited τ^* periods and decides to leave the market because of fear of an imminent attack.

We conclude that there is a unique equilibrium in which the fixed exchange rate collapses when the selling pressure surpasses a certain threshold (κ) or ultimately at a final date $t = \widetilde{t} + \overline{\tau}$, when the central bank's foreign reserves are exhausted, if dispersion of opinion among arbitrageurs is extremely large. This equilibrium is unique, depends on the heterogeneity among agents, and leads to discrete devaluations. This result differs from the zero-devaluation equilibrium in Krugman's model and also from other settings (Broner 2006) in which lack of perfect information brings multiple equilibria.

Appendix 1. The Shadow Price

In this section, we will derive an expression for the shadow price in a first-generation model of currency crises. To simplify the calculations, it is convenient to express magnitudes in logarithms. We will use uppercase letters to represent a variable in levels and lowercase letters to indicate its logarithm.

We consider an economy with a fixed exchange rate regime $(\overline{s} = ln(\overline{S}))$, in which a government runs a persistent deficit.

In particular, we assume that it grows at a positive constant rate μ:

$$\mu = \frac{\dot{D}_t}{D_t} = \frac{1}{D_t}\frac{d(D_t)}{dt} = \dot{d}_t \Rightarrow \dot{d}_t = \mu, \tag{1}$$

where $d_t = ln(D_t)$ is the logarithm of the domestic credit.

The central bank has two main tasks: to finance the government's deficit by issuing debt and to maintain the exchange rate fixed through open market operations. In our economy there are no private banks. Then, from the central bank's balance sheet, the money supply at time t, M_t^s, is made up of domestic credit (D_t) and the value in domestic currency of the international reserves (R_t):

$$M_t^s = D_t + R_t. \tag{2}$$

We assume that the purchasing parity holds. Then, the exchange rate S_t is defined as

$$S_t = \frac{P_t}{P_t^*} \Rightarrow s_t = p_t - p_t^*.$$

We can take the foreign price as the numeraire $(P_t^* = 1 \Rightarrow p_t^* = 0)$. Then,

$$s_t = p_t. \tag{3}$$

The monetary equilibrium is described by the Cagan equation:

$$m_t^s - p_t = -\delta \times \dot{p}_t.$$

By equation (3), the Cagan equation can then be written as

$$m_t^s - s_t = -\delta \times \dot{s}_t. \tag{4}$$

The shadow price is the exchange rate that would prevail in the market if the peg is abandoned. The central bank will defend the peg until reserves reach a minimum level. To simplify the analysis, assume that the central bank abandons the fixed exchange rate when the reserves are exhausted, i.e., when $R_t = 0$. Then, the money supply (equation (2)) is given by

$$M_t^s = D_t \Rightarrow m_t^s = d_t. \tag{5}$$

Equations (1) and (5) imply

$$\dot{m_t^s} = \dot{d_t} = \mu \Rightarrow m_t^s = m_0^s + \mu \times t.$$

Hence, substituting this result in equation (4), we obtain

$$m_0^s + \mu \times t - s_t = -\delta \times \dot{s_t} \Rightarrow m_0^s + \mu \times t - s_t + \delta \times \dot{s_t} = 0.$$

To solve this differential equation, we can try a linear solution:

$$s_t = constant + \mu \times t.$$

Then,

$$m_0^s + \mu \times t - constant - \mu \times t + \delta \times \mu = 0 \Rightarrow constant = m_0^s + \delta \times \mu.$$

Therefore, (the logarithm of) the shadow price is given by

$$s_t = \underbrace{m_0^s + \delta \times \mu}_{\gamma} + \mu \times t = \gamma + \mu \times t \Rightarrow s_t = \gamma + \mu \times t, \qquad (6)$$

where γ and μ are constants and μ represents the rate of growth of the budget deficit.

We have proved that (the logarithm of) the shadow is a linear function of time.

Appendix 2. Sellout Condition

In this section, we derive the sellout condition stated in lemma 2. In our economy, an arbitrageur can choose between holding either local or foreign currency. Investing in domestic currency generates a return equal to r, while the foreign currency yields r^*. Assumption 1 ($r > r^*$) makes the domestic investment more attractive. Therefore, arbitrageurs are initially fully invested in domestic currency. At some random time $t = \widetilde{t}$, the shadow price reaches the fixed exchange rate and from then onward the peg might be attacked.

We want to determine the optimal selling date for the arbitrageur who becomes aware of the mispricing at time $t = t_i$. Each arbitrageur's payoff from selling out depends on the price at which he can sell the domestic currency. At time $t \geq \widetilde{t}$, the peg may or may not hold. The price (in local currency) of an asset that yields a constant rate r is e^{rt}. The payoff function is denominated in foreign currency; hence, the price of domestic currency if the peg still holds is $p_t = e^{rt}\frac{1}{\overline{S}}$, where $\overline{S}$ is the fixed exchange rate. However, if the peg has been abandoned, the price will be $E[p_t|t_i] = E\left[e^{rt}\frac{1}{S_t}|t_i\right]$, which can be expressed as a fraction of the precrisis price as $E[p_t|t_i] = e^{rt}\frac{1}{\overline{S}}E\left[\frac{\overline{S}}{S_t}|t_i\right]$, and $E\left[\frac{\overline{S}}{S_t}|t_i\right]$ can be understood as a rate of variation in the exchange rate. Then, arbitrageur i's payoff from selling out at time t is given by

$$\int_{t_i}^{t} e^{-r^* s}\ e^{rs}\ E\left[\frac{1}{S_s}\middle| t_i\right]\ \pi(s|t_i)\ ds + e^{-r^* t}\ e^{rt}\ \frac{1}{\overline{S}}\ (1-\Pi(t|t_i)),$$

where $\Pi(t|t_i)$ represents agent i's conditional cumulative distribution function of the date on which the peg collapses and $\pi(t|t_i)$ indicates the associated conditional density.[9]

Differentiating the payoff function with respect to t yields

$$\underbrace{\frac{\pi(t|t_i)}{1-\Pi(t|t_i)}}_{h(t|t_i)} = \frac{r-r^*}{1-E\left[\frac{\overline{S}}{S_t}|t_i\right]} \Rightarrow h(t|t_i) = \frac{r-r^*}{A_f^i(t-t_i)},$$

where $A_f^i(t-t_i)$ is the size of the expected appreciation of the foreign currency feared by agent i once the fixed exchange rate is abandoned. $A_f^i(t-t_i)$ is a strictly increasing and continuous function of $t-t_i$, the time elapsed since arbitrageur i becomes aware of the mispricing.

Therefore, arbitrageur i maximizes his payoff to selling out at time t when his hazard rate equals the "greed-to-fear ratio." Thus, arbitrageur i holds

- a maximum long position in local currency, if $h(t|t_i) < \frac{r-r^*}{A_f^i(t-t_i)}$, or
- a maximum short position in local currency, if $h(t|t_i) > \frac{r-r^*}{A_f^i(t-t_i)}$.

[9]We assume there are no transaction costs to simplify the specification of the payoff function. We could easily incorporate transaction costs in our setting. For example, let us define the transaction cost at time t equal to $ce^{r^* t}$ (as in Abreu and Brunnermeier 2003). This convenient formulation guarantees that the optimal solution is independent of the size of the transaction costs.

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Manipulation in Money Markets*

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Interest rate derivatives are among the most actively traded financial instruments in the main currency areas. With values of positions reacting immediately to the underlying index of daily interbank rates, manipulation has become an increasing challenge for the operational implementation of monetary policy. To address this issue, we study a microstructure model in which a commercial bank may have strategic recourse to central bank standing facilities. We characterize an equilibrium in which market rates will be manipulated with strictly positive probability. Our findings have an immediate bearing on recent developments in the sterling and euro money markets.

JEL Codes: D84, E52.

*The opinions expressed are those of the authors and do not necessarily reflect those of the European Central Bank, Danmarks Nationalbank, or the Banque de France. Material contained in this paper has been presented at the conference "Monetary Policy Implementation: Lessons from the Past and Challenges Ahead" at the premises of the ECB in January 2005, at the EEA Meetings 2005 in Amsterdam, at the University of Mainz in July 2005, and at the Finance Seminar in Zurich in November 2006. Insightful comments by Hyun Shin and two anonymous referees are gratefully acknowledged. For helpful discussions and suggestions, the authors would like to thank Markus Brunnermeier, James Clouse, Vítor Gaspar, Michel Habib, Oliver Hart, Thorsten Hens, Hans-Joachim Klöckers, Seamus Macgorain, Alessandro Prati, Thomas Tröger, and Valerio Vacca. All remaining errors are our own. For financial support, Ewerhart thanks the National Centre of Competence in Research "Financial Valuation and Risk Management" (NCCR FINRISK).
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1. Introduction

In the recent past, many central banks have increasingly focused on steering some short-term money market interest rates in their implementation of the monetary policy stance. For example, this is the case of the Federal Reserve in the United States, the European Central Bank (ECB) in the euro area, and the Bank of England in the United Kingdom. More broadly, central banks seem to increasingly attach greater value to stable day-to-day and even intraday money market conditions. With this aim, so-called corridor systems have been adopted in several currency areas—for example, in Australia, Canada, the euro area, and New Zealand. More recently, the Bank of England has also adopted such a system (see Bank of England 2005).[1]

This paper wishes to contribute to the ongoing discussion on the appropriate design of corridor systems[2] by showing that manipulation is a potential issue in such money markets.[3] Specifically, a

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[1]In a corridor system (see, e.g., Woodford 2003), the central bank stands ready to provide overnight liquidity in unlimited amounts, generally against collateral, at a rate somewhat above market rates, and stands ready to absorb liquidity overnight in unlimited amounts at a rate somewhat below market rates. By setting a corridor around the central bank target or policy rate, the range of variation of overnight interest rates will be bounded, on a day-to-day basis, by the rates on the standing lending and deposit facilities, allowing short-term market interest rates to be steered with limited volatility around the desired level. The Federal Reserve has a semicorridor system following the introduction of its primary credit facility, 1 percentage point above the federal funds target, with zero being the standard lower bound.

[2]Furfine (2003) shows with a search model that the actual recourse of a lending facility may be less than suggested by the statistics of individual refinancing costs when the market attaches a stigma to its use, but also that the availability of a lending facility might reduce incentives for active participation in the interbank market. Pérez Quirós and Rodríguez Mendizábal (2006) conclude that the introduction of a deposit facility may lead to a stabilization of market rates. This is because the deposit facility reduces the costs of running into a "lock-in" situation, in which reserve requirements are satisfied before the last day of the reserve maintenance period.

[3]Manipulation in financial markets has attracted significant academic attention during the last two decades. Besides the contributions cited below, see for

commercial bank might hold a position that would gain from, say, a rise in policy rates, so that it would look like an attractive perspective if market rates would increase somewhat. To create temporarily higher rates, this bank may take up loans from the interbank market and deposit the funds with the central bank. Under certain conditions, this will cause a rise in the market rate, adding value to the manipulator's net position.[4] We will discuss under which conditions this and similar strategies are profitable, and which incentive effects are created by this possibility. We will also discuss some of the means at the disposal of the central bank to eliminate this kind of behavior.

In the euro area, variations of this type of manipulative strategy may have occurred on at least two occasions since the start of stage 3 of the Economic and Monetary Union in January 1999.

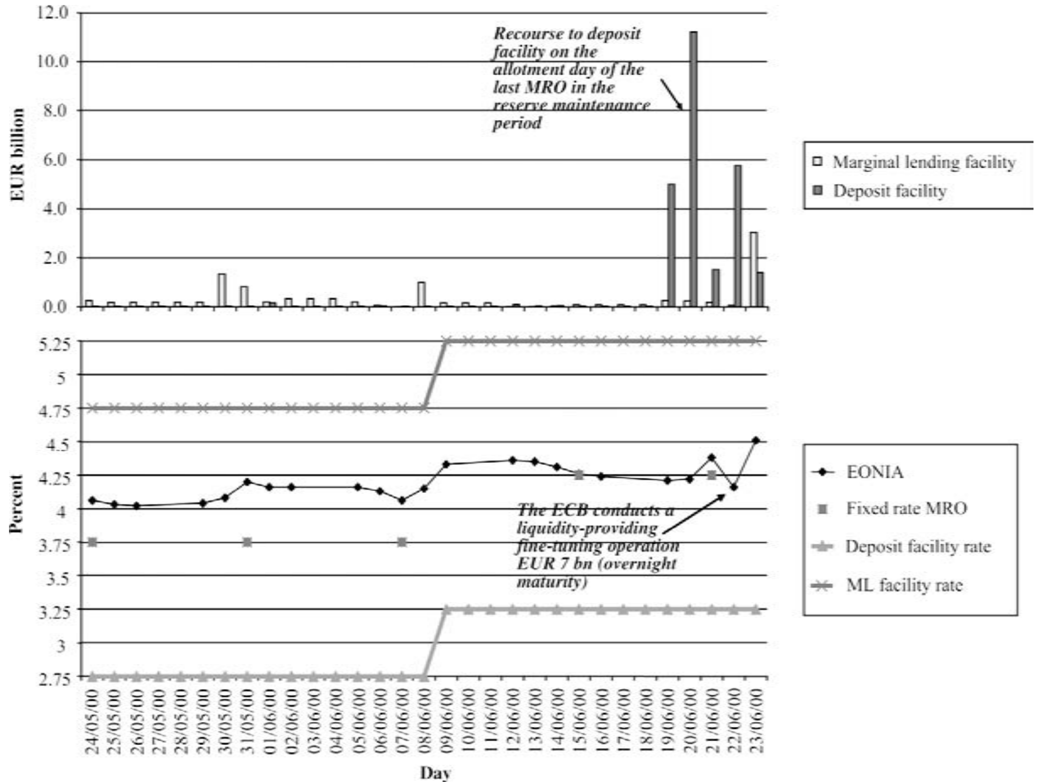
Manipulation Episode at the End of the Maintenance Period May 24–June 23, 2000.[5] In this maintenance period, the ECB raised key policy rates from 3.75 percent to 4.25 percent (cf. figure 1). Ahead of the decision, market participants were speculating on the timing of the policy change and also on the likely scale (25 basis points versus 50 basis points). Indeed, second-quarter turnover in interest rate swaps more than doubled in 2000. Already on the first day of the maintenance period, the money market index EONIA was at 4.06 percent, reflecting market expectations. On Monday, June 19, 2000, there was a EUR 4.999 billion (bn) total recourse to the deposit facility. This recourse occurred before the last main refinancing operation, and consequently did not affect market rates. However, at the close of trading on the next day, the allotment day of the last main refinancing operation in the maintenance period, there was another EUR 11.207 bn total recourse to the deposit facility. This recourse changed the liquidity conditions ahead of a crucial part of the maintenance period; thus the EONIA increased immediately. Made distinctly before the end of the reserve maintenance period, the recourse was indeed quite unusual. It is not

instance Allen and Gale (1992), Allen and Gorton (1992), Bagnoli and Lipman (1996), Benabou and Laroque (1992), Gerard and Nanda (1993), and Vila (1989).

[4]As a side note, a similar strategy was attempted by screenplay adversary Auric Goldfinger of Ian Fleming's James Bond 007, when breaking into Fort Knox to "destroy" massive gold reserves.

[5]For explanations of technical terms in the context of the implementation framework of the Eurosystem, we refer the reader to section 2.

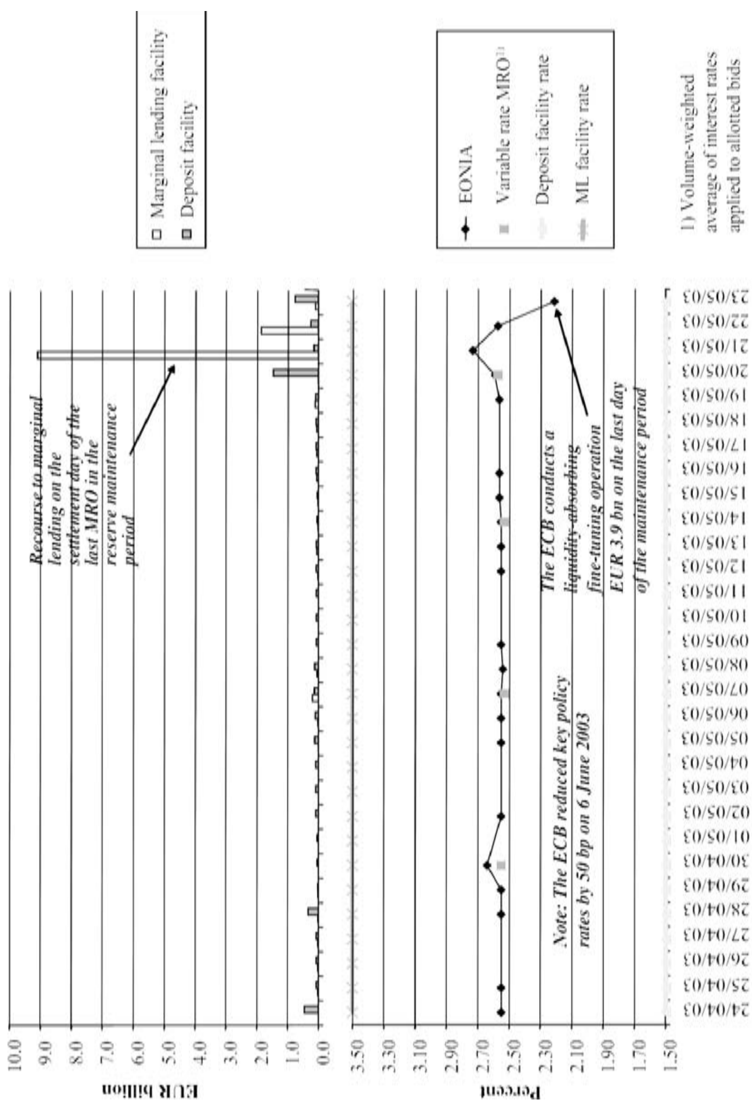
Figure 1. Daily Recourses to Standing Facilities in the Eurosystem, EONIA, and Key Policy Rates (May 24–June 23, 2000)



unlikely that an individual commercial bank had strong incentives to attempt manipulation. The Eurosystem launched a fine-tuning operation and provided EUR 7.000 bn at overnight maturity on Wednesday, June 21, achieving a temporary relief to market conditions. However, on the penultimate day, there was another large composite recourse to the deposit facility of a total size comparable to the fine-tuning operation. The Eurosystem did not perform an additional fine-tuning on the last day of the maintenance period. Overall, the maintenance period ended tight, with a net recourse to the marginal lending facility and EONIA 26 basis points above the new policy rate.

Manipulation Episode at the End of the Maintenance Period April 24–May 23, 2003. At the start of this maintenance period, the EONIA index was at 2.55 percent, and the minimum bid rate at the main refinancing operation was 2.50 percent (cf. figure 2). During the maintenance period, expectations were formed about a policy rate cut by the ECB in the subsequent period. The ECB indeed lowered key policy rates by 50 basis points on June 6, 2003. There was unusually strong activity in the swap market during May 2003. Then, on the allotment day of the last main refinancing operation in the maintenance period—Tuesday, May 20—there were several (nonstrategic) recourses to the deposit facility adding to a total of EUR 1.462 bn. Even though this is not a large total recourse, it seems that it had an impact on liquidity conditions because the EONIA was 23 basis points above the minimum bid rate on the next day. The movement of the market may have triggered the response that followed. On the next day, there was an active request by an individual market participant for lending from the Eurosystem of EUR 9.0 bn. This recourse apparently changed or even reversed liquidity conditions after the last main refinancing operation in the maintenance period. Thus the EONIA decreased immediately. On the following Thursday, there was another recourse to the lending facility of EUR 1.8 bn by the same market participant. Again, the timing of the recourses was unusual. Apparently, there had been an attempt to imitate the manipulation strategy employed in 2000, now in the context of expectations of decreasing policy rates. The ECB launched a liquidity-absorbing fine-tuning operation on Friday, the last day of the maintenance period, drawing EUR 3.850 bn from the market. Overall, the maintenance period ended slightly loose, with

Figure 2. Daily Recourses to Standing Facilities in the Eurosystem, EONIA, and Key Policy Rates (April 24–May 23, 2003)



a net recourse to the deposit facility and EONIA 29 basis points below the policy rate.

For a central bank, manipulation is undesirable mainly for two reasons. First, from an operational perspective, manipulation has the potential to add volatility to the overnight rate and to complicate the liquidity management of both commercial banks and the central bank. Second, manipulation may affect the market's confidence in a smooth implementation of monetary policy, which may have an impact on longer-term refinancing conditions and therefore on the effectiveness of monetary policy.

To address this issue, we consider a model in which a strategic trader with private information may trade in a swap market first and may then manipulate the market rate. The potential manipulator faces a trade-off between the costs of taking control of the market rates and the additional value for her derivatives position. It turns out that the trade-off will sometimes, but not always, induce the trader to leverage her derivatives position and to subsequently manipulate the money market. With several informed traders, a public-good problem reduces individual incentives for manipulation, yet does not eliminate the problem. We then discuss policy measures such as fine-tuning and the narrowing of the corridor set by the standing facilities. The discussion covers both elements of the new operational design by the Bank of England and recent experiences of the Eurosystem.

Technically, our analysis follows the microstructure literature on informed trade that is associated with the seminal work of Kyle (1985). In this literature, an individual trader with private information may cause a price effect because the market extracts the information contained in the aggregate order flow. In an important contribution to this literature, Kumar and Seppi (1992) have studied manipulation in futures markets with cash settlement. The present paper adapts the assumptions underlying the Kumar and Seppi model to reflect the institutional backdrop of a corridor system. The main adaptation concerns the way in which prices are moved in the market for the underlying. In Kumar and Seppi (1992), there is asymmetric information in the spot market. Because market participants may mistake uninformed trading for informed trading, the order flow created by the uninformed manipulator moves the price of the underlying asset. In contrast, there is no informed spot trading in our model. Indeed, while we do not deny the existence of private information in the money market, the evidence discussed above suggests that private information was not necessarily the central element in its mechanics. In our model, it is assumed that the manipulator gains temporary control of the market rate by using the standing facilities.[6]

The difference in the way in which prices are moved in the market for the underlying asset causes a qualitative change in the predictions of the analysis. In our model, a recourse to one of the standing facilities incurs an immediate loss in net interest earnings equivalent to the difference between the corridor rate and the current market rate. To cause the market rate to change marginally, this spread of typically more than 100 basis points has to be paid on the absolute amount of the recourse, which may be unprofitable. Indeed, the strategy does not pay off unless the involved positions exceed a certain size. This is why, in our setup, the probability and the extent of equilibrium manipulation depends on the design of the corridor system, which enables us to discuss alternatives for policymakers within our formal framework.[7]

The rest of the paper is structured as follows. Section 2 provides some background on the euro money market. This section can be skipped by those that are already acquainted with the institutional details. Section 3 sets up the basic model. In section 4, we study the decision problem of the informed trader. Section 5 analyzes the strategic game between manipulator and market makers. In section 6, we consider welfare consequences, policy options, and the extension to several manipulators. Section 7 concludes. All proofs can be found in the appendix.[8]

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[6]In the past, market rates have also reacted to insufficient demand in central bank operations. It is not clear, however, that these so-called underbidding episodes have been deliberate attempts of manipulation (cf. Ewerhart 2002 and Nyborg, Bindseil, and Strebulaev 2002).

[7]Another difference is that in Kumar and Seppi (1992), the manipulator's order in the futures market does not convey any information. In our model, the private information of the manipulator causes the swap rate to exhibit a reaction to the order flow and implies an endogenously finite market order.

[8]Note that strategic recourses, while similar in nature, differ from short squeezes (cf. Nyborg and Strebulaev 2001, 2004). In contrast to a short squeeze, a

2. Institutional Background on the Euro Money Market

When a customer of a commercial bank A requests a transfer of money into another party's account at another commercial bank B, then by purely mechanical consideration, bank A's holdings of central bank money will diminish, and bank B's holdings will increase. This and similar types of transactions may, when accumulating over the business day, re-allocate significant amounts of liquidity between individual credit institutions, which is a motive for them to trade secured and unsecured short-term credit in the e*uro money market*.

A central bank that has chosen to implement monetary policy by steering short-term interest rates may do so by seeking control of aggregate liquidity conditions in the money market and by using additional instruments to stabilize interest rates further. This is the approach favored by many modern central banks (cf. Bindseil 2004 or Borio 1997). In the case of the Eurosystem, the control of liquidity conditions is attained by the combination of open market operations, standing facilities, and reserve requirements.

Through its *open market operations*, the ECB provides the necessary refinancing to the banking system. The bulk of interbank liquidity in the euro area is offered in the weekly main refinancing operations (MROs), which are open to all eligible counterparties of the Eurosystem. Until March 2004, the maturity of these operations was two weeks; it has been one week since then. As a rule, funds extended through main refinancing operations are allotted on Tuesdays, with settlement on the following Wednesday. Other operations include the monthly longer-term refinancing operations (LTROs), with a maturity of three months, and so-called fine-tuning operations (FTOs). The latter can be used in a very flexible way, yet at the cost of addressing only a subpopulation of all eligible counterparties.

The Eurosystem's *standing facilities*—i.e., the marginal lending facility and the deposit facility—constitute the interest rate corridor in the euro area. There is no administrative procedure. That

strategic recourse does not presuppose a temporary monopoly situation. Strategic recourses are also not directly related to bidding behavior in central bank operations.

is, a recourse to either the marginal lending facility or the deposit facility can be requested by any eligible counterparty to the Eurosystem, where intraday debit positions on the counterparty's settlement account with the national central bank are automatically considered as a request for recourse to the lending facility. The use of the facilities occurs after the close of the market (at 6:30 p.m.). By 9:15 a.m. on the subsequent trading day, the market is informed through Reuters page ECB40 about the aggregate recourses to each of the two standing facilities. Significant recourses are typically observed only on the last one or two days of the maintenance period, when demand and supply in the money market become increasingly inelastic.

Reserve requirements for credit institutions are expressed in terms of an average balance to be held over a so-called reserve maintenance period (usually about a month) on the counterparty's settlement account. Noncompliance with minimum reserve obligations implies sanctions. In contrast to the United States, required reserves are remunerated in the euro area at a rate close to funding costs.

The combination of the above instruments makes market conditions in the euro money market usually a very stable signal of the current monetary stance. Nevertheless, both the average level and the volatility of market rates may vary over time. Especially after the last main refinancing operation in the maintenance period, market rates may differ visibly from the middle of the corridor. Deviations of the EONIA from the middle of the interest rate corridor occur in response to liquidity flows, so-called autonomous factors, which are beyond the direct control of the central bank's liquidity management and which affect the aggregate liquidity position of the banking system. These factors include treasury accounts with some national banks, banknotes that are paid out or collected at counters of commercial banks, and changes to consolidated net foreign assets held by the Eurosystem. Movements of the market rates occur also at certain calendar dates such as the end of the quarter and the end of the year, when commercial banks manage their balance sheets more carefully, and in connection with events that are perceived by the market to have a potential effect on financial stability. Further deviations of the market index from the middle of the corridor have been observed occasionally.

The *derivatives market* provides the means to either hedge the risks of a change in short-term interest rates or to speculate on them. Among the most actively traded instruments in this market is the overnight interest rate swap (OIS) of various maturities, ranging from one week to two years. For instance, an institutional investor might speculate on the timing of an expected increase in policy rates using a swap contract with a maturity of one month. In contrast, a commercial bank that wishes to freeze refinancing conditions in the interbank market until the next main refinancing operation may prefer a swap with a maturity of only one week. In terms of payments streams, the OIS is an instrument that exchanges a fixed interest rate against an index of daily interbank rates (almost always EONIA). The OIS differs from the plain vanilla interest rate swap (cf., e.g., Bicksler and Chen 1986), which is used for longer maturities and with reference to the Euribor. Also, for plain vanilla interest rate swaps, the floating rate is determined at one settlement date and paid at the next. In contrast, the floating-rate leg of an OIS is determined and paid at maturity. Overnight interest rate swaps have been known in the United States for quite some time as call money swaps.

For many market participants, it is much easier to realize a short-term interest rate position with swaps than with transactions in the deposit market (see, e.g., Pelham 2003 or Elliott 1997). The swap is the more liquid instrument and involves less credit risk. As a consequence, the swap curve has emerged as one of the main benchmark yield curves for the euro area. In June 2005, Euribor FBE (the European Banking Federation) and Euribor ACI (the Financial Markets Association) launched the EONIA Swap Index, which is published over Telerate for maturities ranging from one week to twelve months. There has been a continued strong expansion of the EONIA swap market over the last few years.

The OIS market is a highly competitive, high-volume OTC market, with dominant players featuring in the main European financial centers. The market organization is highly concentrated, with a handful of dealers accounting for about half of the trading activity. Among the most active dealers are commercial banks that are headquartered in the euro area. Dealers contract both with other dealers and with customers. The range of institutions participating in the OIS market as customers is very broad, originating from both the financial sector (credit institutions, insurance companies, pension funds, hedge funds, money market funds, etc.) and the non-financial sector (European governments). Leveraged funds are especially active in this market. For further details on the euro money market and the overnight swap market, the reader is referred to descriptive studies by Remolona and Wooldridge (2003), Santillán, Bayle, and Thygesen (2000), Hartmann, Manna, and Manzaranes (2001), and to the ECB's annual euro money market study (2001–2006).

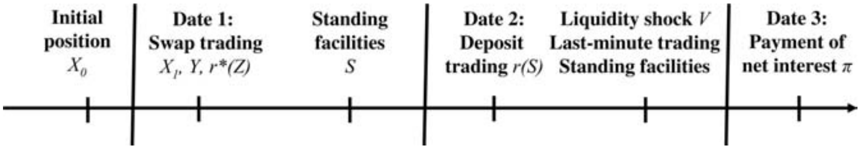
3. Formal Setup

Our market environment is an adapted version of Kumar and Seppi (1992), as discussed in the introduction. We envisage a developed money market with reserve requirements and averaging provision, embedded into a symmetric corridor system. Our analysis will focus on the last two days of the reserve maintenance period, when the regular (weekly) refinancing operations by the central bank have already established "neutral" conditions, and the market is essentially left on its own. Following the conventional terminology used in fixed-income and money markets, prices are replaced by interest rates. The setup is then as follows.

Three assets are traded in the money market: first, a riskless bond ("net interest"), which serves as a numeraire; second, a standardized overnight deposit contract ("liquidity") with endogenous interest rate r; and third, an overnight interest rate swap ("OIS") on the deposit contract, traded at the swap rate r^*. Sign conventions for fixed-for-floating swaps tend to be ambiguous and depend on whether the hedging or the speculation motive is stressed. Throughout the present paper, we will adhere to the convention that the receive-floating party is long the swap, so that the position in her portfolio obtains a positive sign. This convention has the consequence that increasing market rates are desirable for the holder of a long position in the OIS, and conversely for a short position.

The sequence of events is summarized in figure 3. A swap market on date 1, organized in the late morning of the trading day, is followed by a spot market for the underlying deposit contract on date 2, organized at a similar time of the day. A liquidity shock hits the market shortly before the end of date 2. Following the shock, but still before the close of the market at the end of date 2, there

Figure 3. Time Structure of the Model



is last-minute trading in the deposit contract. All net interests on deposit and swap contracts are paid at date 3.

Altogether, five types of traders participate in these markets: first, a risk-neutral informed trader (a commercial bank attempting manipulation); then, risk-neutral discretionary traders in the deposit markets (nonspecialized commercial banks); third, nondiscretionary traders in the swap market that trade for exogenous reasons (nonfinancial firms); and finally, two groups of competitive risk-neutral market makers in the deposit market (money market specialists) and in the swap market (swap dealers). Commercial banks are subject to an individual minimum reserve requirement that must be fulfilled by the end of date 2. They also have access to the central bank's standing facilities at any date before date 3.[9]

The game between the traders has, then, the following structure. The informed trader obtains an initial endowment X_0 in the swap before date 1. This initial position may be the result of OTC trading with nonbank customers, and is assumed to be private information.[10] At date 1, the informed trader submits a market order X_1 to the swap dealers, where $X_1 > 0$ when paying the fixed rate. The nonfinancial firms submit an independent order volume Y with mean $E_Y[Y] = 0$. The dealers observe the aggregate order

[9]Having commercial banks serving as market makers in the model would complicate the analysis without changing the conclusions. In a nutshell, the problem would be that an individual swap dealer, when receiving a too-large share of the total market order, may have an incentive to counteract the strategic recourse of the informed trader. This incentive is absent from the model if the swap dealers are not too few, or if there is not too much trading of swaps by nonfinancial firms at date 2.

[10]In practice, the initial position X_0 may not necessarily be stochastic. A commercial bank could actively manage short-term interest rate positions vis-à-vis nonbank customers in a specific way, e.g., by asking customers to swap variable-interest income into fixed-interest income. That would make the initial position endogenous. However, a commercial bank may be able to do this once, but not several times, because it would openly steal profits from its customers.

flow $Z = X_1 + Y$ in the swap market. Moreover, dealers will be understood to be informed about whether the informed trader submits a nonzero market order.[11] Formally, let $b = 1$ if $X_1 \neq 0$, and $b = 0$ otherwise, and assume that swap dealers observe b. The swap dealers are then willing to clear the swap market at the competitive rate $r^*(Z, b)$. Since only the case $b = 1$ is interesting, we will henceforth drop the second argument and write simply $r^*(Z)$ for $r^*(Z, 1)$.

With the close of the market at the end of date 1, the informed trader may have recourse S to the standing central bank facilities, where $S > 0$ stands for a recourse to the lending facility, and $S < 0$ for a recourse to the deposit facility. On date 2, the recourse S becomes public information. Commercial banks may then submit market orders for the deposit contract. As the order flow is not informative, the market specialists fix the interest rate on the deposit contract at date 2 to some value $r(S)$ that depends only on S.

Shortly before the end of trading on date 2, a liquidity shock V may affect the aggregate liquidity position of the banking system, where $V > 0$ stands for an absorption of liquidity. The dispersion of the shock over commercial banks does not matter under symmetric information and is therefore not explicitly modeled. The liquidity shock is assumed to be distributed independently from X_0 and Y. Given that the central bank implements monetary policy in a neutral way, the median of the distribution of V will be zero. It is assumed that the distribution of V is given by a density $\phi_V(.)$ that is weakly increasing for $S < 0$ and weakly decreasing for $S > 0$.

All commercial banks try to cover their positions at the end of date 2, so that the price in the last-minute trading equals either the central bank's lending rate r^L (when $S - V < 0$) or the central bank's deposit rate r^D (when $S - V > 0$), where $0 < r^D < r^L$. Under these conditions, the liquidity effect resulting from a recourse is determined exclusively by the change in the relative probabilities of a tight or a loose end of the maintenance period. Thus, the market for the overnight contract appears in the reduced form that has become standard in the literature since Poole (1968).

[11] Non-anonymity significantly simplifies the analysis without affecting our main results. For a model without this assumption, the reader is referred to our working paper (Ewerhart et al. 2004).

Poole's Lemma. *The market rate at date 2 for the deposit contract after a net recourse of S is given by a weakly decreasing function*

$$r(S) = \Phi_V(S)r^D + (1 - \Phi_V(S))r^L, \tag{1}$$

where $\Phi_V(S) = \mathrm{pr}\{V \leq S\}$ denotes the cumulative distribution function of the liquidity shock V. In particular, for $S = 0$, the market rate $r(0)$ corresponds to the midpoint $r^0 = (r^D + r^L)/2$ of the corridor.

Indeed, after the last main refinancing operation, money market rates in the euro area are generally expected to move in response to the release of public information about flows of liquidity that affect the aggregate liquidity position of the banking system, e.g., when a recourse to a standing facility of the central bank occurs.[12] As we will discuss now, it is this liquidity effect that opens the door for the profitable abuse of the credit and deposit facilities.

4. Sporadic Manipulation

A market participant who intends to take temporary control of the market rate will be aware of the costs and benefits of such a strategy. There are costs because the use of standing facilities is bound to interest rate levels that almost always differ significantly from market conditions. There are benefits because short-term interest rate positions may gain in value. In this section, we analyze under which conditions a strategic recourse is profitable.

Formally, net interest income π for the informed trader is the sum of three components, as suggested by equation (2) below. First, there is the net return on the initial position X_0 in the swap. The initial position is valued with the interest rate $r(S)$ realized at date 2, while funding costs for this position are already sunk at date 1 and can be normalized to r^0. Next, there is the net return on the market order X_1. Here as well, the position is valued using the interest rate $r(S)$ realized at date 2. Funding costs are given by the swap rate at date 1, which will be denoted by r^*. The third income component

[12] The corresponding empirical evidence for the United States is mixed. See in particular Hamilton (1997), Thornton (2001), and Carpenter and Demiralp (2006).

is the net interest paid for the strategic recourse S to the standing facilities. This component is generally negative; e.g., a recourse to the credit facility costs r^L but yields only $r(S) \leq r^L$. Summing up, the informed trader obtains a net interest income

$$\pi(X_0, X_1, S) = X_0(r(S) - r^0) + X_1(r(S) - r^*) + S(r(S) - r^{L/D}(S)), \tag{2}$$

where we write

$$r^{L/D}(S) = \begin{cases} r^L & \text{if } S > 0 \\ r^0 & \text{if } S = 0 \\ r^D & \text{if } S < 0 \end{cases}$$

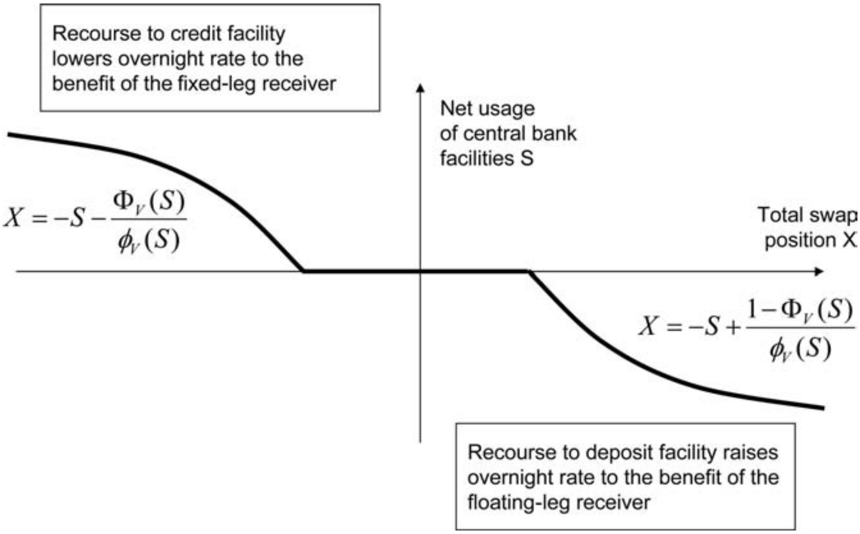
for the interest rate that the informed trader either pays for having recourse to the marginal lending facility or receives for depositing money with the central bank. The terms r^0 and r^* correspond to the fixed leg of the swap positions X_0 and X_1, respectively. The variable interest rate $r(S)$ is received or paid on all three positions.

Controlling the Market Rate. The starting point for the analysis is to note that a strategic recourse to one of the standing facilities is not always optimal. Denote by $X = X_0 + X_1$ the total swap position. For concreteness, assume a long position, i.e., $X > 0$. The reader will note that it is never optimal in this situation to have recourse to the marginal lending facility. Indeed, to increase the value of the position, the market rate must go up and liquidity must become scarcer, so the informed trader will have recourse to the deposit facility ($S < 0$). We differentiate the informed trader's objective function (2) with respect to S. Then the necessary first-order condition governing the informed trader's decision about S at date 1 becomes

$$-r'(S)(X_0 + X_1 + S) = r(S) - r^D. \tag{3}$$

As captured by the left-hand side of equation (3), the marginal benefit of manipulating the interest rate upward is the increase in the market value of the aggregate net position $X + S$. The marginal cost, on the other hand, is the interest rate differential between a deposit in the market and a deposit with the central bank. The resulting trade-off may be one-sided, however. Specifically, it turns out that

Figure 4. Net Usage of Standing Facilities as a Function of the Informed Trader's Swap Position



if X is small enough in absolute terms, then the benefit will always be smaller than the cost, so that manipulation does not pay off. A similar consideration can be made for the case of a negative X. Thus, as depicted in figure 4, the optimal recourse to the standing facilities, drawn as a function of the informed trader's position in short-term interest rate instruments, is zero for small absolute values of X.

PROPOSITION 1. *The optimal strategic use of standing facilities $S^*(X)$ at the end of date 1 involves no recourse for $|X| \leq \Delta/\rho$, where $\Delta = r^L - r^0$ is the half-width of the corridor, and $\rho = |r'(0)|$ is the liquidity effect. Moreover, when $|X| > \Delta/\rho$, then $S^*(X) \neq 0$, and X and $S^*(X)$ are of opposite sign.*

Thus, only a market participant with a sufficiently large exposure has an incentive to attempt manipulation. Such a trader may have built up a sufficiently large long position in the swap market ($X > \Delta/\rho$) and will have recourse to the deposit facility ($S < 0$) to cause prices to rise. In this case, it cannot be optimal to use the lending facility, i.e., to manipulate the market rate downward, because the alternative choice $S = 0$ avoids the nontrivial costs of the lending facility and does not lower the value of the swap position. In the other scenario, a trader with a sufficiently large short position ($X < -\Delta/\rho$) will have recourse to the marginal lending facility ($S > 0$) and will profit from the softening of the market.

Which size of position makes manipulation profitable? We have estimated elsewhere (see Ewerhart et al. 2003) that for the euro area under the system in use before March 2004, $\rho \approx 0.09\%/\text{bn EUR}$. The figure captures the response to a publicly observed, one-day liquidity shock of EUR 1 bn, which occurs immediately after the last main refinancing operation, and which is not corrected for by later fine-tuning. With this estimate, we can perform the following crude calibration. The corridor half-width being $\Delta = 1\%$, proposition 1 predicts that manipulation is the consequence of profit maximization for positions with a notional of at least

$$\frac{\Delta}{\rho} \approx \frac{1\%}{0.09\ \%/\text{bn EUR}} = \text{EUR } 11.1 \text{ bn.}$$

The reader will note that this figure does not take into account expectations about potential central bank interventions after an attempted manipulation (these are difficult to quantify) and may therefore understate the actual threshold.

5. Trading in the Swap Market

Once a market participant considers manipulation as a profitable strategy, she will seek to improve the effectiveness of this strategy by leveraging her initial position in short-term interest-rate instruments. In the model, this possibility is reflected by the informed trader's endogenous choice of the swap market order X_1. As mentioned in section 2, an additional position taking could also be accomplished by satisfying reserve requirements unevenly over time. Which of these and possible other instruments is used by the individual treasurer is ultimately an empirical question. To keep the model tractable, we will focus in the sequel on the case of leverage using the swap market.

While position taking is essentially costless in the liquid OIS market, it cannot be accomplished at zero cost. In an equilibrium with rational expectations, swap dealers will anticipate the possibility of manipulation and will extract the information contained in the order flow. For example, a large positive market order $X_1 = X_1^*(X_0)$, unless compensated by nondiscretionary trading, indicates to the dealers that the informed trader already has a relatively large initial long position X_0, making a recourse to the deposit facility more likely. Competition between swap dealers will force those dealers to set the swap rate close to market expectations about the deposit rate at date 2. More precisely, conditional on the total order volume $Z = X_1^*(X_0) + Y$, the swap rate will be set to

$$r^*(Z) = E_{X_0,Y}[r(S^*(X_0 + X_1)|Z]. \tag{4}$$

Here, the swap rate $r^*(Z)$ will typically be increasing in Z. Thus, as a consequence of the dealers' rational anticipation, creating significant leverage may be costly for the informed trader.

But when large trades can affect market expectations, it will be easier for the informed trader to leverage the existing position than to hedge it. Indeed, as our next result shows, neither hedging nor a change of the market side can be optimal in a symmetric market environment.

PROPOSITION 2. *Assume that X_0, Y, and V are symmetrically distributed with mean zero, and that $E_Y[r^*(X_1 + Y)]$ is increasing in X_1. Then the informed trader's optimal market order satisfies $X_1^*(X_0) \geq 0$ for $X_0 > 0$ and $X_1^*(X_0) \leq 0$ for $X_0 < 0$.*

While the informed trader will never reduce her initial exposure in a symmetric market environment, we will see below that under general conditions, and in intuitive extension of proposition 1, she may choose to let the position unchanged. More precisely, if the initial position X_0 is relatively small in absolute value, then the informed trader does not participate in the swap market and does not manipulate the deposit rate. The intuitive reason for this finding is that the informed trader needs a sizable total position $X = X_0 + X_1$ to make a strategic recourse ex post optimal. But if X_0 is small in absolute terms, a deal X_1 of the required size would reveal too much information, which would make the whole plan unprofitable.

These considerations are reflected in our description of the equilibrium, which will be provided below. By an equilibrium, we mean functions for the market order $X_1^*(.)$ and for the strategic recourse $S^*(.)$, and a pricing rule $r^*(.)$ such that (i) for any X_0 in the support of the initial distribution, the informed trader maximizes expected net income from interest $E_Y[\pi]$ by choice of $X_1 = X_1^*(X_0)$ and $S = S^*(X_0 + X_1)$, and (ii) for any $Z = X_1 + Y$ in the support of the equilibrium distribution, dealers set the swap rate $r^* = r^*(Z)$ competitively as captured by (4).[13]

The "sporadic" nature of manipulation, while valid much more generally, precludes the possibility of a tractable equilibrium with normally distributed random parameters. The point to note is that, as manipulation occurs only for sufficiently large initial positions, the conditional distribution of market orders is determined by the tails of the distribution of the initial position. However, tail distributions of normal distributions are not normal. Thus, despite the theoretical desirability of the normal distribution that has been pointed out by Nöldeke and Tröger (2001, 2006) and Bagnoli, Viswanathan, and Holden (2001), it is preferable in our situation to consider a setup with uniform distributions, just because the tail distribution of a uniform distribution is again uniform. We will assume therefore in the sequel that the random variables X_0, Y, and V are uniformly distributed on intervals $[-\delta_X, \delta_X]$, $[-\delta_Y, \delta_Y]$, and $I_V = [-\delta_V, \delta_V]$, respectively, where $\delta_X, \delta_Y, \delta_V > 0$.

In the uniform setup, boundary conditions must be considered explicitly. Two restrictions on the parameter values have to be imposed. First, we assume that the liquidity shock is sufficiently dispersed, as captured by

$$\delta_V > \frac{\delta_X + \delta_Y}{3}. \tag{5}$$

This restriction will ensure that the manipulated market rate does not reach the boundary of the corridor, which is a useful

[13]In principle, the swap dealers should form expectations also off the equilibrium distribution of net aggregate orders. However, in our setup, these expectations can be assumed to extrapolate the linear price effect in the swap market, making a deviation by the informed trader unattractive.

simplification. Further, to focus on the interesting case of manipulation, we will assume that the initial position of the informed trader is sufficiently large with positive probability, i.e.,

$$\delta_X > \delta_V. \tag{6}$$

When these two conditions are satisfied, we find an explicit equilibrium with the following characteristics.

PROPOSITION 3. *Under conditions (6) and (5), there is an equilibrium in the manipulation game. For* $|X_0| < \delta_V$*, there is no manipulation, i.e.,* $X_1^*(X_0) = S^*(X_0) = 0$*. For* $|X_0| \geq \delta_V$*, however, the informed trader will leverage her position and subsequently manipulate the deposit rate.*

The proposition suggests that those commercial banks that are the most active traders of interest rate derivatives with nonbank customers—i.e., those with a large δ_X—should be among the most likely to manipulate the deposit market. In practice, the decision to manipulate by a commercial bank will depend also on other factors, including (i) the overall trading and collateral capacities of the bank, (ii) the internal allocation of the bank's risk budget between markets, and (iii) its general readiness to take strategic measures in the search of profit opportunities, including the involved daringness vis-à-vis the monetary authority and potentially other regulatory institutions. For these reasons, we would expect that even in a large currency area, only a few commercial banks may be prepared for manipulative actions such as those described in this paper. Depending on the central bank's stance on this issue, it may also be difficult for an individual institution to repeat an unwanted manipulative strategy. Still, a central bank will have to formulate a credible response to such strategies.

6. Welfare Consequences, Policy Measures, and Further Discussion

6.1 Social Cost of Manipulation

As mentioned in the introduction, manipulation is not welcomed by a central bank because it might negatively affect the reputation of the monetary authority and also because it may add volatility to money market conditions. We will use three different measures for the welfare loss: first, the *probability* of manipulation $\text{pr}\{S^* \neq 0\}$; second, the expected *extent* of manipulation $E[|S^*||S^* \neq 0]$, conditional on a strategic recourse; and finally, the *volatility* of the market rate at date 2, measured by the unconditional standard deviation

$$\sigma_M = \sqrt{E[(r(S) - r^0)^2]}.$$

The first two measures are related to central bank reputation, while the volatility measure captures the objective of smooth implementation.

6.2 Preventing Manipulation

What mechanisms could prevent the need of money markets to accommodate volatility caused by strategic recourses?

The Width of the Corridor. In the early discussion of the problem (cf. Vergara 2000), it had been suggested that a wider interest rate corridor should effectively defuse the risk of manipulation. Indeed, it is not implausible to conjecture that a larger average spread between the EONIA and the respective facility rate should increase the cost of affecting the market rate sufficiently to make manipulation unattractive. However, as our next result shows, this intuition is incorrect. Formally, let $\Delta' > \Delta$ denote the enlarged half-width of the interest rate corridor. We increase the lending rate $r^L = r^0 + \Delta$ to $r^0 + \Delta'$ and lower the deposit rate from $r^D = r^0 - \Delta$ to $r^0 - \Delta'$. These changes are then implemented consistently over the whole two-day maintenance period.

PROPOSITION 4. *Widening or narrowing the interest rate corridor has no effect either on the probability or on the extent of manipulation.*

To see why the proposition holds in the case considered in proposition 3, recall that by Poole's lemma, the size of the liquidity effect is proportional to the width of the corridor, i.e.,

$$\rho = |r'(0)| = |\Phi_V'(0)|(r^L - r^D) = 2|\Phi_V'(0)|\Delta. \tag{7}$$

Using (7) in the equilibrium conditions, one can verify that Δ cancels out in all expressions, so that both the probability and the extent of manipulation remain unaffected by the size of the width.

Proposition 4 is much more general and does not depend on distributional assumptions. Intuitively, the interest rate corridor has two roles as an instrument in the implementation of monetary policy. On the one hand, the standing facilities impose an effective boundary to money market conditions. On the other, however, the width of the corridor is a linear scaling factor for the size of the liquidity effect. Once this double role of the corridor is taken into account, the above result should be ultimately straightforward: while a wider corridor makes strategic recourses more costly for the commercial bank, the gains are scaled up as well.

Of course, the volatility caused by manipulation could be lowered by having a tighter corridor. However, in practice, a corridor that is too tight would create incentives for exclusive trading with the central bank and would consequently dry out the interbank market. This would constitute a problem because considerations of credit risk imply a certain dispersion of the interest rates that are applied to bilateral transactions in the money market. The optimal size of the corridor should therefore reflect the central bank's trade-off between smoothing implementation and setting prudential incentives.

Fine-Tuning. The model can be extended in a straightforward way to incorporate the possibility of central bank intervention. Let $\alpha_0 \in [0; 1]$ denote the probability that the central bank intends fine-tuning at the end of date 2.[14] The parameter values $\alpha_0 = 0$ and $\alpha_0 = 1$ correspond to no intervention and regular fine-tuning, respectively. In the case of the Eurosystem, the parameter α_0 has traditionally been close to zero. Indeed, before May 11, 2004, the ECB had generally been quite reluctant to use additional operations to correct for end-of-period imbalances, apparently because there had been no good reason for an intervention, and also because

[14] In a more descriptive setup, the probability of fine-tuning would be correlated with the size of the liquidity imbalance on the last day of the reserve maintenance period. In this case, the manipulator may choose a lower S^* to avoid the fine-tuning. While the corresponding equilibrium would be intractable, we conjecture that the qualitative features of our predictions would be essentially unchanged.

some volatility seems to be desirable to provide incentives for bidding in the main refinancing operations (cf. ECB 2005). However, following the initial experiences with the new operational framework, the ECB gradually increased its willingness to intervene on the last day, with fine-tuning after February 2005 occurring almost regularly at the end of the maintenance period. Thus, nowadays, with quasi-regular fine-tuning at the end of each maintenance period, α_0 should be much closer to one.

Fine-tuning operations may not always lead to the desired result. This indeed happened in the euro area when market participants found the condition in a liquidity-draining fine-tuning operation not sufficiently attractive to participate (cf. ECB 2006). Formally, we assume a conditional probability $\pi > 0$ that a given fine-tuning operation does not lead to the desired outcome. The probability of successful fine-tuning is then given by $\alpha = \alpha_0(1 - \pi)$. We assume that an unsuccessful operation fails completely, while a successful operation ensures that the market rate at the end of date 2 is r^0. The market rate after manipulation will then be $r(S)$ with probability $1 - \alpha$, and r^0 with probability α. In expected terms, a recourse of S in the context of a central bank reaction captured by α implies a market rate at date 2 of

$$r(S, \alpha) = \alpha r^0 + (1 - \alpha) r(S). \tag{8}$$

In particular, with fine-tuning, the deviation of the market rate from r^0 at date 2 is bounded by $(1 - \alpha)\Delta$. Thus, in a sense, fine-tuning attenuates the liquidity effect more effectively than a more dispersed liquidity shock. Adapting proposition 3, we arrive at the following result.

PROPOSITION 5. *Assume that the probability π of an operational failure is smaller than one. Then a higher probability of fine-tuning α_0 lowers the probability and the extent of manipulation, as well as the volatility of money market conditions.*

Thus, deviations of the money market rate caused by strategic recourses can be effectively reduced by an appropriate and immediate reaction of the central bank, and should therefore be expected to be a transient phenomenon in practice. An immediate reaction is needed, however, because if the recourse is not compensated promptly in the morning of the subsequent day, then the market rate could have moved, and a gain for the manipulator would result.

The BoE Design. Our analysis may throw some light on the innovative design of the standing facilities in the new operational framework of the Bank of England (see Macgorain 2006). The final design involves having a corridor half-width of 1 percent, as in the case of the Eurosystem, but having the corridor narrowed down to 0.25 percent on the final day of the reserve maintenance period. This design element effectively drives a wedge between the cost of the strategic recourse on the right-hand side of equation (3), which remains high, and the benefit from the interest rate movement on the left-hand side of (3), which is significantly reduced. Formally, for $t = 1, 2$, denote by r_t^L and r_t^D the facility rates at date t, and by $\Delta_t = \left(r_t^D - r_t^D\right)/2$ the corridor half-width at date t.

PROPOSITION 6. *Narrowing of the corridor only on date 2 by some factor $\beta = \Delta_1/\Delta_2 > 1$ is equivalent to successful fine-tuning with probability $\alpha = 1 - 1/\beta$.*

The narrowing of the corridor on the last day of the reserve maintenance period may therefore become a complement or substitute for fine-tuning, for instance, when the probability π of an operational failure is not negligible. The Bank of England has combined narrowing of the corridor with a regular fine-tuning policy and flexible reserve requirements. Preliminary evidence from the sterling money market suggests that this combination of policy measures is indeed quite powerful.[15]

6.3 Several Manipulators

Intuitively, the possibility of profitable manipulation should provoke imitation or climbing on the bandwagon by other major players in

[15] Information policy does not appear to us as a useful instrument to combat manipulation. While, in principle, the central bank could withhold information about recourses, the manipulator has an incentive to actively disseminate this information. Moreover, the resulting ambiguity might lead to even more gaming.

the interbank market. To study this possibility in formal terms, we generalize our model to the case of $N \geq 2$ informed traders $i = 1, \ldots, N$. Consider an informed trader i with an initial position X_0^i and a submitted market order X_1^i. There is an interaction with the other informed traders at the end of date 1 because the value of i's position does not only depend on her own recourse S^i, but also on the aggregate net recourse

$$S^{-i} = \sum_{j \neq i} S_j$$

of the other informed traders. Formally, this interdependence is reflected in the net income from interest for trader i, which is given by

$$\pi^i \left(X_0^i, X_1^i, S^i, S^{-i} \right) = X_0^i (r(S^i + S^{-i}) - r^0) + X_1^i (r(S^i + S^{-i}) - r^*) + S^i (r(S^i + S^{-i}) - r^{L/D}(S^i)),$$

in straightforward generalization of (2). To keep the model tractable, we focus on the second stage of the manipulation game. Formally, we will disallow swap trading at date 1 and assume that initial swap positions X_0^i are perfectly correlated.

PROPOSITION 7. *There exists an equilibrium in the second stage of the manipulation game with $N \geq 2$ informed traders. Similar to the case $N = 1$, there is no recourse provided that $|X^i| \leq \delta_V$. If, however, $\delta_V < |X^i| < (2 + 1/N)\delta_V$, the informed trader i's equilibrium recourse $S^{i,*}$ is given by*

$$S^{i,*} = -sign(X^i) \frac{|X^i| - \delta_V}{N + 1}.$$

Thus, with $N \geq 2$ informed traders, there is a public-good problem between the informed traders because all informed traders will benefit from an individual trader's strategic recourse. However, it must be conjectured that competition among potential manipulators alone will not preclude the possibility of manipulation.

7. Conclusion

In this paper, we have pointed out that in money markets that are embedded in a corridor system, composed of central bank lending and deposit facilities, there is the potential for manipulative action that abuses these facilities. Anecdotal evidence for the euro area suggests that this strategy may be perceived by the market as more than just a theoretical possibility. We have used a microstructure model to show that manipulation can be profitable for a commercial bank with suitable ex ante characteristics. Manipulation remains a feature of the equilibrium even if dealers in the derivatives market form rational expectations about potential manipulation. A widening of the interest rate corridor over the whole reserve maintenance period is not helpful. Instead, regular fine-tuning fights manipulation effectively, as does narrowing the corridor on the last day of the maintenance period. Indeed, these measures ensure that the costs of manipulation remain high, while the benefits decrease. Our analysis supports the common perception that the monetary authority has powerful instruments to combat manipulation, but also that further vigilance in these operational matters appears recommendable.

Appendix. Proofs

Proof of Poole's Lemma. The distribution of V having no mass points, the probability that the maintenance period ends with ample liquidity amounts to

$$\text{pr}\{S - V > 0\} = \text{pr}\{V < S\} = \text{pr}\{V \leq S\} = \Phi_V(S).$$

Similarly, the probability that $S - V < 0$ is given by $1 - \Phi_V(S)$. This proves (1). The monotonicity of $r(S)$ follows from

$$r(S) = r^L - \Phi_V(S)\big(r^L - r^D\big).$$

As the median of the distribution of V is zero, we have $\Phi_V(0) = 1/2$, which proves the lemma.

Proof of Proposition 1. Assume first that $X \geq 0$. Then any $S > 0$ is strictly inferior to no recourse, i.e., to $S = 0$. Thus, $S^*(X) \leq 0$. Using (3) and Poole's lemma, we find the necessary first-order condition

$$X = -S + \frac{1 - \Phi_V(S)}{\phi_V(S)}, \tag{9}$$

where $S < 0$ and such that $\phi_V(S) > 0$. It is easy to check that the right-hand side of equation (9) is strictly decreasing in $S < 0$ and approaches Δ/ρ for $S \to 0$. Hence, equation (9) has a unique solution $S^*(X) < 0$ for any $X > \Delta/\rho$. Clearly, this is the global optimum when the support interval I_V of the distribution of V is not bounded from below. Assume now a finite lower boundary $\underline{V} < 0$ of I_V. Then clearly, any $S < \underline{V}$ is inferior to $S = \underline{V}$, so that also in this case, the global optimum is determined by (9). For $0 \leq X \leq \Delta/\rho$, an interior solution is not feasible. Therefore, $S^*(X) = 0$ when I_V is unbounded from below. When I_V is bounded from below, then $\underline{V} \leq -\Delta/\rho$ because $\Phi_V(S)$ is convex for $S < 0$. But then,

$$\pi(X_0, X_1, \underline{V}) - \pi(X_0, X_1, 0) = X\left(r^L - r^0\right) + \underline{V}\left(r^L - r^D\right) < 0.$$

Thus, also when I_V is bounded from below, $S^*(X) = 0$ for $0 \leq X \leq \Delta/\rho$. The case $X < 0$ can be treated in an analogous way. Hence the assertion.

Proof of Proposition 2. Without loss of generality, assume $X_0 > 0$ (the other case follows by symmetry). Consider first a change in the market side, i.e., a market order $X_1 < 0$ such that $X_0 + X_1 < 0$. We claim that submitting this market order is suboptimal, even if followed by $S = S^*(X_0 + X_1)$. As an alternative plan of action, consider $\hat{X}_1 = -2X_0 - X_1$, followed by $\hat{S} = -S$. Indeed, in this case $X_0 + \hat{X}_1 = -(X_0 + X_1)$, so that in a symmetric market environment,

$$\begin{aligned} &\pi(X_0, \hat{X}_1, \hat{S}) - \pi(X_0, X_1, S) \\ &\quad = \underbrace{X_1(E_Y[r^*(X_1 + Z)] - r^0)}_{>0} - \underbrace{\hat{X}_1(E_Y[r^*(\hat{X}_1 + Z)] - r^0)}_{>0}. \end{aligned} \tag{10}$$

Clearly, $|X_1| > |\hat{X}_1|$ and consequently also

$$|E_Y[r^*(X_1 + Z)] - r^0| > |E_Y[r^*(\hat{X}_1 + Z)] - r^0|.$$

Thus, (10) is positive, proving our claim. Consider now the case of hedging, i.e., $-X_0 \leq X_1 < 0$. Then $X_0 + X_1 \geq 0$ and therefore $S^*(X_0 + X_1) \leq 0$ by proposition 1. We claim that a deviation to $\hat{X}_1 = 0$ *without changing* $S = S^*(X_0 + X_1)$ is already a better trading strategy. To see why, note that $r(S) \geq r^0$ and that $r^0 > E_Y[r^*(X_1 + Z)]$. But then,

$$\pi(X_0, \hat{X}_1, \hat{S}) - \pi(X_0, X_1, S) = -X_1(r(S) - E_Y[r^*(X_1 + Z)]) > 0.$$

Thus, also hedging cannot be optimal.

Proof of Proposition 3. This result follows immediately from lemma A.1 below for $\alpha = 0$ (i.e., no fine-tuning).

Proof of Proposition 4. Start from an equilibrium in the manipulation game. Assume first that the half-width of the corridor is scaled up from $\Delta > 0$ to some $\Delta' > 0$, where $\Delta' < r^0$. Let $\gamma = \Delta'/\Delta > 1$. Then, by Poole's lemma, the liquidity effect $r(S) - r^0$ is scaled up by the factor γ. Consider now, as an equilibrium candidate in the model with corridor Δ', a competitive swap spread $r^* - r^0$ that is scaled up by the factor γ. It is then straightforward to check that the objective function (2) of the manipulator is multiplied by γ. The optimal strategy of the informed trader concerning the choice of X_1 and S as a function of X_0 remains unchanged. Thus, neither the distribution of aggregate market orders Z arriving at the dealer's desk nor the dealer's posterior belief on S given his observation of Z is affected. From equation (4), we get that the scaled-down pricing function in the swap market is indeed competitive. A similar argument can be made for a narrowing of the corridor. Hence the assertion.

Proof of Proposition 5. This result follows immediately from lemma A.1 below.

Lemma A.1. *For $\alpha < 1$, let $\hat{\delta}_V = \delta_V/(1-\alpha)$. Assume*

$$\delta_X > \hat{\delta}_V \text{ and } \delta_X + \delta_Y < 2\delta_V + \hat{\delta}_V. \tag{11}$$

Then the following is an equilibrium in the manipulation game with fine-tuning. For $|X_0| < \hat{\delta}_V$, there is no manipulation, i.e.,

$$X_1^*(X_0, \alpha) = S^*(X_0 + X_1^*(X_0, \alpha), \alpha) = 0.$$

For $|X_0| \geq \hat{\delta}_V$, however, the informed trader will submit a market order

$$X_1^*(X_0, \alpha) = \theta sign(X_0)(|X_0| - \hat{\delta}_V) \tag{12}$$

and will have recourse to the standing facilities

$$S^*(X_0 + X_1^*(X_0, \alpha), \alpha) = -\frac{1+\theta}{2} sign(X_0)(|X_0| - \hat{\delta}_V) \qquad (13)$$

at the end of date 1. Here, $\theta = \delta_Y/(\delta_X - \hat{\delta}_V) > 0$ *is a measure for the informational advantage of the informed trader. The swap dealers set the competitive rate to*

$$r^*(Z, \alpha) = r^0 + \frac{\rho}{4}\frac{1+\theta}{\theta}Z. \qquad (14)$$

The probability of manipulation, the extent of manipulation, and the volatility of the market rate at date 2 are respectively given by

$$pr\{S^* \neq 0\} = \frac{\delta_X - \hat{\delta}_V}{\delta_X}, \qquad (15)$$

$$E[|S^*|\,|S^* \neq 0] = \frac{\delta_X - \hat{\delta}_V + \delta_Y}{4}, \text{ and} \qquad (16)$$

$$\sigma_M = \frac{\delta_X - \hat{\delta}_V + \delta_Y}{2\delta_V}\sqrt{\frac{\delta_X - \hat{\delta}_V}{3\delta_X}}(r^L - r^0). \qquad (17)$$

Proof. We have to show that conditions (i) and (ii) in the definition of the equilibrium are satisfied. First, we consider the decision problem of the informed trader. Let $X_0 \in [-\delta_X; \delta_X]$. Assume that the swap dealers apply the linear pricing rule

$$r^*(X_1 + Y) = r^0 + \lambda(X_1 + Y), \qquad (18)$$

where $\lambda > 0$ is a constant. We will show at a later stage of the proof that

$$\lambda > \frac{\rho}{2}\frac{\delta_V}{2\delta_V + \hat{\delta}_V - \delta_X}. \qquad (19)$$

But then, by lemma A.2 below, the informed trader does not participate in the swap market for $|X_0| < \hat{\delta}_V$, and submits the bid

$$X_1^*(X_0, \alpha) = \frac{\rho}{4\lambda - \rho}(X_0 - \hat{\delta}_V \text{sign}(X_0)) \qquad (20)$$

for $|X_0| \geq \hat{\delta}_V$. From (20), the distribution of X_1, conditional on $b = 1$, is uniform on the interval $[-\delta_1; \delta_1]$, where

$$\delta_1 = \frac{\rho}{4\lambda - \rho}(\delta_X - \hat{\delta}_V) \tag{21}$$

is the maximum market order of the informed trader. By theorem 3.1 in Bagnoli, Viswanathan, and Holden (2001), a linear equilibrium requires $\delta_Y = \delta_1$. This proves (12). Solving (21) for λ and subsequently using (18) proves (14). Further, inequality (19) is equivalent to

$$\frac{4\lambda}{\rho} = 1 + \frac{\delta_X - \hat{\delta}_V}{\delta_Y} > 1 + \frac{\delta_X - \hat{\delta}_V}{2\delta_V + \hat{\delta}_V - \delta_X}.$$

Subtracting one on both sides and invoking (11) shows that (19) is indeed satisfied. Finally, lemma A.3 below and (12) deliver (13). Checking the expressions (15), (16), and (17) is a straightforward exercise. This completes the proof of lemma A.1.

LEMMA A.2. *Assume (11) and (19). Then the informed trader does not participate in the swap market for* $|X_0| < \hat{\delta}_V$, *and submits the bid (20) whenever* $|X_0| \geq \hat{\delta}_V$.

Proof. When the central bank fine-tunes successfully with probability α, then the net interest for the informed trader amounts to

$$\begin{aligned}\pi(X_0, X_1, S, \alpha) &= X_0\big(r(S,\alpha) - r^0\big) \\ &\quad + X_1(r(S,\alpha) - r^*) + S\big(r(S,\alpha) - r^{L/D}(S)\big).\end{aligned} \tag{22}$$

Assuming (18), the expected profit for the informed trader is given by

$$E_Y[\pi] = -\lambda X_1^2 + (X_0 + X_1 + S)\big(r(S,\alpha) - r^0\big) + S\big(r^0 - r^{L/D}(S)\big).$$

Using lemma A.3, the informed trader's objective function reads

$$h(X_1) = E_Y[\pi(X_0, X_1, S^*(X_0 + X_1), \alpha)]$$
$$= \begin{cases} -\lambda X_1^2 & \text{if } |X| < \hat{\delta}_V \\ -\lambda X_1^2 + \dfrac{\rho}{4}(|X| - \hat{\delta}_V)^2 & \text{if } \hat{\delta}_V \leq |X| < \hat{\delta}_V + 2\delta_V \\ -\lambda X_1^2 + \rho\delta_V(|X| - \delta_V - \hat{\delta}_V) & \text{if } |X| \geq \hat{\delta}_V + 2\delta_V. \end{cases} \tag{23}$$

From (11) and (19), we obtain $4\lambda > \rho$. Under this condition, the objective function $h(X_1)$ is continuously differentiable and strictly concave on $\mathbb{R}$. The necessary and sufficient condition for the optimum is therefore $h'(X_1) = 0$. Note that the third case, $|X_0 + X_1^*| \geq \hat{\delta}_V + 2\delta_V$, is not possible. This is because in this case the first-order condition would imply $|X_1^*| = \rho\delta_V/(2\lambda)$, but then, using (19), we obtain $|X| \leq |X_0| + |X_1^*| < \hat{\delta}_V + 2\delta_V$, a contradiction. Assume now $|X_0| \geq \hat{\delta}_V$. By straightforward extension of proposition 2, we have $\text{sign}(X_1^*) = \text{sign}(X_0)$ for $X_0 \neq 0$. But then clearly $|X| < \hat{\delta}_V$ is impossible, which yields (20). Consider now $|X_0| < \hat{\delta}_V$. Formula (20) would imply a reversed sign for X_1, so this is clearly not feasible. Hence $X_1^* = 0$ in this case. This proves the assertion.

LEMMA A.3. *In the uniform model with fine-tuning, let* $\hat{\delta}_V = \delta_V/(1-\alpha)$, *as before. Then* $S^*(X, \alpha) = 0$ *for* $|X| < \hat{\delta}_V$, *while* $S^*(X, \alpha) = -sign(X)(|X| - \hat{\delta}_V)/2$ *for* $\hat{\delta}_V \leq |X| < \hat{\delta}_V + 2\delta_V$, *and* $S^*(X, \alpha) = -sign(X)\delta_V$ *for* $|X| \geq \hat{\delta}_V + 2\delta_V$.

Proof. Consider first the case $X > 0$. Without fine-tuning, Poole's lemma implies $r(S) = r^0 - S\Delta/\delta_V$ for $|S| \leq \delta_V$. Using (8) yields $r(S, \alpha) = r^0 - S\Delta/\hat{\delta}_V$ for $|S| \leq \delta_V$. Clearly, $S^*(X, \alpha) \leq 0$. The necessary first-order condition for an interior solution reads $X = \hat{\delta}_V - 2S$. Thus, an interior solution of the informed trader's problem at the end of date 1 exists and is given by $S^*(X, \alpha) = -(X - \hat{\delta}_V)/2$ for $\hat{\delta}_V < X < \hat{\delta}_V + 2\delta_V$. Otherwise, there is a boundary solution. From

$$\pi(X_0, X_1, -\delta_V, \alpha) - \pi(X_0, X_1, 0, \alpha) = (1-\alpha)(X - 2\hat{\delta}_V)\Delta$$

it is obvious that $S^*(X,\alpha) = 0$ for $|X| \leq \hat{\delta}_V$, and $S^*(X,\alpha) = -\delta_V$ for $X \geq \hat{\delta}_V + 2\delta_V$. An analogous consideration can be made for the case $X < 0$. Hence, the assertion.

Proof of Proposition 6. Write $r(S,\alpha,\Delta)$ for the market rate in a corridor system with half-width Δ at date 2 around r^0, after a recourse of S, and with a probability α of successful fine-tuning. Using (8) and Poole's lemma yields

$$\begin{aligned} r(S,\alpha,\Delta) &= \alpha r^0 + (1-\alpha)\left\{\Phi_V(S) r_2^D + (1-\Phi_V(S)) r_2^L\right\} \\ &= \Phi_V(S)\left(\alpha r^0 + (1-\alpha) r_2^D\right) \\ &\quad + (1-\Phi_V(S))\left(\alpha r^0 + (1-\alpha) r_2^L\right) \\ &= r(S, 0, (1-\alpha)\Delta). \end{aligned}$$

Thus, fine-tuning with probability $\alpha = 1 - 1/\beta$ is equivalent to narrowing the interest rate corridor on date 2 from Δ_1 to $\Delta_2 = (1-\alpha)\Delta_1 = \Delta_1/\beta$.

Proof of Proposition 7. Under the assumptions made, trader i's objective function reads

$$\bar{\pi}^i(X^i, S^i, S^{-i}) = X^i(r(S^i + S^{-i}) - r^0) + S^i(r(S^i + S^{-i}) - r^{L/D}(S^i)),$$

where $X^i = X_0^i$. Consider first the case $X^i \geq 0$. Then, for any S^{-i}, choosing $S^i > 0$ is always (weakly) inferior for trader i than $S^i = 0$ because

$$\begin{aligned} &\bar{\pi}^i(X^i, S^i, S^{-i}) - \bar{\pi}^i(X^i, 0, S^{-i}) \\ &\quad = X^i(\underbrace{r(S^i + S^{-i}) - r(S^{-i})}_{\leq 0}) + S^i(\underbrace{r(S^i + S^{-i}) - r^L}_{\leq 0}) \leq 0. \end{aligned}$$

Thus, $S^i \leq 0$. Moreover, in the uniform case, choosing S^i such that $S^i + S^{-i} < -\delta_V$ is inferior to choosing S^i equal to $-\delta_V - S^{-i}$ because

$$\begin{aligned} &\bar{\pi}^i(X^i, S^i, S^{-i}) - \bar{\pi}^i\left(X^i, -\delta_V - S^{-i}, S^{-i}\right) \\ &\quad = (S^i + S^{-i} + \delta_V)(r^L - r^D) < 0. \end{aligned}$$

Thus, if $S^{-i} < -\delta_V$ then an optimal recourse is given by $S^{i,*}(X^i, S^{-i}) = 0$. Moreover, if $S^{-i} \geq -\delta_V$ then $S^{i,*}(X^i, S^{-i}) \in$

$J^- = [-\delta_V - S^{-i}; 0]$. For values $S^i \in J^-$, trader i's objective function is differentiable and strictly concave with respect to S^i. The interior solution $S^{i,*}(X^i, S^{-i}) = (\delta_V - X^i - S^{-i})/2$ stays within J^- provided that $\delta_V - S^{-i} \leq X^i \leq 3\delta_V + S^{-i}$. In a symmetric equilibrium, $S^{-i} = (N-1)S^i$. Thus $S^{i,*}(X^i) = (\delta_V - X^i)/(N+1)$ for $\delta_V \leq X^i \leq 2 + \delta_V/N$, and we have established an equilibrium. The case of $X^i \leq 0$ can be treated in an analogous way.

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Monetary Policy under Imperfect Commitment: Reconciling Theory with Evidence*

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In the standard forward-looking models of the recent literature, theoretical optimal monetary policy rules imply much higher inertia of interest rates than estimated historical policy rules. Motivated by the observation that theoretical policy rules often assume perfect commitment on the part of the monetary authority, this study formulates the monetary policy behavior with a continuum from discretion to full commitment and, using this setup, seeks to match the theory with evidence. It is shown that optimal instrument rules under imperfect commitment exhibit less inertia on the policy instrument; the degree of inertia declines as the policy moves from full commitment to discretion. Therefore, under the assumption that the monetary authorities operate somewhere in between discretion and commitment, historically observed policy behavior can be reconciled with the optimal policy rules—even in a purely forward-looking framework. As a by-product, we propose a method to measure the stance of monetary policy from the perspective of discretion versus commitment. To test our proposal, we estimate a structural monetary policy rule for the Federal Reserve, which nests discretion and commitment as special cases. Empirical results suggest that recent practice of monetary policy has been closer to commitment than the policy pursued in the 1970s.

JEL Codes: E52, E58.

*I would like to thank Pierpaolo Benigno, Oriol Carbonell, Efrem Castelnuovo, Faruk Gul, Mark Gertler, Marc Giannoni, Ken Kuttner, John Williams, an anonymous referee, and seminar participants at Boğaziçi University, Bilkent University,

1. Introduction

In the standard forward-looking models of the recent literature, theoretical optimal monetary policy rules under commitment imply much higher inertia of interest rates than estimated historical policy rules. For example, Rotemberg and Woodford (1998) and Giannoni and Woodford (2003) derive optimal policy rules under commitment using standard baseline forward-looking models. These authors emphasize that *theoretical* optimal rules not only involve intrinsic inertia in the dynamics of the funds rate, but also are actually "super-inertial," i.e., implied dynamics involves a root larger than one. However, as is also emphasized in these and many other studies, *estimated* historical rules typically do not have this property. On the other hand, optimal rules computed under discretion in forward-looking models are far less inertial—if inertial at all—than the estimated rules. This observation suggests that a policy rule somewhere in between commitment and discretion may reconcile the observed degree of inertia with theoretically implied ones in forward-looking models.

This paper, then, attempts to match recommendations of the theoretical models with actual estimates of the historical rule, by incorporating some degree of imperfection to typical full-commitment solutions. We introduce the notion of "imperfect commitment" to emphasize that the policymaker acts in a state between discretion and commitment. Accordingly, we construct a continuous metric for the stance of monetary policy from a discretion versus commitment standpoint, in which full discretion and full commitment correspond to one and zero, respectively, while imperfect commitment is in between. Using this metric, we seek to answer how much discretion (or equivalently how much commitment) must be introduced into the standard baseline model, so that the degree of inertia implied by the theoretically optimal policy rule matches the historical one.

Recently, there have been a number of attempts to match the theoretical rules with the estimated rules. However, these studies

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consider backward-looking models, where the discretionary solution is exactly the same as the solution under commitment—incorporating no intrinsic inertia in the behavior of the policymaker other than that embedded in the structural law of motions. Moreover, these studies either assume an ad hoc interest rate smoothing objective (as explained, e.g., in Sack and Wieland 2000) or introduce uncertainty (e.g., as in Rudebusch 2001) to obtain more inertial theoretical rules. Therefore, the problem they need to address is how to obtain *more* history dependence in theoretical rules—exactly the opposite of what we have in this study.

We argue that deviations of the actual monetary policy rule from the full-commitment rule can be decomposed into two main sources: first, as in Schaumburg and Tambalotti (2006), commitments are imperfect, because they do not last forever. One interpretation may be that, due to publicly known factors such as reappointments of the central bank administrations, large aggregate shocks, or institutional environment, the policymaker reoptimizes with a fixed probability that is common knowledge. Second, commitments are imperfect because the central bank lacks some credibility, in the sense that private agents in general expect the commitment to last a shorter period of time than is intended by the central bank.

The notion of imperfect commitment we consider here is purely exogenous rather than behavioral. But still, the mechanism gives us enough room to formulate a continuum between discretion and commitment. We show that, under imperfect commitment, observed behavior of the instrument of the central bank will be related to past values of the instrument itself and other target variables in a less inertial way, rendering the implied theoretical policy behavior closer to the estimated ones. In fact, within the setting, by choosing the "appropriate" degree of commitment, any degree of interest rate inertia can be obtained from the central bank's optimization problem.

On the other hand, our theoretical approach to represent instrument rules under imperfect commitment suggests a method to construct a performance measure of the policy pursued by the central banks. For once the dynamic inefficiency is parametrized and incorporated into the policy rule, it can be identified directly by estimating the structural instrument rule. This provides a stance of monetary policy on the grounds of proximity to full-commitment behavior. If one regards the full commitment with perfect credibility as the ideal policymaking, then it can be argued that the more the policy behavior deviates from it, the less efficient is the policy rule.

Accordingly, we specify an instrument rule embedding the assumptions just mentioned and estimate the theoretically constructed commitment parameter for the terms of three Federal Reserve governors. Empirical findings suggest that monetary policy during the Volcker and Greenspan tenures were conducted with a similar degree of commitment. Moreover, provided that the policymakers had a similar model in their mind, post-1980 (Volcker-Greenspan) policy was closer to commitment than the policy followed during the 1970s (Burns-Miller).

While estimating the policy preferences directly from the policy rule is common in recent studies,[1] to our knowledge, there is no reported attempt in the literature to quantify a measure of the degree of commitment of the monetary policy by directly estimating a structural policy rule. In that sense, we believe, our approach is novel.

To illustrate the main theme, the next section summarizes the instrument rule (or the policy reaction function) derived by Giannoni and Woodford (2003). Section 3 derives an imperfect commitment version of the rule and discusses under what conditions it can match theory with evidence. Section 4 carries out a structural empirical exercise to estimate the stance of monetary policy during different periods by using the metric introduced in the previous section, and section 5 concludes.

2. A Standard Optimal Interest Rate Rule

Giannoni and Woodford (2003) derive an instrument rule that is in the same form as estimated Taylor-wise rules. Using a similar setup explained below, these authors' proposed policy rule consistent with the optimal state-contingent plan takes the form

$$i_t = (1 - \rho_1 + \rho_2)i^* + \rho_1 i_{t-1} - \rho_2 i_{t-2} + \phi_\pi \pi_t + \phi_x \Delta x_t, \qquad (1)$$

[1] See Favero and Rovelli (2003) and Özlale (2003), for example.

where

$$\rho_1 = 1 + \frac{\kappa}{\sigma\beta} + \beta^{-1} > 2, \quad \rho_2 = \beta^{-1} > 1, \tag{2a}$$

$$\phi_\pi = \frac{\kappa}{\sigma\lambda_i} > 0, \quad \phi_x = \frac{\lambda_x}{\sigma\lambda_i} > 0, \tag{2b}$$

and $\sigma, \beta, \kappa, \lambda_x, \lambda_i$ are structural parameters and policy preference parameters to be explained below.[2] One can use the calibrated values of structural parameters to contrast the theoretical rule under full commitment with the empirical ones. Using the values estimated by Judd and Rudebush (1998) for the period 1987–96 of Greenspan's term, and the parameters calibrated in Woodford (2003a), for example, Giannoni and Woodford (2003) obtain the following:

	ρ_1	ρ_2	ϕ_π	ϕ_x
estimated	1.16	.43	.42	.30
theoretical	2.16	1.01	.64	.33

Note that in the empirical reaction function, ϕ_x represents the coefficient on the level of, rather than the change in, the output gap. This is because estimated historical rule shows no reaction to past output gaps for the Greenspan period.[3] It is clear that, in parametric terms, the theoretical rule, which is derived under infinitely lasting and perfectly credible commitment, explains *qualitatively* how forward-looking models can deliver the interest rate inertia that is observed in empirical reaction functions. Moreover, the signs of the reaction parameters are consistent with the historical evidence.

Nevertheless, the table reveals an important *quantitative* distinction. The estimated rule (like all other estimated rules in recent studies) exhibits much less inertia on the part of the instrument than the theoretical rule would suggest: as explained above, microfoundations for the theoretical model imply that $\sigma > 0$, $\kappa > 0$, and $0 < \beta < 1$,[4] and thus ρ_1 and ρ_2 have to satisfy conditions (2a),

[2] When the policy is time dependent, initial conditions of $x_1 = i_0 = i_1 = 0$ have to be added to (1).

[3] It involves a significant reaction to the difference of the output gap for the Volcker period, though.

[4] See Woodford (2003a, chap. 4).

implying super-inertial behavior of the instrument *regardless of any specific calibration of the model.*[5] Therefore, not only do the two rules look different in terms of magnitudes of the reaction coefficients, but indeed, there are no feasible parameter values reconciling the super-inertial behavior of the theoretical rule with the historical ones.

3. Optimal Instrument Rule under Imperfect Commitment

In this section, we introduce a generalized version of the instrument rule (1). Our purpose is twofold: First, we wish to explore the implications of relaxing the assumption of full commitment (or perfect credibility) to allow for partial degree of discretion and to see if this can be helpful in matching empirically observed rules with the theoretical ones. Second, we want to prepare grounds for deriving a method to measure the dynamic efficiency of the Federal Reserve policy by direct structural estimation of the instrument rule, and for conducting an assessment of past U.S. monetary policy on these grounds.

3.1 The Model

The structural model and the objective of the central bank is identical to Giannoni and Woodford (2003) except that we assume the central bank targets a positive rate of inflation.[6] The baseline model is a standard forward-looking model consisting of an IS curve and an AS curve, which have increasingly became the workhorses of contemporary monetary policy analysis.[7]

The model consists of two structural equations that are derived from optimizing behavior of the private sector: an aggregate-supply

[5] This can be seen by writing the instrument rule as $i_t = (1-\rho_1+\rho_2)i^* + (\rho_1 - \rho_2)i_{t-1} - \rho_2 \Delta i_{t-1} + \phi_\pi \pi_t + \phi_x \Delta x_t$ and observing that $\rho_1 - \rho_2 = 1 + \frac{\kappa}{\sigma\beta} > 1$ and $\rho_2 = \beta^{-1} > 0$. Note that the restrictions imposed in (2a) and (2b) are not model specific. Thus, super-inertia is a fairly general property of the optimal interest rate rules in forward-looking models.

[6] This assumption only affects the constant term in the theoretical instrument rule.

[7] See, for example, Clarida, Galí, and Gertler (1999) and Woodford (1999, 2003b), among others.

equation derived from the first-order condition for optimal price setting by the representative supplier and an IS curve derived from a Euler equation for the optimal timing of purchases. The New Keynesian aggregate-supply (AS) equation takes the form

$$\pi_t = \kappa x_t + \beta E_t \pi_{t+1} + u_t, \tag{3}$$

where π_t is the period t inflation rate defined as the percentage change in the price level from $t-1$ to t; x_t is the output gap, which is defined as the percentage by which output exceeds its potential; $0 < \beta < 1$ is a discount factor; κ is a positive coefficient; and u_t is an exogenous disturbance term. We use the notation $E_t \pi_{t+1}$ to denote private-sector expectations regarding $t+1$ conditional on information available in period t. Equation (3) relates inflation to output gap in the spirit of a traditional Phillips curve. In contrast to the traditional Phillips curve, current inflation depends on the expected future course of the economy, and thus on expectations of future monetary policy, because firms set prices based on expected marginal costs. Within the framework, monetary policy affects real economy, because sellers cannot change their price every period. The parameter κ can be interpreted as a measure of the speed of the price adjustment. Output gap x_t captures marginal costs associated with excess demand. This specification allows for a shock u_t, which shifts the distance between the potential output and the level of output that would be consistent with zero inflation. These shifts are not considered to represent variation in potential output, and thus appear as a residual in (4). We will name u_t simply the "supply shock."

The aggregate-demand (IS) equation takes the form

$$x_t = -\sigma^{-1}\left[i_t - E_t \pi_{t+1} - r_t^n\right] + E_t x_{t+1}, \tag{4}$$

where i_t is the central bank's instrument, which is a short-term nominal interest rate; σ is a positive coefficient (the intertemporal elasticity of substitution); and r_t^n is the natural rate of interest. Deviations of output from the potential output depend upon real interest rate, expected future output gap, and the natural rate of interest. These structural equations can be derived as log-linear approximations to equilibrium conditions of a simple dynamic general equilibrium model in which an infinitely lived representative household maximizes its lifetime utility. For analytical tractability of the solution, exogenous disturbances u_t and r_t^n are assumed to be i.i.d., and $E(r_t^n - \bar{r}) = E(u_t) = 0$. The two structural equations (3) and (4), together with a policy rule, determine the equilibrium evolution of endogenous variables π_t, x_t, and i_t.

The objective of the monetary policy is of the form

$$W = E_0 \left\{ \sum_{t=0}^{\infty} \beta^t \left[(\pi_t - \pi^*)^2 + \lambda_x (x_t - x^*)^2 + \lambda_i (i_t - i^*)^2 \right] \right\}, \quad (5)$$

where π^*, x^*, and i^* are target values for inflation, output gap, and interest rate, respectively. Although their theoretical value can be derived from the quadratic approximation of the representative agent's utility function, we will assume that the parameters λ_x and λ_i can be treated as the policymaker's preferences. As will be clear later, the analysis in this study goes through any objective function that can be represented in the form as (5), whether it represents theoretical welfare or not. It is important to note here that, unlike many empirical studies that attempt to match the inertial nature of the empirical reaction functions with the theoretical ones,[8] the objective (5) does not contain an ad hoc interest rate *smoothing*. Introducing interest rate *targeting* into objective function, on the other hand, is justified in Woodford (2003a). Accordingly, the only source of inertia in this study will stem from the *optimal* inertia due to forward-looking behavior.

The problem the policymaker faces is having to choose a policy rule to implement the equilibrium processes that minimize (5) subject to (3) and (4). Depending on the availability of "commitment technology," there are two main approaches in the literature to solve this problem: Under full commitment, the central bank optimizes once and for all, and announces a state-contingent policy rule that will be implemented forever.[9] Under discretion, the central bank reoptimizes each period.

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[8]See, for example, Rudebush (2001) or Sack and Wieland (2000), among others. These authors use a purely backward-looking model of the economy; hence, in their framework, dynamic inconsistency does not exist. Therefore, the notion of imperfect commitment is irrelevant to these studies.

[9]It is important to note here that what we mean by full commitment is Woodford's (2003a, chap. 7) timelessly optimal commitment.

3.2 Formulating Imperfect Commitment

A convenient way to introduce an intermediate behavior between discretion and full commitment is to divert from the two main assumptions underlying commonly used full-commitment setup in the literature. The first assumption is that commitments last forever. Following Roberds (1987) and Schaumburg and Tambalotti (2006), we generalize this condition by assuming an exogenous process that generates stochastic reformulation of the commitment, thereby creating finite lasting commitments on average. On the other hand, a second crucial assumption in full-commitment models is that the central bank has perfect credibility of intentions. That is, the private sector expects the future course of monetary policy to be in line with the central bank's true intentions. We relax this assumption and introduce imperfect credibility into the model by allowing the private sector's expected regime duration to differ from the policymaker's true intentions.

3.2.1 Finite Commitment Regime

Suppose there is an exogenous stochastic signal realized at the beginning of each period that takes the values "optimize" with probability α^o and "do not optimize" with probability $(1 - \alpha^o)$; i.e., the central bank reformulates the policy with probability α^o each period. In this case, average duration of a commitment regime turns out to be $\frac{1}{\alpha^o}$; hence, the commitment will be finite for nonzero values of α^o. The private agents take the probability of a reoptimization correctly into account, and the policymaker is aware of the fact that it may be necessary to reformulate the policy with probability α^o. After each reoptimization, the central bank commits to a rule that is optimal as of the most recent period. The new commitment is also expected to end with probability α^o, and so on.[10]

[10]It is worth emphasizing that the central bank does not face a typical time-inconsistency problem here. The central bank is able to formulate an ex ante time-consistent plan but still may have to reoptimize at some point, depending on the outcome of the stochastic process. The stochastic process that generates the reoptimizations is completely exogenous. That is, the imperfection in the commitment is not a behavioral concept.

3.2.2 Imperfect Credibility of Intentions

Now, assume that the central bank still expects to reoptimize with probability α^o; however, the private agents expect the central bank to reformulate the policy with a probability $\alpha^o + \mu$, where μ represents the imperfect credibility of intentions.[11] In other words, the private sector thinks the regime will, on average, last for $\frac{1}{\alpha^o+\mu}$ periods, which is shorter than $\frac{1}{\alpha^o}$. The central bank knows μ and takes the behavior of the private sector into account while computing the optimal rule. In other words, the central bank takes the private sector's beliefs into account to the extent that they affect expectations of future inflation and output gap, but the central bank still reoptimizes its policy with the probability α^o.

We will assume that $1 - \alpha^o > \mu > 0$, and μ is exogenously given and cannot be changed by the central bank in the short run. Given α^o, the higher is μ, the less credible is the central bank. When $\mu = 1 - \alpha^o$, private agents expect the central bank to reoptimize every single period, reflecting complete lack of credibility. If $\mu = 0$, the monetary authority has fully credible intentions, since the private sector expects the regime to last on average $\frac{1}{\alpha^o}$ periods, as intended by the policymaker. Consequently, the policy is conducted in such a way that it incorporates these two imperfections, impeding the commitment behavior. Solving the optimal monetary policy problem subject to these two assumptions will yield a policy rule that nests discretion and commitment as special cases.[12]

To summarize, $1 - (\alpha^o + \mu)$ stands for the overall proximity to full-commitment behavior. In this setup, commitment is imperfect for two reasons: α^o represents the finite nature of the commitment, while μ represents the imperfect *credibility* of intentions. In what follows, we will use a composite index to denote the overall imperfection in the policy (or equivalently the degree of dynamic

[11]This can happen, e.g., when there is a sudden shift to a longer commitment regime, due to natural or administrative factors, which may not be perceived by the private agents immediately.

[12]Note that there are many credibility definitions in the literature. For example, Miller (1997) decomposes credibility in two terms: credibility of ability and credibility of intentions. From that perspective, α^o can be used to quantify credibility of ability, μ can be used for credibility of intention, and consequently, $1 - \alpha^o - \mu$ stands for the overall credibility of the central bank.

inefficiency), simply as $\alpha^o + \mu = \alpha$, which also denotes the private agents' subjective belief of the probability of a reoptimization.

3.3 Central Bank's Problem under Imperfect Commitment

In general, a Lagrangian of the monetary authority under full commitment can be constructed as

$$E_0\Bigg\{\sum_{t=0}^{\infty}\beta^t\Big[(\pi_t-\pi^*)^2+\lambda_x(x_t-x^*)^2+\lambda_i(i_t-i^*)^2 \\ +\varphi_{1,t+1}(\pi_t-\kappa x_t-\beta E_t\pi_{t+1}-u_t) \\ +\varphi_{2,t+1}(x_t+\sigma^{-1}\left[i_t-E_t\pi_{t+1}-r_t^n\right]-E_t x_{t+1})\Big]\Bigg\}. \tag{6}$$

In an environment where commitments end stochastically and the central bank has only partial credibility, the problem is not trivial. The key question here is whether the peculiar nature of the policymaker's and the private sector's expectations can be incorporated into the conventional Lagrangian form or it will be more convenient to use a Bellman-type setting. As will be seen below, the answer turns out to be both.[13]

Following Schaumburg and Tambalotti (2006), it will be useful to decompose the private-sector expectations into intra-regime and inter-regime components. For example, one-period-ahead expectations of the private sector can be written as

$$E_t[z_{t+1}]=\alpha E_t[z_{t+1}|\textit{inter-regime}]+(1-\alpha)E_t[z_{t+1}|\textit{intra-regime}], \tag{7}$$

where inter-regime means conditional on a regime change (i.e., period t and $t+1$ belong to different regimes), intra-regime means the current regime goes through the next period (i.e., periods t and $t+1$ belong to the same regime), and z_t stands for any endogenous forward-looking variable at time t.

Note that, due to the quasi-discretionary nature of the policy formulation, the problem is circular. In order to compute the optimal rule and the equilibrium processes, one has to solve for the

[13]See Kara (2004) for a detailed exposition.

expectations; on the other hand, in order to solve for expectations, one has to determine the optimal equilibrium. Fortunately, this problem can be solved analytically by exploiting the purely forward-looking nature of the structural model, and with the help of a plausible guess. The main idea is to represent private-sector expectations with intra-regime terms only (i.e., steering away the overlapping expectations problem), so that all the choice variables in the optimization problem belong to the same commitment regime.

In order to understand fully the monetary authority's problem, it will be helpful to note the recursive nature of the problem at a glance. Let $\Delta\tau$ be the (random) duration of the regime that started at time 0. Then, the minimum achievable value of (5) can be expressed recursively as

$$V_0 = \min_{\pi_t, x_t, i_t} E_0 \left\{ \sum_{t=0}^{\Delta\tau - 1} \left[(\pi_t - \pi^*)^2 + \lambda_x (x_t - x^*)^2 + \lambda_i (i_t - i^*)^2 \right] + \beta^{\Delta\tau} V_{\Delta\tau} \right\} \tag{8}$$

subject to (3) and (4),

where V_t is defined as a value function associated with the central banker's optimal loss at time t. This term appears because the central banker is assumed to take into account not only the losses accrued during the current regime but also the losses of all subsequent regimes. The latter is summarized by a terminal payoff $V_{\Delta\tau}$ in the objective function.

The central bank's loss function involves a random running cost function (the first term on the right-hand side). When the commitment term ends unexpectedly—say, at $t + \Delta\tau$—the central banker's successor faces exactly the same type of problem. The recursive formulation implies that the solution to (8) will be optimal for the successive central bankers as well.

We will be looking for a solution in which the endogenous variables will be linear functions of the state of the economy. To break in the recursive nature of the problem, one can exploit the linear structure by proposing an "educated guess" of the state variables and the solution form.

Claim 1. *Optimum equilibrium processes for the endogenous variables at time t can be expressed as a linear combination of the Lagrange multipliers $\varphi_{1,t}$, $\varphi_{2,t}$, and the exogenous processes u_t, r_t^n.*

Verification. Using the claim, one can obtain a simple characterization of the one-period-ahead private-sector expectations by noting that

$$E_t[\hat{z}_{t+1}|inter\ regime] = E_t[a_1\varphi_{1,t+1} + a_2\varphi_{2,t+1} + b_1 u_{t+1} + b_2\hat{r}^n_{t+1}|inter\ regime] = 0, \quad (9)$$

where $\hat{z}$ denotes the deviation of a variable z from the steady state and $\hat{r}^n_{t+1} = r^n_{t+1} - \bar{r}$. The second equality in (9) is obtained by noting that Lagrange multipliers will be zero at the period of policy reformulation, reflecting the notion that the central bank is not bound by any past promises. Thus (7) can be simplified to

$$E_t[\hat{z}_{t+1}] = (1-\alpha)\tilde{E}_t\hat{z}_{t+1}, \quad (10)$$

where $\tilde{E}$ stands for the expectation operator conditional on the regime staying the same. On the other hand, V_t will be a quadratic function of the state variables—namely $\varphi_{1,t}$, $\varphi_{2,t}$—and the exogenous processes u_t, r_t^n at the regime starting at time t.[14] However, at the beginning of a new regime, the Lagrange multipliers will be set to zero, indicating the disregard of past commitments. Therefore, the value function will only depend on the exogenous processes u_t and $\hat{r}_t^n$. Accordingly, the Lagrangian of the central bank can be written as

$$E_0\left\{\sum_{j=0}^{\infty}(1-\alpha^o)^{j-1}\alpha^o\left[\beta^j V\left(u_j, \hat{r}_j^n\right) + \sum_{t=0}^{j-1}\beta^t\frac{1}{2}\left(\hat{\pi}_t^2 + \lambda_x\hat{x}_t^2 + \lambda_i\hat{\imath}_t^2\right) + \varphi_{1,t+1}(\hat{\pi}_t - \kappa\hat{x}_t - \beta(1-\alpha)\hat{\pi}_{t+1} - u_t) + \varphi_{2,t+1}\left(\hat{x}_t + \sigma^{-1}\left[\hat{\imath}_t - \hat{\pi}_{t+1} - \hat{r}_t^n\right] - (1-\alpha)\hat{x}_{t+1}\right)\right]\right\},$$

[14]See Ljungqvist and Sargent (2000, chap. 4).

which can be simplified to

$$E_0\left\{\sum_{t=0}^{\infty}((1-\alpha^o)\beta)^t\left[\alpha^o\beta V\left(u_{t+1},\hat{r}^n_{t+1}\right)+\frac{1}{2}\left(\hat{\pi}_t^2+\lambda_x\hat{x}_t^2+\lambda_i\hat{\imath}_t^2\right)\right.\right.$$
$$+\varphi_{1,t+1}(\hat{\pi}_t-\kappa\hat{x}_t-\beta(1-\alpha)\hat{\pi}_{t+1}-u_t)$$
$$\left.\left.+\varphi_{2,t+1}\left(\hat{x}_t+\sigma^{-1}\left[\hat{\imath}_t-\hat{\pi}_{t+1}-\hat{r}^n_t\right]-(1-\alpha)\hat{x}_{t+1}\right)\right]\right\}.$$

First-order necessary conditions with respect to π_t, x_t, and i_t are

$$\hat{\pi}_t+\varphi_{1,t+1}-\varphi_{1,t}\frac{1-\alpha}{1-\alpha^o}-(\beta\sigma^{-1})\varphi_{1,t}=0 \tag{11}$$

$$\lambda_x\hat{x}_t-\kappa\varphi_{1,t+1}+\varphi_{2,t+1}-\frac{1-\alpha}{1-\alpha^o}\beta^{-1}\varphi_{2,t}=0 \tag{12}$$

$$\lambda_i\hat{\imath}_t+\varphi_{2,t+1}=0, \tag{13}$$

at each date $t\geq 0$, within the regime starting at time 0. In addition, initial conditions $\varphi_{2,0}=\varphi_{1,0}=0$ have to be added, reflecting the fact that at the period of optimization, the monetary authority is not bound by past promises. One has to note that these first-order conditions define the optimal behavior of the policymaker at any regime: once a reoptimization takes place at time t, it will lead to exactly the same policy as the previous ones, given the initial conditions $\varphi_{2,t}=\varphi_{1,t}=0$.[15] In that sense, first-order conditions represent the optimal policy behavior inside *any* commitment regime.

Moreover, since the problem is linear quadratic, first-order conditions (11), (12), and (13) and the constraints (4) and (3) together with the initial conditions are sufficient to determine the optimal plan. Using (13) to substitute for the interest rate, the dynamic system (11), (12), (4), and (3) can be represented in the matrix form as

$$\begin{bmatrix}E_t\hat{z}_{t+1}\\ \varphi_{t+1}\end{bmatrix}=H\begin{bmatrix}\hat{z}_t\\ \varphi_t\end{bmatrix}+G\xi_{t+1}, \tag{14}$$

[15]It may appear that the conditions (11), (12), and (13) reflect the once-and-for-all solution to the optimization problem as in the full-commitment case. However, in this setup, monetary authority optimizes more than once, leading to a completely different equilibrium than the equilibrium characterized by solving (11), (12), and (13) together with (4) and (3).

where $\hat{z}_t \equiv [\hat{\pi}_t, \hat{x}_t]'$, $\varphi_t = [\varphi_{1,t}, \varphi_{2,t}]'$, $\xi_t = [u_t, \hat{r}_t^n]$ and H and G are matrices whose elements involve structural parameters. This system has a unique bounded solution if and only if H has exactly two eigenvalues outside the unit circle. It turns out that the system satisfies this condition, in which case the solution for the endogenous variables can be expressed as

$$q_t = A\varphi_t + \sum_{j=0}^{\infty} B_j E_t \xi_{t+j} = A\varphi_t + B_0 \xi_t, \tag{15}$$

verifying the guessed solution (9).

Theoretical Interest Rate Rule under Imperfect Commitment. Following Woodford and Giannoni (2003), it is possible to rearrange the first-order conditions to obtain an instrument rule for the interest rates. From (12) and (13), one can solve the Lagrange multipliers as functions of x_t, i_t, and i_{t-1}. Using these expressions to substitute out the Lagrange multipliers in (11), one can obtain a linear relation among the variables π_t, x_t, i_t, i_{t-1}, and i_{t-2}, which can also be expressed as an *instrument rule* of the form[16]

$$i_t = \bar{\delta} + \bar{\eta}_1 i_{t-1} - \bar{\eta}_2 i_{t-2} + \phi_\pi \pi_t + \phi_x x_t - (1-\alpha)\phi_x x_{t-1}, \tag{16}$$

with initial conditions of

$$i_{-1} = 0, \quad i_{-2} = 0, \tag{17}$$

where

$$\bar{\eta}_1 = \frac{1-\alpha}{1-\alpha^o}\rho_1, \;\; \bar{\eta}_2 = (\frac{1-\alpha}{1-\alpha^o})^2 \rho_2.$$

As explained above, (16) and (17) represent behavior of the central bank *within* a specific commitment regime. In other words, (16) is the average instrument rule inside any regime (starting at time 0 here, without loss of generality), conditional on the regime staying the same forever. However, overall behavior of the central bank

[16] Had the optimality conditions not involved the contemporaneous interest rate, then they would have been called targeting rules as defined by Giannoni and Woodford (2003).

will be different since there will be reoptimizations with an average frequency of α. This exactly amounts to incorporating the finite commitment effect.[17] Accordingly, one can characterize the overall behavior of the instrument rule by summing over regime shocks, i.e., by taking into account that there will be a reoptimization with probability α^o each period. The instrument rule averaged over regime shocks will be given by

$$\begin{aligned} i_t = \delta + (1-\alpha)\rho_1 i_{t-1} - (1-\alpha)^2 \rho_2 i_{t-2} \\ + \phi_\pi \pi_t + \phi_x x_t - (1-\alpha)\phi_x x_{t-1}, \end{aligned} \tag{18}$$

where

$$\delta = (1 - \eta_1 + \eta_2) i^* + \frac{1}{\lambda_i \sigma}(\kappa \pi^* - \alpha x^*). \tag{19}$$

At first sight, it may be surprising to see that the policy rule that is observed on average across regimes only depends on the private sector's assessment of the regime change (α) and not at all on α^o. However, this may not be exactly true since $\alpha = \alpha^o + \mu$. To understand how the observed rule may depend on α^o, just assume that $\mu = 0$. In this case the average rule will look like exactly as in (18), except that α is replaced with α^o.

It is important to notice that imperfections in the commitment process can be decomposed into two sources: α^o reflects the finite duration of the commitment regime, and a nonzero μ represents imperfect credibility of intentions. Suppose, for example, that $\alpha^o = .2$ and $\mu = .3$. In this case, the central bank contemplates an average regime duration of five quarters $\left(\frac{1}{\alpha^o}\right)$, while the private sector expects on average the commitments to last two quarters $\left(\frac{1}{\alpha^o+\mu} = \frac{1}{\alpha}\right)$. Now, the commitment is imperfect because of two reasons: First, commitment is finite (lasts five quarters on average); i.e., the central bank *does* reoptimize every five quarters on average. Moreover, there is a credibility gap (μ), causing the policy response to act in a less inertial way than it would have acted under full credibility.

If both of the parameters are zero, then α is equal to zero; i.e., the central bank can commit for an infinite period *and* the private sector

[17] Recall that the imperfect credibility effect is already embedded in (16).

expects the current commitment to last forever. In such a case, we are at the perfect commitment case that corresponds to Woodford's (2003b) *timelessly optimal commitment*. Once α is allowed to be nonzero (i.e., either α^o or μ is different than zero), then the nature of commitment deviates from the notion of timelessly optimal commitment, since the central bank has to automatically reoptimize as the signal arrives, regardless of the type of the commitment. On the other hand, when α^o is equal to 1 and μ is equal to 0—i.e., if the central bank optimizes each period so that credibility is irrelevant—policy instrument only reacts to current levels of inflation and the output gap, involving no intrinsic inertia. This corresponds exactly to full discretion. For the values in between, (18) reflects the average behavior of the policy instrument under varying degrees of "efficiency."[18] Accordingly, the term $1 - \alpha$ can be named as "proximity to commitment," "degree of commitment," or "degree of dynamic efficiency." As a consequence, $1 - \alpha$ may yield a reasonable metric to rank past monetary policy from the perspective of how efficiently gains from commitment are accrued by the central bank.[19]

3.4 Empirical Rule versus Theoretical Rule: A Comparison under Imperfect Commitment

The theoretical instrument rule (1) derived under full commitment and perfect credibility involves much higher inertia than empirically observed ones. A natural question to ask at this point is, Can the concept of imperfect commitment of the kind introduced here reconcile this discrepancy? Or, to what extent can the observed

[18]We define the optimal policy rule under full commitment as the most dynamically efficient rule.

[19]Our setup does not involve time inconsistency in the sense of Barro and Gordon (1983) since the objective of the policymaker involves target variables that are consistent with the steady state. However, as shown by Woodford (1999) and Clarida, Galí, and Gertler (1999), there are still gains from commitment resulting from forward-looking behavior of the agents—namely, stabilization bias, as it is called by Svensson (1997). In such an environment, the commitment still matters since it can improve the constraints faced by the policymaker, delivering a more efficient output-inflation frontier. In that sense the measure we derive for the stance of monetary policy can be interpreted as a measure of dynamic efficiency, where the most efficient policy corresponds to full commitment under perfect credibility, and the least efficient is the period-by-period optimization.

lack of super-inertia be justified by the imperfect commitment behavior?

Parameters of the instrument rule (18) under imperfect commitment already suggest an interesting result: for any $\alpha \in (0,1)$, (18) will imply a less inertial interest rate path than the rule with full commitment under perfect credibility. This can be seen simply by noting that the largest root of the lag polynomial $(1-\rho_1 z^{-1}+\rho_2 z^{-2})$ is greater than the largest root of the polynomial $(1-\rho_1(1-\alpha)z^{-1}+\rho_2(1-\alpha)^2 z^{-2})$. The former is a measure of the inertia under the full-commitment rule, while the latter reflects the inertia of the rule under imperfect commitment. It is straightforward to show that the ratio of the latter to the former is $(1-\alpha)$; i.e., the degree of inertia is monotonically decreasing in α. This also implies that, given any specific couple of theoretical and empirical interest rates, there exists a level of commitment (equivalently some level of α) that reconciles theory with evidence. More importantly, this result *does not depend on any specific calibration* of the model or any of the estimated coefficients.

What is the range of α that implies a super-inertial rule? This can be answered directly by examining the largest root of the lag polynomial involving the interest rate in (18). Using the calibration in Woodford (2003a), we find that for $\alpha < .32$, (18) exhibits a super-inertial behavior on the part of the instrument. Note that this result is independent of the policy parameters λ_x and λ_i but depends on the calibrated ratio $\frac{\kappa}{\sigma}$. Therefore, for robustness concerns, the same exercise is carried among a range of $\frac{\kappa}{\sigma}$ in table 1. For a wide range

Table 1. Imperfect Commitment and the Degree of Inertia in Interest Rates

κ/σ	Highest α Implying Super-Inertial Behavior
.05	.21
.10	.27
.15	.32
.20	.36
.25	.39
.30	.42

of $\frac{\kappa}{\sigma}$, the lowest α that does *not* deliver a super-inertial behavior varies between .2 and .4. Moreover, for every plausible $\frac{\kappa}{\sigma}$, it is possible to find some degree of commitment under which the policy instrument does not exhibit super-inertial behavior. On the other hand, (18) reveals that under imperfect commitment, the interest rate responds more to the current output gap than the past output gap—qualitatively similar to the estimated historical policy rules.

How much imperfection—whether it originates from finite duration or lack of credibility of intention—has to be introduced into a forward-looking model to deliver an optimal policy behavior that mimics the historically estimated rules? One can make a better quantitative judgment by constructing a table of coefficients for a range of α's. Table 2 tabulates the coefficients of the optimal rule under varying degrees of commitment. For some range of α's (between .4 and .5), theoretical rules and estimated rules look surprisingly close. Therefore, imperfect commitment of the kind that is analyzed here

Table 2. Comparison of Estimated Rules with Theoretical Rules under Imperfect Commitment

		$\mathbf{i_{t-1}}$	$\mathbf{i_{t-2}}$	$\boldsymbol{\pi_t}$	$\mathbf{x_t}$	$\mathbf{x_{t-1}}$
ESTIMATED		**1.16**	**−0.43**	**0.42**	**0.30**	**−0.03**
T	$\alpha = 0$	2.16	−1.01	0.64	0.33	−0.33
H	$\alpha = .1$	1.94	−0.82	0.64	0.33	−0.30
E	$\alpha = .2$	1.73	−0.65	0.64	0.33	−0.26
O	$\alpha = .3$	1.51	−0.49	0.64	0.33	−0.23
R	$\alpha = .4$	**1.30**	**−0.36**	**0.64**	**0.33**	**−0.20**
E	$\alpha = .5$	1.08	−0.25	0.64	0.33	−0.17
T	$\alpha = .6$	0.86	−0.16	0.64	0.33	−0.13
I	$\alpha = .7$	0.65	−0.09	0.64	0.33	−0.10
C	$\alpha = .8$	0.43	−0.04	0.64	0.33	−0.07
A	$\alpha = .9$	0.22	−0.01	0.64	0.33	−0.03
L	$\alpha = 1$	0.00	0.00	0.64	0.33	0.00

may be helpful in reconciling the theoretical policy rules with the empirically observed behavior of the policymakers.

It is important to remind at this point that we do not provide any explanation about why imperfect commitment may occur,[20] since the existence of a finite lasting commitment along with some degree of lack of credibility is exogenously given. Nor do we claim that the mechanism introduced in this study is the only way to model inertia in the interest rates. What is crucial here is to realize that if monetary authorities are assumed to operate under imperfect commitment, implied theoretical instrument rules—even under the purely forward-looking model considered here—may be largely consistent with observed instrument rules.

4. Federal Reserve and the Dynamic Efficiency of Instrument Rules

The shift in U.S. monetary policy after the 1980s is widely documented evidence among the scholars of monetary policy. Several authors have already reported this finding either by directly estimating Taylor-type rules or by counterfactual model exercises.[21] Nevertheless, these studies generally use a reduced-form instrument rule or a mechanic reaction function to represent the systematic component of monetary policy and, thus, do not reveal much information about the possible behavioral sources of changes. On the contrary, this study seeks to add another dimension by explaining the documented changes in the instrument rules by a behavioral change—namely, shift toward commitment.

Therefore, the goal is to derive a measure of the behavioral shift in the Federal Reserve policy from the perspective of efficiency in exploiting the gains from commitment. Indeed, our characterization of imperfect commitment in the previous section already suggests a method to measure the overall stance of monetary policy, in terms of how close it appears to the full-commitment regime: recall that

[20] Nor do we seek to explain why—with the common terminology—a perfect commitment technology may not be available.

[21] For the evidence using Taylor-type reaction functions, see Clarida, Galí, and Gertler (2000) and Judd and Rudebush (1998). For a fully specified counterfactual model exercise, see Giannoni and Boivin (2003).

the parameter α reflects the overall imperfections in the commitment process. Thus, the model suggests that once the parameter α is identified and estimated, it can be used to construct a measure for proximity to commitment.

4.1 Specification

Recall that the theoretical interest rate rule is given by

$$\begin{aligned} i_t = \bar{c} + \frac{\kappa}{\sigma\lambda_i}\pi_t + \frac{\lambda_x}{\sigma\lambda_i}x_t - (1-\alpha)\frac{\lambda_x}{\sigma\lambda_i}x_{t-1} \\ + (1-\alpha)(1 + \frac{\kappa}{\sigma\beta} + \beta^{-1})i_{t-1} - (1-\alpha)^2\beta^{-1}i_{t-2}, \end{aligned} \tag{20}$$

where

$$\begin{aligned} \bar{c} = (1 - (1-\alpha)(1 + \frac{\kappa}{\sigma\beta} + \beta^{-1}) + (1-\alpha)^2\beta^{-1})i^* \\ - \frac{1}{\lambda_i\sigma}\pi^*(\kappa + \frac{\lambda_x\alpha(1-\beta)}{\kappa}), \end{aligned} \tag{21}$$

since $\pi^* = \frac{\kappa}{1-\beta}x^*$.

An empirical counterpart of the instrument rule would be

$$i_t = c + \eta_1 i_{t-1} + \eta_2 i_{t-2} + \phi_\pi \pi_t + \phi_{1x}x_t + \phi_{2x}x_{t-1} + \epsilon_t, \tag{22}$$

where ϵ_t can be interpreted as money demand shocks. It is clear that coefficients of the reduced-form instrument rule are combinations of the structural parameters $\alpha, \beta, \sigma, \kappa$; relative weights λ_x and λ_i; the target values π^*, x^*, i^*; and the degree of commitment, $(1-\alpha)$. An empirically observed change in the instrument rule may result from a change in any of these parameters. Direct estimation of the reduced-form instrument rule (22) will not reveal much information about the behavioral shifts in the conduct of monetary policy across regimes. It is, rather, necessary to identify the "deep" parameters in order to assess the sources of changes in policy behavior.

Indeed, there are studies in the literature estimating the preference parameters (λ_x and λ_i) from interest rate rules.[22] However,

[22]See Lippi (1999, chap. 8); Cecchetti, McConnell, and Perez-Quiros (2002); Favero and Rovelli (2003); and Özlale (2003), among others.

there is no reported attempt on extracting information about the commitment behavior of the central bank. Our setup provides a simple way to fill this gap, since the degree of deviation from the perfect commitment behavior, α, appears directly in the instrument rule (20) along with other structural parameters. Once α is identified, it is straightforward to rank policy rules across regimes in terms of proximity to full commitment, since, according to our setup, the lower is α, the closer is the policy to full commitment.

It is clear that not all the structural parameters can be identified by estimating (20). One way to solve this problem is to borrow calibrated values of some of the parameters from other studies that use a similar model, and estimate the rest. The parameters β, σ, and κ have already been calibrated in the literature by using the structural equations (4) and (3). In what follows, we will adopt the calibrated values from Giannoni and Woodford (2003), which can be tabulated as

β	σ	κ
0.99	0.16	0.024

,

and maintain the assumption that these parameters do not depend on policy.[23]

On the other hand, relative weights on output gap and interest rate variability, λ_x and λ_i will be allowed to change across different tenures. We believe that this is plausible, since these parameters reflect the policy preferences and may vary with the changes in the composition of the Federal Open Market Committee, especially with changes in the Federal Reserve chairmanship. Therefore, calibrated values of λ_x and λ_i, used to determine the theoretical rule in the previous section, will not be used for the empirical exercise; instead they will be identified directly from the structural instrument rule. Doing so will provide the estimates of chairman-specific policy preferences—an extra by-product of the analysis.[24] Therefore,

[23]Note that β, σ, and κ are deep parameters originating from individual behavior of agents. Since they are determined by microfoundations, it is reasonable to argue that these parameters should stay constant across different policy regimes—a property necessary to be immune to the Lucas (1976) critique.

[24]Note that the values of λ_x and λ_i do not affect the inertia of the policy instrument, but they matter for the response of monetary policy to inflation and the output gap.

it will be possible to contrast across regimes the policy preferences as well as the degree of commitment, $(1-\alpha)$.

As is clear from equations (20) and (21), the target variables π^* and i^* cannot be identified simultaneously, for two terms are embedded in the constant term c, and thus cannot be pinned down separately.[25] Of course, one can assume a specific value for the inflation target; then, through the estimates of the other parameters, it is possible to obtain an estimate of the funds rate target. Conversely, assuming a specific funds rate target, one can pin down the inflation target. However, given the uncertainty in choosing the values for i^* and π^*, we will not put much emphasis on target rates but will treat the parameter δ as an independent constant. Moreover, since α does not enter the intercept, the constant term adds no additional information about the policy behavior (of the type we analyze here).

Consequently, equation (20) will be used to identify the degree of dynamic efficiency of the policy rule, $(1-\alpha)$, as well as the policy preferences λ_x, λ_i.

4.2 Estimation

4.2.1 Some Structural Issues

Defining the ideal (most efficient) policymaking as full commitment under perfect credibility, we explore how close to ideal was the policy conducted during the tenures of different Federal Reserve chairmen. Our main hypothesis is that the documented changes in the behavior of the monetary policy instrument in the United States after the 1980s can be largely reconciled with a shift toward full-commitment behavior.[26] In order to conduct this test, we simply estimate the parameters α, λ_x, and λ_i for the terms of three Federal Reserve chairmen, using the structural specification of the instrument rule. The value $1-\alpha$ is of particular interest, since it reflects the performance of the policy according to the criterion we propose.

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[25] Note that x^* and $\bar{r}$ can be identified once the values of π^* and i^* are determined.

[26] Note that, according to the model, this shift can be due to either increased credibility or increased ability of the Federal Reserve.

The parameters of interest can be directly pinned down by simply estimating equation (20) using nonlinear least squares. However, the theoretical model imposes some complications. Note that the output gap, inflation, and the interest rates are determined simultaneously: instrument reacts to the contemporaneous values of the endogenous variables but also affects them. It is possible to solve this problem by using a delayed-effect version of the structural model, as proposed by Giannoni and Woodford (2003), where the inflation and output gap are determined one period in advance. In this case, the policy rule stays exactly the same, except that we can use the nonlinear least-squares estimation using the contemporaneous values of the variables, since shocks to the policy are not correlated with the right-hand-side variables due to the delayed effect.[27] In what follows, we will simply refer to Giannoni and Woodford (2003) and estimate (20) using the method of nonlinear least squares.

4.2.2 Results

In the remainder of this section, we present the estimates of the structural instrument rule. We document the role of the policy preferences and the proximity to full commitment for the policy reaction function. First we estimate the parameters of interest for each chairman using nonlinear least squares and then construct various stability tests across periods.

Our estimates use quarterly time series, spanning the period 1970:Q3–2001:Q4, i.e., mostly the term of three chairmen: Burns, Volcker, and Greenspan.[28] All the data were drawn from the Federal Reserve Bank of St. Louis database (FRED). We use the average federal funds rate in the first month of each quarter, expressed in annual rates, as the interest rate variable. Our inflation variable is the annualized rate of change of the GDP deflator between two subsequent

[27]See Giannoni and Woodford (2003) for a detailed exposition. These authors also consider a more general case than is mentioned here.

[28]We skip the Miller period since it is not long enough to test the rule. The terms are 1970:Q3–1978:Q2 for Burns, 1979:Q3–1987:Q2 for Volcker, and 1987:Q3–2001:Q4 for Greenspan. However, since the operating instrument was borrowed reserves during 1979:Q3–1982:Q3, we prefer to discard this period from the estimations.

Table 3. Structural Estimate of the Instrument Rule

	α	λ_x	λ_i
Greenspan	0.51 (0.04)	0.087 (0.042)	0.98 (0.47)
Volcker	0.53 (0.09)	0.11 (0.12)	0.9 (1.1)
Burns	0.71 (0.06)	0.11 (0.05)	0.53 (0.23)
Structural Change	**p-values**		
Greenspan-Volcker	0.43	0.88	0.86
Greenspan-Burns	<0.01	0.87	0.32
Volcker-Burns	0.023	0.99	0.069

Note: Samples are Greenspan: 1987:Q3–2001:Q4, Volcker: 1982:Q3–1987:Q2, Burns: 1970:Q3–1978:Q2.

quarters. Our "output gap" series is constructed as the deviation of the logarithm of GDP from a fitted quadratic function of time.[29]

Table 3 reports the nonlinear least-squares estimation of the coefficients α, λ_x, and λ_i for the tenure of three Federal Reserve chairmen. Recall that overall efficiency of policy is measured by $(1 - \alpha)$. Namely, we consider the ideal policymaking as $\alpha = 0$, i.e., when the monetary authority operates under full commitment with perfect credibility, while $\alpha = 1$ corresponds to period-by-period optimization or zero credibility.

One noteworthy feature of the estimations is that the (post-1982) Volcker and Greenspan periods involve a similar degree of efficiency (0.47 and 0.49), while the monetary policy in the Burns period seems to have been conducted in a less efficient way (with a degree of 0.29). In other words, these results point out that Volcker and Greenspan pursued a policy that is closer to the ideal case of full commitment than the policy in the 1970s. These findings suggest that there has been an improvement either in policy ability or in policy credibility after the 1980s.

[29]We also repeated the estimations based on CPI and CBO output gap. The results did not change much; hence, we do not report them here.

Whether the change originates from favorable natural factors or from improvement of the Federal Reserve's credible track, the conclusion is the same: the Federal Reserve's implied instrument rule suggests a more efficient rule after the 1980s compared to the 1970s.

The bottom panel of table 3 tabulates several stability tests across periods. It is clear that the hypothesis that α is equal in the Volcker and Greenspan periods cannot be rejected. On the other hand, monetary policy under the Burns period seems to have been conducted under a significantly different style than it was under post-1980s chairmen. Therefore, the recent approach of analyzing the monetary policy under two different eras—before and after Volcker—seems to be appropriate.

Moreover, the estimated policy preferences are very similar in the Volcker and Greenspan periods. However, we cannot reject the hypothesis that, during the former's term, the policymaker's objective was pure inflation targeting, while we can reject it during the latter's term. This result is remarkable, since it suggests that although the policy preferences seem to be different, the regimes were similar in terms of dynamic efficiency. In other words, the policy was conducted in a relatively efficient way in both periods, exploiting the forward-looking expectations in such a way that the central bank faces an improved output-inflation trade-off compared to Burns's period.

One other noteworthy feature of the estimations is the sizable change in the magnitude of the weight on interest rate stabilization after the 1980s. Nevertheless, this result should not be strongly emphasized since the stability tests cannot be rejected for this parameter.

5. Summary and Conclusion

The purpose of this study has been twofold. First, we attempted to reconcile the theoretical rule implied by a purely forward-looking model with the historically estimated Taylor-like rules. Second, we aimed to construct and estimate a measure of monetary policy on the grounds of dynamic efficiency—namely, proximity to a full-commitment regime.

To achieve these goals, first, the concept of imperfect commitment is introduced into the standard optimal monetary policy problem of recent forward-looking models. A theoretical rule that nests discretion and commitment as special cases is used to identify the dynamic efficiency of the commitment policy. It is shown that the notion of imperfect commitment, by and large, explains the discrepancy between theory and evidence. In particular, it is possible to obtain non-super-inertial rules by using the appropriate degree of dynamic efficiency—a feature that theoretical rules under full commitment have not delivered.

Second, we estimate the preference parameters of the monetary authority and the proximity to full commitment directly from the structural policy rule for three different Federal Reserve chairmen. Empirical results suggest that late Volcker and Greenspan periods were conducted under a similar philosophy, in the sense that both periods reveal a similar degree of efficiency, exploiting the forward-looking expectations in such a way as to achieve a more favorable trade-off between target variables. On the other hand, monetary policy under the tenure of Burns was relatively less efficient.

Recall that the definition of proximity to commitment was derived under two assumptions; that is, commitment regimes are finite, and the private sector expects the commitment to end, on average, sooner than originally intended by the central bank. Stretching our imagination, these assumptions can be combined under two related definitions of credibility—namely, credibility of ability and credibility of intention. Therefore, our analysis implicitly proposes a method to measure the overall credibility of the monetary authority, and the empirical findings confirm that the Federal Reserve's credibility has improved since the 1980s.

Needless to say, there are some caveats regarding our findings. Although our main theoretical result is robust to model variability, the empirical findings regarding the estimated degree of commitment may be highly dependent on the specific model under consideration. It may be worthwhile to reestimate our measure of the degree of commitment by employing various families of models and exploring how the results change across models. Especially, it could be interesting to observe how our results depend on the degree of "forward-lookingness" in the models.

As a secondary caveat, it could be argued that the notion of imperfect commitment introduced here is purely mechanical and exogenous, which makes our results hard to interpret. It may be an interesting exercise to explore the implications of making the probability of reoptimizations endogenous. That could be achieved, e.g., by allowing private-sector expectations to be dependent on the central bank's track record. Also, introducing learning behavior on the part of the private sector could be a related worthwhile extension. This exercise would be particularly helpful in understanding the underlying dynamics upon a regime change, such as reappointment of the central bank governor.

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Transparency, Disclosure, and the Federal Reserve*

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This paper provides an assessment of central bank transparency for the efficiency of monetary policy implementation, using the introduction of balance-of-risks assessments by the Federal Reserve as a testing device. We find that markets anticipated monetary policy decisions equally well under this new disclosure regime as before, but arrived at their expectations differently. Now, markets extract information from the statements, whereas before, they reverted to other types of Federal Reserve communication in the intermeeting periods. These findings suggest that the Federal Reserve's new disclosure practice may have improved transparency, as information is now released at an earlier time and with clearer signals.

JEL Codes: E43, E52, E58, G12.

1. Introduction

Over the past decade, there has been a remarkable change in the way central banks conduct monetary policy. For example, until February 1994 the Federal Open Market Committee (FOMC) did not publicly announce its decisions about changes in the target federal funds rate after its meetings. In current monetary policymaking, an unprecedented degree of transparency has become common practice. Such

*We would like to thank two anonymous referees, the editor, and Michael Woodford, as well as Ignazio Angeloni, Ben Bernanke, Laurent Bilke, Petra Geraats, Hans-Joachim Klöckers, Bernhard Winkler, and seminar participants at the ECB and the BIS for comments and discussions, and Terhi Jokipii for excellent research assistance. We are grateful to Reuters and Standard & Poor's for providing some of the data series. This paper presents the authors' personal opinions and does not necessarily reflect the views of the European Central Bank; e-mail: Michael.Ehrmann@ecb.int, Marcel.Fratzscher@ecb.int.

transparency relates to various parts of the policy process, such as the publication of the policy objectives and institutional arrangements, of the policy models and central bank forecasts of relevant variables, or of the communication of monetary policy decisions, often including an explanation of the underlying considerations that led to the decision or an indication of the likely future outlook for monetary policy.[1] Different central banks have opted for different approaches in this respect. In the communication of monetary policy decisions, for example, the European Central Bank holds press conferences after each decision on policy rates. Others, like the U.S. Federal Reserve, publish immediately after each meeting a press statement that contains not only an assessment of the current economic developments and the monetary policy stance but also an assessment of the balance of risks in the near future.

The rationale behind increased transparency is manifold; for the purpose of this paper, we want to highlight the role of transparency for improving the *efficiency of policy implementation* (see, e.g., Bernanke 2004). Financial markets need to *infer* the intentions of policymakers, but such inference is necessarily prone to mistakes, e.g., if financial markets attribute inappropriate weights to indicators (such as communication by policymakers or macroeconomic news), or if there is dissent among market participants about the interpretation of relevant news, which induces uncertainty in financial markets. Central banks can reduce this uncertainty through *deeds*, i.e., monetary policy decisions, as well as through *words*, i.e., the communication of their intentions and views about the future path of monetary policy and the economic outlook.

In this paper, we focus on the question of whether central bank transparency can indeed improve the efficiency of monetary policymaking. Our testing vehicle is the change in regime that occurred

[1]For two influential works on the importance of transparency, see Cukierman and Meltzer (1986) and Blinder (1998). An overview of the various forms of central bank transparency, the theoretical justifications for transparency, and the recent empirical evidence of its effects is provided in Geraats (2002). On a cautious note that transparency might go too far and should only be supported if it helps achieve the central bank's tasks, see Mishkin (2004). The seminal work by Stein (1989) and Goodfriend (1986) emphasizes the potential time-inconsistency problem of communication in a monetary policy setting, and possible solutions to it.

in 1999 at the Federal Reserve, when the FOMC decided to publish immediately after its meetings a statement that not only explains its monetary policy decision but also contains a forward-looking element—initially in the form of an outlook for the monetary policy stance and, later, in the form of a balance-of-risks assessment concerning inflationary pressures and economic conditions in the “foreseeable future.” As a first step, we analyze whether the release of such a forward-looking statement has helped markets anticipate the upcoming monetary policy decisions better. We find that financial markets were equally good at anticipating the decisions under both regimes, as the magnitude of the surprises of FOMC decisions on meeting days was equally large under both regimes.

We next ask whether the statements influence financial markets. We test the impact of words versus deeds—i.e., of FOMC statements as well as monetary policy actions—on the yield curve, comparing the period February 1994–April 1999 with the period since the regular issuance of FOMC statements after May 1999. We find that both monetary policy decisions and the FOMC balance-of-risks statements have had a statistically and economically meaningful impact on interest rates of up to a five-year maturity. FOMC surprises are found to have the largest effect on the short end of the maturity spectrum. By contrast, FOMC statements have the largest effect on medium-term interest rate horizons. Moreover, once the effect of monetary policy surprises on interest rate levels is taken into account, we find that conditional market volatility rose significantly in response to the surprises prior to 1999, which is no longer the case afterward. These results are compelling as well as intuitive. In particular, the significant impact of FOMC statements suggests that the FOMC managed to influence market expectations about monetary policy, and that it has been able to do so not only over the short run but especially at medium-term horizons of up to two years. In addition, the fact that the existence of the balance-of-risks statements reduces conditional interest rate volatility in response to monetary policy surprises indicates that this communication has generally been successful in lowering market uncertainty about the future path of monetary policy.

The results that markets extract information from the released statements yet arrived at equally good expectations of the decisions when the statements were not released seem to contradict each other.

There are two potential explanations for this finding. First, monetary policy decisions may be inconsistent with earlier bias statements if the FOMC decides to deviate from the statements due to the arrival of new information, leading to larger surprises. We show that this has generally not been the case, as most FOMC decisions since 1999 have been consistent with previous balance-of-risks assessments. The second potential explanation is that market participants have obtained information necessary to anticipate monetary policy decisions in fundamentally different ways under the old versus the new disclosure regimes. We find significant evidence in favor of this hypothesis. In particular, we show that under the old regime, markets reacted more strongly to other types of Federal Reserve communication—such as testimonies, interviews, and speeches by FOMC members[2]—in the intermeeting periods. Based on these findings, we argue that the regime change increased transparency, as markets are provided with relevant information at an earlier stage and in a more-transparent manner. This makes it easier and less costly for markets to obtain the information, and helps reduce market uncertainty about the future course of monetary policy. On the other hand, our finding that markets attach such a strong importance to the statements by the FOMC is contrary in spirit to King (2000), who argues that, with a transparent monetary-policy reaction function, news should not be in the announcements of central banks but should entirely arise in the development of the economy.

The present paper is closely related to a number of studies in the literature. In their seminal work, Romer and Romer (2000) stress the close link between expectations about the path of monetary policy and expectations of output and inflation. Gürkaynak, Sack, and Swanson (2005a) use a two-factor model, where they interpret their two unobserved factors as reflecting monetary policy surprises and FOMC meeting statements, and find that both have a significant impact on the yield curve. Their results are similar to ours in the present paper; however, we not only identify the effect of FOMC statements directly but also link our assessment of the statements

[2]We also test for the effect of the releases of macroeconomic fundamentals and find some, though limited, evidence that prior to 1999 markets reacted more to some news.

of the FOMC on meeting days, on the one hand, with the importance of communication in the intermeeting periods and macroeconomic news, on the other hand. Kohn and Sack (2004) focus on and find evidence for the effect of intermeeting communication by former FOMC Chairman Greenspan on the volatility of financial markets since 1994. Again, the present paper attempts to broaden this analysis by linking meeting statements with intermeeting communication and macroeconomic news, by estimating their impact on the level and conditional volatility of interest rates, and by underlining the differences under the two disclosure regimes. In line with our findings, Gürkaynak, Sack, and Swanson (2005b) stress the importance of macroeconomic data releases on inflation and output as drivers of long-term interest rates. Our empirical analysis and findings are consistent with the theoretical analysis by Reifschneider and Williams (2000) and Eggertsson and Woodford (2003), who stress the role of communication in shaping market expectations about future monetary policy and thus in reducing interest rate volatility, as well as the work by Bernanke, Reinhart, and Sack (2004) and Woodford (2005), who emphasize the importance of communication for policy effectiveness if the zero lower bound is binding.

Finally, a number of papers analyze potential effects of the increased transparency of the Federal Reserve. The most recent paper in that context is Swanson (2006), who finds that private-sector interest rate forecasts have improved considerably over time, along with movements toward more transparency in the Federal Reserve's policy process. Swanson's study covers the period from 1988 to 2003, which includes the regime change that is of interest in this paper. However, Swanson focuses in particular on the change in 1994, when the FOMC started announcing decisions on the intended federal funds rate on the day of its meetings. He models this change by a step dummy and alternatively allows for a time trend. As such, his analysis cannot single out *further* effects on predictability of the regime change in 1999, which is the focus of this paper. Furthermore, we will study not only the effects on predictability but also how market participants form their expectations about upcoming monetary policy decisions.

The remainder of this paper is organized as follows. In section 2, we describe the changes in the FOMC disclosure practices that have occurred since 1994 and ask whether the balance-of-risks statements have provided an accurate signal about future monetary policy decisions. Section 3 introduces the data underlying our analysis. Section 4 analyzes the effect of the new disclosure regime, looking at the accuracy of market expectations of monetary policy decisions, the reaction of markets to monetary policy, and the role of alternative sources of information—namely, other central bank communication and releases of macroeconomic fundamentals. Section 5 summarizes the results and concludes.

2. The Balance-of-Risks Assessments of the FOMC

2.1 Changes in the FOMC Disclosure Practices

2.1.1 1994: Immediate Release of Decisions on the Target Federal Funds Rate

A major change in the disclosure practice of the Federal Reserve took place in February 1994, when the FOMC started announcing decisions on the intended federal funds rate on the day of its meetings. Before, markets needed to infer the intended rate from the type and size of the open market operations by the Federal Reserve, until the decision was published after the subsequent FOMC meeting. There is substantial evidence that this change has improved the markets' understanding of monetary policy considerably: Demiralp (2001), Lange, Sack, and Whitesell (2003), and Poole and Rasche (2003) observe that markets were able to improve their forecasts of monetary policy decisions, and they relate this to the change in transparency.[3] The most recent paper in this literature is Swanson (2006), who also finds that private-sector interest rate forecasts have improved substantially since 1994. Importantly, he shows that the improved forecast performance is not driven by an improvement in the private sector's ability to assess the state of the economy, such that it must arise from a better understanding of the Federal Reserve's monetary policy. The regime change has also affected market uncertainty. Lee (2002) shows that the effect of Federal Reserve announcements on interest rate volatility has decreased in the last

[3]Bomfim and Reinhart (2000), however, observe that the reactions of financial markets to monetary policy surprises did not change pre- and post-1994.

decades. Swanson (2006) finds that market uncertainty has been strongly reduced in response to the FOMC announcements since 1994. Finally, Demiralp and Jorda (2002) provide evidence that by announcing changes in the intended federal funds rate, it was possible to move the federal funds rate with a smaller volume of open market operations than was possible prior to 1994, which indicates clearly that increased transparency can indeed be beneficial for the efficiency of policy implementation. Given the importance of this structural change, we will use only the post-1994 period in our analysis.

2.1.2 1999: Immediate Release of an Assessment about the Likely Future Path of Monetary Policy

Between 1983 and 1998, the FOMC issued a policy directive comprising the committee's expectations about the relative chances of an increase or decrease in the target federal funds rate as well as instructions for current policy to the Open Market Trading Desk. These directives focused in particular on the intermeeting period and were not made public until after subsequent FOMC meetings. In December 1998, the FOMC decided that it would release its assessment about the likely future path of monetary policy without delay after its meetings, "to communicate to the public a major shift in its views about the balance of risks or the likely direction of future policy" (Federal Reserve Board 1998). The first such announcement was released in May 1999, with a total of six announcements in the course of 1999.

2.1.3 2000: Modifications to the Release: The Balance-of-Risks Assessments

One year later, at its meeting in December 1999, the FOMC decided to modify its disclosure proceedings in four ways: (i) a statement would now be issued after *every* FOMC meeting, not only in the case of policy action or a major shift in the views about future developments; (ii) the statement would cover a time horizon that extends beyond the next FOMC meeting; (iii) the statement would no longer be phrased in terms of a bias with respect to future interest rate changes but, instead, in terms of the balance of risks to the goals of price stability and economic growth; and (iv) the balance-of-risks statement would be assembled from a set of predefined sentences. The FOMC strictly adhered to the new rules until March 2003, when it decided not to convey a balance of risks in light of the large uncertainties due to the U.S. intervention in Iraq. In the subsequent meetings, an assessment of the balance of risks was provided again, although it was no longer taken from the set of predefined sentences.

In this paper, we will analyze, in general, the period from May 1999 to April 2004 and compare it with the period from February 1994 to April 1999.[4] Our sample ends in April 2004, as we do not want to include in our analysis the statements of the recent tightening cycle, which might be qualitatively different from the regular statements made otherwise and most likely to be made again in the near future (Woodford 2005).

2.2 How Informative Are Balance-of-Risks Assessments?

As one of the objectives of the balance-of-risks assessments is to help markets anticipate better the path of monetary policy, the assessments should generally be consistent with future monetary policy decisions. Of course, one needs to keep in mind that any forward-looking statement is conditional on the information available at the time of the statement. Accordingly, a policy action might appear to look inconsistent with a statement ex post, if conditions have altered in the meantime. However, we would expect that, on average, the information set will not change in a systematic fashion that makes actions seemingly inconsistent with statements. In our consistency analysis, we assume that markets interpreted an assessment highlighting the risks of inflation as pointing to higher interest rates,

[4]Although there could potentially be differences in the way markets react to the statements made in 1999 and those released since, we will not analyze these two types of statements separately, due to the few observations that are available for the first type. In the remainder of the paper, we will use the phrases “bias,” “balance-of-risks assessments,” or “the statements” interchangeably, generally referring to both types of statements.

Table 1. Consistency of FOMC Balance-of-Risks Assessments and Monetary Policy Decisions

February 1994–April 1999				
	Monetary Policy Decision			
Bias	Easing	No Change	Tightening	All
Easing	2	1	0	3
Symmetric	4	15	4	23
Tightening	0	14	4	18
All	6	30	8	**44**
May 1999–2004				
	Monetary Policy Decision			
Bias	Easing	No Change	Tightening	All
Easing	13	7	0	20
Symmetric	0	11	2	13
Tightening	0	5	4	9
All	13	23	6	**42**

Note: The table shows which bias announcement in the *current* FOMC meeting has been followed by what policy action in the *subsequent* meeting. As the stated horizon of the bias has been not only on the next meeting but also on the "foreseeable future," note that there is one case since 1999 in which an asymmetric bias has been announced for *two* consecutive meetings, with a corresponding monetary policy change at the *third* meeting only (August 13, September 24, and November 6, 2002). We have included the bias announcements for *both* meetings preceding the interest rate change as correctly anticipating the next move.

and an assessment that stresses the risks to economic growth as pointing to lower interest rates.[5]

Table 1 reveals that twenty-eight out of forty-two bias announcements (67 percent) in 1999–2004 were followed by corresponding

[5]Poole (2004) argues that employment and inflation are not highly correlated, such that "an unbalanced balance-of-risks statement should not be interpreted as an indication of a future policy action in a specific direction," although he admits that "unfortunately, it is too often interpreted that way by market participants."

monetary policy decisions.[6] A closer look at the remaining fourteen announcements reveals that there has not been a single case in this period when the Federal Reserve changed interest rates with an asymmetric bias pointing in the opposite direction. In two cases, interest rates were tightened while the bias released at the preceding meeting was symmetric. The other twelve cases consist of situations where an asymmetric bias was not acted upon—which is not necessarily inconsistent, as the bias is by no means meant to indicate that action will automatically follow. Overall, these statistics indicate that FOMC biases were consistent with policy actions in the 1999–2004 period.

A comparison of the old and the new disclosure regimes provides some revealing differences and a better understanding of the underlying motivations of the different disclosure practices. Table 1 for 1994–99 shows that the FOMC provided fewer asymmetric policy directives and also made fewer interest rate changes than in 1999–2004. However, the table also reveals that the directives provided a poor prediction of monetary policy actions at the subsequent FOMC meetings, as there are far fewer entries on the diagonal of this table. This raises the question of why there is such a sharp difference in the biases across the two regimes. One central factor is that the policy directives until May 1999 were clearly directed at *internal* Federal Reserve objectives and were not intended to provide public information since they focused on the intermeeting period and were released only after the next FOMC meeting. By contrast, the balance-of-risks assessments since 1999 mainly have an *external* objective in that they intend to provide the markets with additional information about possible future policy decisions and existing risks. For

[6] A potential caveat is that since 2000 the focus of the statements has been not on the intermeeting period but over the foreseeable future. Hence a balance-of-risks assessment may still be consistent with future monetary policy decisions if there is an asymmetric assessment and a corresponding policy change occurs two or more meetings later, *and* the same assessment was issued at the next meetings as well. Since 1999, there was only one such case—August 13, 2002—which is classified as a "correct" anticipation of future decisions in the tables. Moreover, throughout the paper, we have excluded the FOMC meeting on September 17, 2001—when interest rates were decreased by 50 basis points in response to the terrorist attacks on September 11—due to the exceptional circumstances of this FOMC meeting. Excluding other unscheduled meetings also does not affect our results.

this information to be credible, the biases need to be broadly in line with actual policy decisions.[7]

3. The Data

3.1 Interest Rates

Our interest rate data consist of constant maturity treasury rates that are provided by the U.S. Treasury. We expect the effect of monetary policy actions to differ depending on the maturity of the interest rate. For instance, a tightening of monetary policy can be compatible with a reduction in long-term interest rates if markets perceive the tightening as a credible step by monetary authorities to reduce inflation in the long run. The effect of a monetary policy decision on long rates can therefore be not only quantitatively but also qualitatively different from that on shorter maturities. Furthermore, in order to understand the effects of communication on market expectations about the future course of monetary policy, it will be revealing to see which maturity spectrum reacts strongest. Accordingly, we look at maturities of three and six months as well as one, two, five, and ten years.

As to the frequency of the analysis, we use daily frequency rather than intraday or tick-by-tick data (see also Gürkaynak, Sack, and Swanson 2005b). The drawback of choosing a lower frequency is that other events and news during the day may introduce some noise, thereby possibly making the measurement of announcement effects less accurate. However, over a sufficiently long time sample, the effect of other news should average out to zero, such that the

[7]This nevertheless leaves open the question of why the policy directives before 1999 were so out of sync with monetary policy decisions. One possible explanation is that because the assessments were targeted at an external audience after May 1999, their consistency was ensured—or, alternatively, that only once their consistency became feasible, the FOMC decided to target them to an external audience. Nonetheless, even in these cases, the purpose of the earlier directives is not clear. Thornton and Wheelock (2000) argue that the main internal Federal Reserve objective of the directive before 1999 was that of consensus building. In other words, the policy directive may have been used to increase the number of FOMC members supporting the current decision. For instance, FOMC members may be more willing to agree to a change in policy if a neutral directive is adopted at the same time, indicating the FOMC's intention not to embark on further changes.

coefficient estimates are estimated with larger standard errors but are nonetheless unbiased. The advantage of using daily data is to avoid estimating biased coefficients that can arise if overshooting occurs in the very short run.

The daily interest rate data are characterized by negative skewness, excess kurtosis, and serial correlation. The econometric model therefore needs to take into account these specific data characteristics.

3.2 Expectations of Monetary Policy Decisions and Macroeconomic Announcements

Our expectations data for monetary policy decisions and macroeconomic announcements originate from surveys conducted by Reuters and Money Market Services International among market participants, conducted on Fridays before each FOMC meeting and the release of the various macroeconomic data. We use the mean of the survey as our benchmark expectations measure, although using the median yields similar results.[8] We construct the *surprise component* contained in each announcement by deducting the expectation from the actual announcement.[9] To match the frequency of this data source with the daily interest rate data, we construct a daily series for each announcement, which is set to zero on days without announcements and contains the surprise component on announcement days. We will make use of this surprise variable to measure the effect of announcements on markets. The reason why we do not use the actual announcements is that their expected component is already priced into the market prior to the announcement. At the point of the announcement, the market reacts merely to the surprise component contained in the news (Kuttner 2001). Analyzing the reaction of markets to surprises is therefore a proxy to assess the importance of the underlying announcement.

As an alternative to *survey* data on monetary policy decisions, expectations can be extracted from the federal funds futures rate,

[8] This has consistently been found also in earlier work with this type of data (Ehrmann and Fratzscher 2006, who also show that the survey data are unbiased and efficient).

[9] Additionally, we standardize the surprises regarding the macro data with the standard deviation of the announcements.

as proposed by Kuttner (2001). We have used both measures and find that the results are qualitatively identical for both measures of market expectations.

3.3 FOMC Communication

We analyze two types of central bank communication. First, we look at the effect of the FOMC bias statements. We classify these statements according to their implications for the future interest rate path, and construct two indicator variables. The indicator "symmetric bias" takes the value 1 on those days where the FOMC released a statement that it perceives the risks of economic weakness and of inflationary pressure as balanced, and the value 0 on all other days. The indicator "asymmetric bias" takes the value 1 for statements that highlight a risk of inflationary pressure, the value −1 for statements that consider the risk to be tilted toward economic weakness, and the value 0 otherwise.[10]

Second, we look at other communication made by FOMC members in the intermeeting periods. For that purpose, we make use of the data set developed in Ehrmann and Fratzscher (2006). This data set includes three types of communication—speeches, interviews, and testimonies—and includes all FOMC members. The data are extracted from a widely used newswire service, *Reuters News*, which provides a news report usually within minutes after the corresponding communication. This way of collecting the data is somewhat different from that used by Kohn and Sack (2004), who take all speeches and testimonies made by FOMC members. The key difference is that *Reuters News* reports about the great majority but not about all central bank communication, e.g., if it deems it as not providing new or market-relevant information. Since our primary focus is on the market reaction and perception in response to communication by the Federal Reserve, the *Reuters News* source may be more appropriate for this purpose.

The data set separates communication about the economic outlook (C^{EC}) or future monetary policy (C^{MP}) and classifies

[10]Obviously, Poole's (2004) caveats mentioned in footnote 5 apply here also.

each type in the following way:

$$C_t^{EC} = \begin{cases} +1 & \textit{strong economic outlook} \\ 0 & \textit{neutral economic outlook} \\ -1 & \textit{weak economic outlook} \end{cases}$$

$$C_t^{MP} = \begin{cases} +1 & \textit{tightening inclination} \\ 0 & \textit{no inclination} \\ -1 & \textit{easing inclination} \end{cases}$$

Again, to match the frequency of these data with the interest rates, we construct a daily series for each indicator, which is set to zero on days without corresponding communication and contains the classification values on communication days. More details on this data set and the classification scheme are provided in Ehrmann and Fratzscher (2006). Clearly, however, we should stress the important caveat that this classification is judgmental. It is therefore possible that some reports are misclassified relative to the market's interpretation or the speaker's intention. However, our objective is to assess communication from the perspective of financial markets, and we therefore want to focus on the information that market participants actually receive.

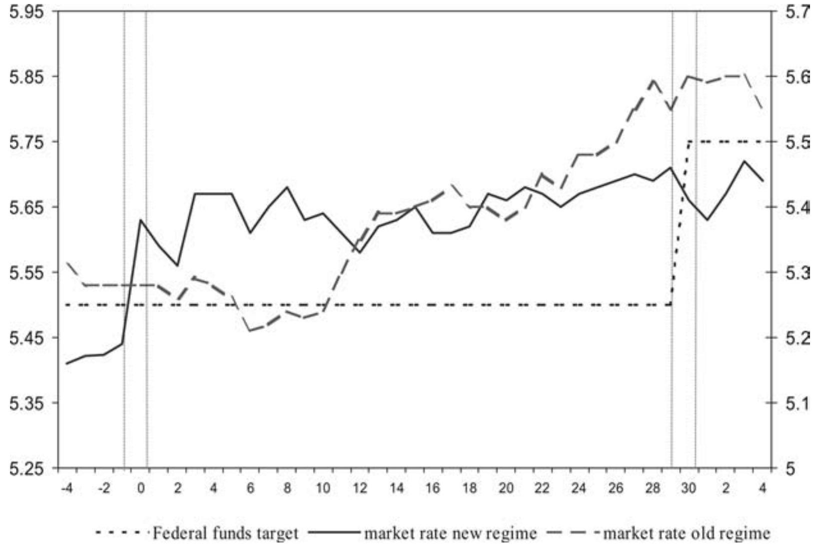
4. The Effect of the New Disclosure Regime

4.1 Hypotheses on the Effect of the New Regime: An Illustrative Example

Figure 1 provides an illustration of the differences in the adjustment of the three-month T-bill rate around two consecutive FOMC meeting dates under the two disclosure regimes. Both cases are very similar in that no change occurred at the first of the two FOMC meetings (marked as day 0 on the horizontal axis) and a rise in the target federal funds rate of 25 basis points took place at the subsequent meetings (marked as day 30). Furthermore, in both cases, the FOMC had actually adopted a tightening bias at the previous meeting. The main difference between the meetings lies in the communication of this bias, which had been released immediately in

Figure 1. Adjustment of Market Interest Rates under Alternative Disclosure Regimes

(Comparison of 25-Basis-Point Tightening on March 25, 1997, versus February 2, 2000)



Note: Three-month money market rates for the March 25, 1997, tightening episode are shown on the right-hand-side axis, whereas those for the February 2, 2000, episode are depicted on the left-hand-side axis. Both tightening days are scaled so as to be shown on day 30 on the horizontal axis. Day 0 refers to the corresponding previous FOMC meetings.

one case (February 2, 2000) but had been released only after the subsequent meeting in the other case (March 25, 1997).

In both instances, the policy decision to change interest rates (on day 30) was well predicted by the market, as can be seen by the fact that interest rates had already increased substantially by the time the FOMC met. However, it is apparent that this anticipation of the decision was achieved through very different mechanisms in the two regimes.

Although the example shown in the figure certainly provides an exceptionally strong case, it illustrates most of the potential effects of the bias announcements. First, when a tightening bias was released at day 0, markets already priced in most of the interest rate rise of the next meeting within one day. After this initial jump, market interest rates remained relatively stable and rose gradually until the next meeting. By contrast, in the case without a released statement, interest rates adjusted much later. Interestingly, interest rates started anticipating the interest rate move on the day of then-Chairman Greenspan's testimony before the U.S. Senate on February 26, 1997 (day 11 in the chart).[11]

This illustration raises various questions about the effect of the change in regime, which we will attempt to answer empirically in the subsequent sections:

- Has the release of the balance-of-risks assessments improved the ability of markets to anticipate a monetary policy decision by the time when the FOMC meets?
- Have markets changed their behavior on the days of the FOMC meetings? Do they react to the release of the statements, and if so, how?
- Do interest rate reactions in response to the release of the statements anticipate the required adjustment between FOMC meetings, such that lower intermeeting interest rate adjustments are needed under the new regime?
- Is the release of the statements a substitute or a complement to other sources of information, like intermeeting communication by FOMC members or macroeconomic data releases that might have allowed markets in the earlier regime to anticipate monetary policy decisions equally well?

4.2 Market Expectations of Monetary Policy Actions

Since the FOMC statements are released in order to communicate to the markets the FOMC's assessment of future developments, a first natural question is whether they have improved the predictability of monetary policy decisions. However, it has been shown that monetary policy decisions had been anticipated by market participants very well since 1994 (Demiralp 2001; Lange, Sack, and Whitesell

[11] A finding in our paper that is not reflected in the figure, however, relates to the reduction in conditional volatility—that is, once the immediate response of interest rate levels is taken into account, we find that market volatility is significantly lowered in the new regime relative to the time prior to 1999, a pattern that is not reflected in the figure.

2003; Poole and Rasche 2003; Swanson 2006), such that it might be difficult to improve upon this performance.

Table 2 reports various statistics regarding the expectations data, using both the Reuters survey-based expectations and the surprises as calculated from federal funds futures, separately for all scheduled FOMC meeting dates as well as for those where interest rates were actually changed. We analyze these dates separately because, on several occasions, the decision that interest rates would remain unchanged was extremely easy to predict. As such, we think that the prediction of actual interest rate *changes* is an interesting additional test of the forecastability of FOMC decisions. The columns denoted by Δ report the results of tests for differences across the subsamples: we cannot find any difference in the size of the mean surprise. However, even if the surprises have the same mean, they could be drawn from different distributions, e.g., if for one period there are more large (positive and negative) surprises. We test for this in four different ways: (i) by checking whether the variance of the surprise over time is different across time periods, (ii) by calculating the mean absolute surprise, (iii) through the variance of the absolute surprise, and (iv) with the maximum absolute surprise. In no case do we find a statistically significant difference. Importantly, using Reuters-based expectations or surprises extracted from the federal funds futures does not alter any of the results.

This leads us to the conclusions that market anticipations of monetary policy decisions have been relatively accurate throughout the period since 1994, and that there has basically been no improvement since 1999.[12]

4.3 Market Reactions to Monetary Policy

The finding that financial markets are as surprised by monetary policy decisions under the new disclosure regime as they were under the old regime does not necessarily imply that there is no difference in the process through which markets arrive at their expectations.

[12] Swanson (2006) estimates a model for private-sector interest rate forecasts that allows for a linear trend, ranging over a sample from 1988 to 2003, and finds a significant improvement over time. As his sample includes the important change of 1994, the effect of the changes introduced in 1999 cannot be singled out in his study.

Table 2. Market Expectations about Monetary Policy Decisions

	Reuters Polls			Federal Funds Futures		
	Feb. 1994–Apr. 1999	**May 1999–Apr. 2004**	**Δ**	**Feb. 1994–Apr. 1999**	**May 1999–Apr. 2004**	**Δ**
All FOMC Meeting Days						
Number of Meetings	44	42		44	42	
Mean Surprise	−0.006	−0.018		−0.008	−0.020	
Variance of the Surprise	0.010	0.016		0.005	0.010	
Mean Absolute Surprise	0.050	0.050		0.050	0.053	
Variance of the Absolute Surprise	0.007	0.013		0.003	0.008	
Maximum Absolute Surprise	0.250	0.500		0.203	0.425	
FOMC Meeting Days with Interest Rate Changes						
Number of Meetings	14	18		14	18	
Mean Surprise	0.012	−0.049		0.022	−0.051	
Variance of the Surprise	0.027	0.035		0.011	0.022	
Mean Absolute Surprise	0.114	0.108		0.091	0.102	
Variance of the Absolute Surprise	0.013	0.026		0.003	0.014	
Maximum Absolute Surprise	0.250	0.500		0.203	0.425	

Note: Δ denotes whether the parameters in the respective row are statistically significantly different for the two samples. *, **, and *** denote significance at the 90 percent, 95 percent, and 99 percent level, respectively.

For example, it could be that markets do indeed learn important information about future monetary policy decisions from the balance-of-risks assessments, whereas under the old regime, markets acquired this information through alternative channels. The focus of this section is therefore to analyze, first, whether financial markets behave differently on FOMC meeting days under the two regimes. Second, we investigate whether the balance-of-risks statements themselves affect interest rates and whether the reaction of markets to monetary policy surprises depends on the content of the accompanying balance-of-risks statements.

4.3.1 Market Behavior on FOMC Meeting Days

Do markets behave differently on FOMC meeting days under the new disclosure regime, where a statement accompanies each meeting? To test this hypothesis, we employ an EGARCH(1,1) model following Nelson (1991), explaining the entire set of daily changes in the market interest rates Δr_t (i.e., not only including days with FOMC meetings, macro announcements, or FOMC communication). The conditional mean equations are expressed as a function of the surprise component of a monetary policy decision, s_t; of the surprise component of the releases of important macroeconomic data; and of communication by the members of the FOMC ($z_{i.t}$; the results for these will be discussed further below). The effects of all variables are modeled separately for each disclosure regime by interacting them with a dummy, D_t, which is equal to one for the new regime, and zero otherwise. Additionally, we enter the regime dummy separately and control for past interest rate changes as well as day-of-the-week effects (*Mon, Fri*):[13]

$$\begin{aligned}\Delta r_t = \alpha_1 + \alpha_2 D_t + \beta \Delta r_{t-1} + \gamma_1\, s_t(1 - D_t) + \gamma_2\, s_t D_t \\ + \sum_i \lambda_{i,1}\, z_{i,t}(1 - D_t) + \sum_i \lambda_{i,2}\, z_{i,t} D_t \\ + \delta_M Mon + \delta_F Fri + \varepsilon_t. \qquad (1)\end{aligned}$$

[13] Day-of-the-week effects were also tested for other days, but only the coefficients for the Friday and Monday dummies were found to be significant in some specifications.

We assume that $\varepsilon_t = \sqrt{h_t} \cdot v_t$, where v_t is an i.i.d. sequence with zero mean and unit variance. The conditional variance h_t is formulated as a function of the past variance (h_{t-1}) and innovations (ε_{t-1}), as well as the day-of-the-week effects (*Mon, Fri*). The effect of FOMC meeting days is modeled by a dummy variable (n_t), as is the effect of macro announcements and FOMC communication $(w_{i,t})$, all of which take the value 1 on days when the corresponding event has occurred, and 0 otherwise. The EGARCH approach accounts for the skewness, the kurtosis, and the time-varying volatility of the interest rate data by formulating a non-normal density for the residuals of the interest rate processes in the following way:

$$\begin{aligned}\ln(h_t) = {} & \omega_1 + \omega_2 D_t + \theta_1 \left(\left| \frac{\varepsilon_{t-1}}{\sqrt{h_{t-1}}} \right| - \sqrt{\frac{2}{\pi}} \right) + \theta_2 \left(\frac{\varepsilon_{t-1}}{\sqrt{h_{t-1}}} \right) \\ & + \theta_3 \ln(h_{t-1}) + \kappa_1 \, n_t (1 - D_t) + \kappa_2 \, n_t D_t \\ & + \sum_i \tau_{i,1} \, w_{i,t} (1 - D_t) + \sum_i \tau_{i,2} \, w_{i,t} D_t + \varphi_M Mon + \varphi_F Fri. \end{aligned} \tag{2}$$

A further advantage of the EGARCH approach is that it does not require us to impose non-negativity constraints on the coefficients of the conditional second moments. The model is estimated via log-likelihood estimation of the function

$$L(\mu) = -\left(\frac{T}{2}\right) \ln(2\pi) - \frac{1}{2} \sum_{t=1}^{T} \left(\ln(h_t) + \frac{\varepsilon_t^2}{h_t} \right), \tag{3}$$

with T the number of observations and μ the vector of parameters of interest.

An alternative approach adopted in a number of related studies (e.g., Kohn and Sack 2004) consists of estimating the effect of an event dummy (taking the value of 1 on days with events, such as FOMC communication, and 0 otherwise) on *absolute* returns. This approach has the advantage that no classification of communication data in terms of their intended direction is required. However, the limitation of this approach is that it cannot distinguish the effect of an event on the level of interest rates and on conditional market volatility, as in the EGARCH model.

This distinction is important, as it allows testing of two different hypotheses. If a central bank announces its decision, this is likely to trigger a contemporaneous market reaction, measured as γ_1 and γ_2 in the mean equation (1). As persistence in the mean equation is usually estimated to be very low, consistent with market efficiency, this reaction is basically concluded within the day of the announcement. On top of this, the model estimates a possible effect of the announced decision on conditional volatility through κ_1 and κ_2 in the conditional variance equation (2). Given the extremely high persistence parameters that are usually (and in our case) estimated for the conditional volatility, significant parameter estimates for κ_1 and κ_2 suggest that the announcement triggers a longer-lasting effect on market volatility that can be interpreted as market uncertainty in response to the announcement. It is therefore possible for a monetary policy decision to have a large contemporaneous effect on the level of interest rates while at the same time reducing their *conditional* volatility over time.

In the case of a transparent central bank, where markets understand well the implications of a release on the future path of monetary policy, we would expect to see a relatively small effect on conditional market volatility, whereas in the case of an opaque central bank, a release would trigger market uncertainty, such that we would expect to find $\kappa_1 > \kappa_2$. Evidence for such an effect has been provided by Swanson (2006), who shows that market uncertainty decreases substantially in response to the FOMC announcements made since 1994. In this paper, we test whether there has been a further decrease in market uncertainty since 1999 as compared to before 1999.

The implications of increased transparency for the mean equation are less straightforward. A more-opaque monetary policy communication is likely to imply that markets will need longer to come to a final assessment of the implications of any given policy decision—which is precisely why we would expect to see market volatility rising. For the level of interest rates, this implies that the reactions are more protracted, whereas a transparent monetary policy will trigger the full adjustment of interest rates instantaneously. Whether we would expect a larger or smaller instantaneous average response depends on the adjustment path in the opaque regime, though. On the one hand, if there is an overshooting on the day

Table 3. The Effect of Monetary Policy Surprises (I): Mean Equation

Maturity	Feb. 1994–April 1999		May 1999–April 2004		Δ
Three Months	0.484***	*0.078*	0.456***	*0.048*	
Six Months	0.433***	*0.045*	0.417***	*0.037*	
One Year	0.401***	*0.048*	0.294***	*0.058*	
Two Years	0.242***	*0.058*	0.216**	*0.105*	
Five Years	0.200***	*0.059*	0.210	*0.142*	
Ten Years	0.040	*0.054*	0.143	*0.158*	

Note: The table shows estimates for γ_1 and γ_2 in equation (1). *, **, and *** denote significance at the 90 percent, 95 percent, and 99 percent level, respectively. Numbers in italics are standard errors. Δ denotes whether the parameters are different for the two subsamples.

of the announcement that is corrected later on, the effect is larger in the opaque regime than in the transparent one. On the other hand, if rates react gradually until they reach their new equilibrium level, the market reaction on the announcement day is smaller in the relatively more-opaque regime.[14]

Table 3 shows the coefficients for the monetary policy surprise in the mean equation (1), γ_1 and γ_2, for the various interest rate maturities, separated for the different disclosure regimes.[15] As the two coefficients are estimated jointly in one model, we can test for differences in the coefficients across the two samples. The corresponding results are reported in the last column of table 3. We find that, generally, there is no significant difference across regimes.

[14]This reasoning is, in two respects, different from the one proposed by Demiralp (2001), who argues that the effect on the day of the announcement should be smaller if more of the announcement has been anticipated. First, we only look at the surprise component, not the announcement itself, and second, we have shown in the previous section that the anticipation effect has not changed across the disclosure regimes, in that the expectations of decisions just before FOMC meetings have not improved.

[15]The results are based on monetary policy surprises from Reuters survey data. As discussed above, the results using federal funds futures are very similar and qualitatively identical to those for the Reuters surveys. For brevity, results for the estimates with federal funds futures are not shown.

Table 4. The Effect of Monetary Policy Surprises (II): Variance Equation

Maturity	**Feb. 1994–April 1999**		**May 1999–April 2004**		**Δ**
Three Months	0.510***	*0.072*	−0.016	*0.061*	***
Six Months	0.294***	*0.065*	0.040	*0.065*	***
One Year	0.165***	*0.058*	−0.094	*0.076*	***
Two Years	−0.034	*0.062*	0.122*	*0.068*	*
Five Years	0.053	*0.069*	0.126	*0.085*	
Ten Years	0.055	*0.072*	0.147*	*0.083*	

Note: The table shows estimates for κ_1 and κ_2 in equation (2). *, **, and *** denote significance at the 90 percent, 95 percent, and 99 percent level, respectively. Numbers in italics are standard errors. Δ denotes whether the parameters are different for the two subsamples.

The test for the effect of FOMC meetings on conditional volatility is more revealing. Table 4 reports the coefficients for the monetary policy surprise in the conditional volatility equation (2), κ_1 and κ_2, for the two regimes. Conditional volatility in response to FOMC decisions is generally lower under the new disclosure regime. In particular, FOMC decisions that are accompanied by statements under the new regime no longer increase conditional volatility for maturities up to and including one year. Importantly, these results are robust to dropping all meetings where interest rates were changed. Interest rate changes were accompanied by FOMC statements also prior to 1999 (yet without containing a bias statement), such that a control for the existence of a statement as such is advisable. However, such a control is observationally equivalent to a control for interest rate changes prior to 1999. A valid robustness test does therefore consist of dropping all such meetings before and after 1999. The robustness of the results confirms that there is an effect of the content, and not merely of the existence, of a statement.

In sum, the results suggest that the change in the Federal Reserve's disclosure practice has indeed had a significant effect on financial markets, mainly by reducing the conditional volatility of interest rates at short maturities on the day of the FOMC meetings.

4.3.2 Market Reactions to the FOMC Balance-of-Risks Statements

So far we have analyzed whether FOMC meetings per se have a different effect on markets in the two regimes. In this subsection, we go one step further and analyze whether the balance-of-risks assessments of the new regime affect markets differently, depending on whether they are tilted toward easing or tightening as compared to being neutral, and whether markets react differently to the monetary policy surprise, depending on whether the balance of risk is symmetric or asymmetric. To test these hypotheses, we modify the model of (1)–(2) further and estimate

$$\Delta r_t = \alpha_1 + \alpha_2\, S_t + \alpha_3\, A_t + \beta \Delta r_{t-1} + \gamma_1\, s_t S_t + \gamma_2\, s_t |A_t| + \sum_i \lambda_i\, z_{i,t} + \delta_M Mon + \delta_F Fri + \varepsilon_t \tag{4}$$

$$\ln(h_t) = \omega_1 + \omega_2 S_t + \omega_3 |A_t| + \theta_1 \left(\left| \frac{\varepsilon_{t-1}}{\sqrt{h_{t-1}}} \right| - \sqrt{\frac{2}{\pi}} \right) + \theta_2 \left(\frac{\varepsilon_{t-1}}{\sqrt{h_{t-1}}} \right) + \theta_3 \ln(h_{t-1}) + \kappa_1 |s_t| + \sum_i \tau_i\, w_{i,t} + \varphi_M Mon + \varphi_F Fri \tag{5}$$

over the new disclosure regime only. All variables and parameters are defined as for model (1)–(2), except that we now introduce a dummy variable S_t, which takes the value 1 if the FOMC meeting is accompanied by a symmetric balance-of-risks statement, and a dummy variable A_t, which is set to 1 if the risk assessment points toward a tightening of monetary policy, to -1 in case of a tilt toward easing of monetary policy, and to 0 otherwise. The hypotheses that this model allows us to test are whether the release of an asymmetric bias has an effect on market interest rates compared to the release of a symmetric bias (α_2 and α_3), whether such a release induces conditional market volatility (ω_2 and ω_3), and whether markets react differently to the surprise component contained in a monetary policy decision, depending on whether the accompanying risk assessment is symmetric or asymmetric (γ_1 and γ_2).

As shown in the first two columns of table 5, the release of an asymmetric bias in itself led to a change in market rates: a tightening (easing) bias increases (decreases) interest rates by around 1 to 2 basis points, predominantly at the shorter maturities. However, there does not seem to be an important difference in the effect of the statements themselves on conditional market volatility. Generally, the differences between the effect of a symmetric and an asymmetric bias are not statistically significant (table 6).

Interestingly, the strength of the response of short-term interest rates to monetary policy *surprises* depends on the type of statement (last two columns of table 5): in the case of an asymmetric bias, the response is significantly larger than the responses to surprises that are accompanied by symmetric statements. This implies that the release of an asymmetric bias can not only change the assessment of the *future* path of monetary policy, it can also be useful information for markets in interpreting the *present* decision.

We conclude that the release of balance-of-risks statements after each meeting under the new regime has had a significant effect on financial markets. Overall, we find that balance-of-risks statements provide information that reduces market uncertainty. Asymmetric balance-of-risks statements are particularly important since they affect the level of interest rates and can, at times, increase their response to monetary policy surprises.

4.4 Interest Rate Adjustment in the Intermeeting Periods

The evidence presented so far shows that the balance-of-risks statements are used by financial markets to predict the future course of monetary policy, which leads to reduced market uncertainty, a reaction of interest rates to asymmetric statements, and a differential response to announced monetary policy decisions when these are accompanied by asymmetric statements. However, this does not necessarily mean that market participants can indeed also better anticipate future monetary policy decisions already at the time when the statements are released, i.e., immediately after the FOMC meetings. The aim of this section is therefore to analyze whether markets have improved their ability to anticipate future decisions at such an early stage. A necessary condition for this is the consistency of the policy bias with future monetary policy decisions, for which we

Table 5. The Effect of Balance-of-Risks Statements (I): Mean Equation

Maturity	Symmetric Bias		Asymmetric Bias		Δ	Policy Surprise with Symmetric Bias		Policy Surprise with Asymmetric Bias		Δ
Three Months	−0.010***	*0.003*	0.011***	*0.004*	***	0.301**	*0.118*	0.627***	*0.065*	**
Six Months	−0.005	*0.004*	0.014***	*0.004*	***	0.250***	*0.061*	0.498***	*0.066*	***
One Year	0.001	*0.007*	0.012**	*0.006*		0.468***	*0.109*	0.270***	*0.070*	
Two Years	0.005	*0.012*	0.022**	*0.010*		0.350	*0.302*	0.172	*0.118*	
Five Years	−0.010	*0.012*	0.015	*0.012*		0.270***	*0.064*	0.169	*0.105*	
Ten Years	0.001	*0.012*	0.013	*0.014*		0.222	*0.359*	0.121	*0.179*	

Note: The table shows estimates for $\alpha_2, \alpha_3, \gamma_1$, and γ_2 in equation (4). *, **, and *** denote significance at the 90 percent, 95 percent, and 99 percent level, respectively. Numbers in italics are standard errors. Δ denotes whether the parameters are different for the two subsamples. Sample period: May 1999–April 2004.

Table 6. The Effect of Balance-of-Risks Statements (II): Variance Equation

Maturity	Symmetric Bias		Asymmetric Bias		Δ
Three Months	−0.216	*0.136*	−0.089	*0.074*	
Six Months	−0.173	*0.161*	−0.106	*0.091*	
One Year	−0.166	*0.117*	−0.249***	*0.087*	
Two Years	0.114	*0.078*	−0.015	*0.053*	
Five Years	0.081	*0.083*	0.010	*0.038*	
Ten Years	−0.043	*0.123*	−0.071	*0.089*	

Note: The table shows estimates for ω_2 and ω_3 in equation (5). *, **, and *** denote significance at the 90 percent, 95 percent, and 99 percent level, respectively. Numbers in italics are standard errors. Δ denotes whether the parameters are different for the two subsamples. Sample period: May 1999–April 2004.

have found supportive evidence in section 2. However, the fact that we know this today *with hindsight* does not necessarily imply that markets believed this at the time when the biases were released. Markets may have had to learn how to respond and act under the new policy regime, and this may mean that markets possibly attached limited weight to these balance-of-risks assessments. Although markets reacted more strongly to monetary policy news on FOMC days with biases, as shown above, this does not necessarily mean that markets were better at anticipating future monetary policy decisions under the new disclosure regime at the time when the bias assessment was made.

To analyze this issue, we test whether market interest rates changed as much during the intermeeting period under the new disclosure regime as under the old regime. The hypothesis is that if the statements and biases issued under the new regime have helped markets anticipate future monetary policy decisions better, then one should see a smaller change in market interest rates between the point in time when the bias announcement has been priced into the market and the next FOMC meeting.

Table 7 reports statistics for the mean absolute changes, the variance of the absolute changes, and the maximum absolute change in

Table 7. Adjustment of Market Interest Rates in the FOMC Intermeeting Period (Three-Month T-Bill Rates)

	Feb. 1994–Apr. 1999	May 1999–Apr. 2004	Δ
All FOMC Meetings			
Number of Meetings	44	42	
Mean Absolute Change	0.187	0.146	
Variance of the Absolute Change	0.038	0.018	**
Maximum Absolute Change	0.870	0.480	
FOMC Meetings with Interest Rate Changes			
Number of Meetings	14	18	
Mean Absolute Change	0.362	0.205	**
Variance of the Absolute Change	0.063	0.013	**
Maximum Absolute Change	0.870	0.480	

Note: Δ denotes whether the parameters in the respective row are statistically significantly different over the two samples. *, **, and *** denote significance at the 90 percent, 95 percent, and 99 percent level, respectively.

the three-month interest rates between the day following an FOMC meeting and the day preceding the next FOMC meeting (i.e., from $t_1 + 1$ to $t_2 - 1$). The upper panel presents the results for all FOMC meeting days, the lower one only for those days when monetary policy rates were changed in the subsequent meeting.

The results reveal that the intermeeting adjustment in market interest rates was statistically significantly lower in 1999–2004, in particular when monetary policy changed in the subsequent meeting. When policy changes occurred, the average absolute intermeeting change in market interest rates in the intermeeting period was 36.2 basis points in 1994–99, whereas it fell to 20.5 basis points in 1999–2004. This finding is even more remarkable considering that the policy changes in 1999–2004 were much larger (nine of the eighteen changes being 50-basis-point changes) than those in 1994–99, when only three of the fourteen changes were 50 basis points and one was 75 basis points. It is also consistent with the findings in table 5:

the balance-of-risks assessments seem to be particularly valuable to markets when they are asymmetric, and thus foreshadow an interest rate adjustment. Finally, also the variance of the absolute daily changes in market rates across the FOMC meetings has been significantly smaller under the new than under the old disclosure regime, both for all FOMC meetings and those with interest rate changes.

4.5 Alternative Sources of Information: Communication and Macro News

So far, we have presented three pieces of evidence: First, we have found that markets have been surprised as much by monetary policy decisions, when comparing the expectations just before each meeting with the actual decisions, under the new disclosure regime as under the old one (section 4.2). Second, markets react more strongly to monetary policy surprises under the new regime if an asymmetric bias has been adopted by the FOMC (section 4.3). And third, markets also are better at anticipating the next monetary policy decision under the new disclosure regime (section 4.4). The first of these findings may seem to contradict the second and third of the results. The question therefore is how, even without the statements, markets managed to predict the upcoming decision equally well just prior to the next FOMC meeting.

It must be the case that under the old regime, markets were capable of extracting information from other sources in the intermeeting period. In this section, we ask what this information may have been. We look in particular at two types of information: other Federal Reserve communication—such as speeches, interviews, and testimonies by FOMC members—and macroeconomic news about the economic outlook and inflationary pressures.

4.5.1 The Role of Central Bank Communication

In between their meetings, FOMC members have the opportunity to convey new information to the markets by making public speeches. Kohn and Sack (2004) and Ehrmann and Fratzscher (2006) argue that such communication conveys important information to market participants and, as such, can affect market interest rates. As mentioned above, we would expect that markets have understood the future course of monetary policy better since 1999, such that their need to extract information from intermeeting communication by FOMC members might be reduced. In our estimates of model (1)–(2) in the preceding section, we already entered the communication of FOMC members as a control variable. The results for the corresponding variables will be of interest here. In the benchmark model, we distinguished communication by content (with respect to the economic outlook and monetary policy, as described in section 3.3). In this section, we will furthermore distinguish it by occasion (namely, hearings and speeches). In the estimation of the benchmark models, all communication events had been entered, although separately for communication about the monetary policy inclination and the economic outlook. The variables had been coded with the value 1 if the content of communication points toward higher interest rates or a strong economic outlook, with the value −1 if it suggests lower interest rates or a weak economic outlook, and with the value 0 if it is neutral. Accordingly, if central bank communication is an effective tool to move markets, the corresponding regression coefficients should be positive and significant.

Table 8 shows the estimated parameters $\lambda_{i,1}$ and $\lambda_{i,2}$ for the mean equation (1), separately for the periods 1994–99 and 1999–2004. Looking at the first subsample, it becomes clear that communication by FOMC members is indeed a means to move markets: interest rates respond significantly to communication, although somewhat more consistently if communication is about monetary policy, whereas the effect of communication about the economic outlook is mainly found for the shorter maturities. The occasions with the largest effect on interest rates are the Congress hearings, where interest rates responded to monetary-policy-related communication with a hump-shaped pattern, by up to 8 basis points for intermediate maturities.

Over the second subsample, 1999–2004, we find significantly lower parameter estimates in a large number of cases. Whereas communication in general still moves the markets, we do not find any significant response of interest rates to Congress hearings any longer. We conclude from this that in the period without FOMC statements, markets needed to infer the future course of monetary policy to a much larger extent from intermeeting communication.

Table 8. The Effect of FOMC Communication on (I): Mean Equation

	Maturity	Feb. 1994–April 1999		May 1999–April 2004		Δ
Communication on Economic Outlook	Three Months	0.010***	*0.003*	0.006***	*0.002*	
	Six Months	0.013***	*0.004*	0.010***	*0.002*	
	One Year	0.011**	*0.004*	0.017***	*0.004*	
	Two Years	0.012*	*0.006*	0.023***	*0.006*	
	Five Years	0.007	*0.007*	0.024***	*0.007*	*
	Ten Years	0.004	*0.007*	0.018***	*0.007*	
Communication on Monetary Policy	Three Months	0.055***	*0.003*	0.011***	*0.003*	***
	Six Months	0.031***	*0.004*	0.005*	*0.003*	***
	One Year	0.033***	*0.005*	0.012***	*0.004*	***
	Two Years	0.029***	*0.006*	0.015**	*0.007*	
	Five Years	0.033***	*0.006*	0.014**	*0.007*	**
	Ten Years	0.027***	*0.006*	0.010	*0.007*	*
Hearings, Economic Outlook	Three Months	0.042***	*0.007*	−0.001	*0.011*	***
	Six Months	0.040***	*0.010*	0.008	*0.007*	***
	One Year	0.064***	*0.014*	0.006	*0.010*	***
	Two Years	0.059***	*0.016*	−0.005	*0.013*	***
	Five Years	0.052***	*0.018*	0.010	*0.015*	*
	Ten Years	0.037*	*0.020*	0.007***	*0.000*	

(*continued*)

Table 8 (continued). The Effect of FOMC Communication on (I): Mean Equation

	Maturity	Feb. 1994–April 1999		May 1999–April 2004		Δ
Hearings, Monetary Policy	Three Months	0.030**	*0.012*	0.008	*0.010*	
	Six Months	0.035**	*0.015*	0.012	*0.015*	
	One Year	0.068***	*0.013*	0.021	*0.016*	**
	Two Years	0.075***	*0.013*	0.016	*0.026*	**
	Five Years	0.081***	*0.018*	0.010	*0.022*	**
	Ten Years	0.078***	*0.017*	0.031*	*0.017*	**
Speeches, Economic Outlook	Three Months	0.011***	*0.004*	0.003	*0.003*	
	Six Months	0.008	*0.006*	0.006	*0.005*	
	One Year	0.007	*0.008*	0.006	*0.009*	
	Two Years	0.006	*0.010*	0.007	*0.013*	
	Five Years	0.008	*0.010*	0.000	*0.014*	
	Ten Years	0.009	*0.010*	−0.001	*0.013*	
Speeches, Monetary Policy	Three Months	0.044***	*0.006*	0.013***	*0.003*	***
	Six Months	0.020***	*0.007*	0.003	*0.004*	**
	One Year	0.009	*0.008*	0.015**	*0.006*	
	Two Years	0.007	*0.011*	0.014	*0.009*	
	Five Years	0.011	*0.011*	0.012	*0.010*	
	Ten Years	0.009	*0.010*	0.006	*0.010*	

Note: The table shows estimates for λ_1 and λ_2 in equation (1). *, **, and *** denote significance at the 90 percent, 95 percent, and 99 percent level, respectively. Numbers in italics are standard errors. Δ denotes whether the parameters are different for the two subsamples.

The results are less clear-cut when looking at the effects of communication on conditional market volatility (parameters $\tau_{i,1}$ and $\tau_{i,2}$ in equation (2), shown in table 9).[16] Consistent with the reduced effect of Congress hearings on the level of interest rates, we find that the response of conditional market volatility to communication has disappeared entirely under the new regime. For communication made on other occasions, there is a clear difference with respect to the content of communication: whereas we find that conditional market volatility is generally reduced more in the second regime in response to communication about the economic outlook, it has significantly risen for monetary-policy-related communication. One potential explanation for this could be the fact that communication about monetary policy has, during the second subsample, intensified relative to the time prior to 1999 (we count such communication on 9 percent of all days since 1999 and on 6.9 percent of all days before) and relative to communication about the economic outlook (which remained stable, at 4.5 percent and 4.9 percent of all days, respectively). Furthermore, in the presence of a released bias statement, there is now the possibility that intermeeting communication could potentially be different from what is implied by the bias. Both the increase in communication frequency and the possibility that the views expressed stand in contrast with the bias might have led to increased conditional market volatility.

4.5.2 The Role of Macroeconomic News

An alternative source of information from which markets can infer about the likely future course of monetary policy and the economic development obviously are the releases of macroeconomic fundamentals. This source of information should therefore have been used more intensely under the old disclosure regime than nowadays. We test therefore whether markets reacted more strongly to the surprise component contained in the released macroeconomic news prior to 1999, both in the sense that interest rates showed a stronger response and that conditional volatility increased more.

[16] As mentioned above, the variables that distinguish the speeches according to content (with respect to the economic outlook or monetary policy) take the values of 1 and –1; we enter these with their absolute values in the variance equations.

Table 9. The Effect of FOMC Communication on (II): Variance Equation

	Maturity	Feb. 1994–April 1999		May 1999–April 2004		Δ
Communication on Economic Outlook	Three Months	−0.355***	*0.044*	−0.245***	*0.037*	*
	Six Months	−0.101***	*0.035*	−0.144***	*0.039*	
	One Year	−0.028	*0.023*	−0.003	*0.045*	
	Two Years	0.017	*0.028*	−0.019	*0.046*	
	Five Years	0.010	*0.041*	0.017	*0.051*	
	Ten Years	0.044	*0.042*	0.011	*0.049*	
Communication on Monetary Policy	Three Months	0.253***	*0.035*	0.250***	*0.018*	
	Six Months	0.178***	*0.032*	0.176***	*0.021*	
	One Year	0.164***	*0.030*	0.123***	*0.025*	
	Two Years	0.107***	*0.031*	0.153***	*0.026*	
	Five Years	0.052	*0.036*	0.155***	*0.030*	**
	Ten Years	0.030	*0.040*	0.145***	*0.032*	**
Hearings, Economic Outlook	Three Months	−0.748***	*0.203*	0.256*	*0.154*	***
	Six Months	0.411**	*0.175*	0.153	*0.160*	
	One Year	0.875***	*0.167*	0.305*	*0.174*	**
	Two Years	0.943***	*0.163*	0.157	*0.190*	***
	Five Years	0.757***	*0.198*	0.171	*0.172*	**
	Ten Years	1.160***	*0.202*	0.276	*0.194*	***

(*continued*)

Table 9 (continued). The Effect of FOMC Communication on (II): Variance Equation

	Maturity	Feb. 1994–April 1999		May 1999–April 2004		Δ
Hearings, Monetary Policy	Three Months	0.450***	*0.160*	−0.141	*0.185*	**
	Six Months	−0.234	*0.164*	−0.043	*0.229*	
	One Year	−0.205	*0.171*	0.146	*0.249*	
	Two Years	−0.440***	*0.148*	0.290	*0.220*	***
	Five Years	−0.229	*0.173*	0.017	*0.226*	
	Ten Years	−0.388**	*0.187*	−0.243	*0.226*	
Speeches, Economic Outlook	Three Months	−0.274***	*0.078*	−0.445***	*0.065*	*
	Six Months	−0.228***	*0.065*	−0.504***	*0.077*	***
	One Year	−0.086	*0.058*	−0.421***	*0.084*	***
	Two Years	−0.020	*0.063*	−0.206***	*0.079*	*
	Five Years	0.007	*0.080*	−0.045	*0.089*	
	Ten Years	−0.006	*0.082*	−0.015	*0.092*	
Speeches, Monetary Policy	Three Months	0.051	*0.066*	0.347***	*0.023*	***
	Six Months	0.100**	*0.050*	0.257***	*0.027*	***
	One Year	0.019	*0.055*	0.243***	*0.033*	***
	Two Years	0.080	*0.057*	0.287***	*0.036*	***
	Five Years	−0.034	*0.061*	0.254***	*0.041*	***
	Ten Years	−0.083	*0.063*	0.196***	*0.046*	***

Note: The table shows estimates for τ_1 and τ_2 in equation (2). *, **, and *** denote significance at the 90 percent, 95 percent, and 99 percent level, respectively. Numbers in italics are standard errors. Δ denotes whether the parameters are different for the two subsamples.

Again, we can resort to our earlier estimates of equations (1) and (2), where we already had included the macroeconomic releases as control variables. Table 10 shows the results for parameters $\lambda_{i,1}$ and $\lambda_{i,2}$ for the mean equation (1) for a number of macroeconomic announcements that have been found to be important (Andersen et al. 2003; Ehrmann and Fratzscher 2005), including leading indicators like the consumer confidence and ISM surveys and retail sales; real variables like industrial production; productivity; employment data like the nonfarm payroll and unemployment figures; and, finally, releases of the consumer price index. The parameters show generally the correct sign: stronger than expected leading indicators, output, employment, and price data should increase interest rates, whereas larger unemployment rates should lead to falling interest rates. The largest reactions are found for the intermediate maturities, which is a common finding in the literature (e.g., Fleming and Remolona 1999) and is intuitive in the sense that monetary policy is likely to react to such surprises in the medium run rather than the short run.

Comparing the two subperiods, it turns out that there are only very few instances where the parameters differ significantly across regimes. Nonetheless, there is an overall tendency for markets to react less to macroeconomic announcements under the new disclosure regimes. The estimated parameters are generally smaller; in more than 80 percent of all cases—namely, for thirty-nine of the forty-eight estimated coefficients—a drop in the market response is observed. Furthermore, the share of significant parameters (at least at the 90 percent level) drops from 73 percent to 60 percent.[17] Looking at the results for the conditional volatility equation in table 11, a similar picture emerges: the reaction of conditional market volatility is generally smaller under the new disclosure regime, with the exceptions of the ISM survey and the unemployment rate. In some cases, like for nonfarm payrolls or the CPI, consistent conditional volatility effects throughout the maturity spectrum have disappeared entirely.

Overall, there is therefore only weak evidence about a reduction in the importance markets attribute to macroeconomic releases; they still form an important source of information for markets. One possibility for this could be that macroeconomic releases are particularly

[17] Omitting observations for a few months after September 11, 2001, when some unusually large surprises were observed, does not alter the results.

Table 10. Market Reactions to Macro Announcements (I): Mean Equation

	Maturity	Feb. 1994–April 1999		May 1999–April 2004		Δ
Consumer Confidence	Three Months	0.009	*0.024*	−0.010	*0.008*	
	Six Months	0.088***	*0.027*	0.021	*0.015*	**
	One Year	0.120***	*0.030*	0.054*	*0.030*	
	Two Years	0.137***	*0.037*	0.066	*0.041*	
	Five Years	0.149***	*0.041*	0.090**	*0.038*	
	Ten Years	0.109***	*0.040*	0.088**	*0.038*	
ISM Survey	Three Months	0.015**	*0.006*	−0.005	*0.006*	**
	Six Months	0.029***	*0.009*	0.020**	*0.008*	
	One Year	0.062***	*0.013*	0.058***	*0.010*	
	Two Years	0.086***	*0.016*	0.099***	*0.019*	
	Five Years	0.095***	*0.017*	0.102***	*0.021*	
	Ten Years	0.077***	*0.017*	0.098***	*0.020*	
Retail Sales	Three Months	0.067***	*0.015*	0.086***	*0.018*	
	Six Months	0.012	*0.011*	0.010*	*0.005*	**
	One Year	0.033***	*0.011*	0.004	*0.006*	
	Two Years	0.052***	*0.015*	0.033**	*0.013*	
	Five Years	0.070***	*0.018*	0.067***	*0.015*	
	Ten Years	0.078***	*0.020*	0.059***	*0.016*	

(*continued*)

Table 10 (continued). Market Reactions to Macro Announcements (I): Mean Equation

	Maturity	Feb. 1994–April 1999		May 1999–April 2004		Δ
Industrial Production	Three Months	0.010	*0.012*	0.007	*0.005*	
	Six Months	0.011	*0.014*	0.005	*0.005*	
	One Year	0.035**	*0.015*	0.010	*0.010*	
	Two Years	0.048**	*0.019*	0.036**	*0.014*	
	Five Years	0.042**	*0.019*	0.039**	*0.016*	
	Ten Years	0.025	*0.017*	0.033**	*0.015*	
Productivity (Preliminary)	Three Months	0.022	*0.044*	0.002	*0.012*	
	Six Months	−0.001	*0.059*	−0.002	*0.015*	
	One Year	0.023	*0.038*	−0.006	*0.045*	
	Two Years	0.013	*0.048*	−0.008	*0.046*	
	Five Years	0.034	*0.030*	−0.017	*0.038*	
	Ten Years	0.036	*0.090*	−0.048	*0.056*	
Unemployment Rate	Three Months	−0.100***	*0.029*	−0.032	*0.032*	
	Six Months	−0.157***	*0.034*	−0.121**	*0.052*	
	One Year	−0.111***	*0.042*	−0.100	*0.078*	
	Two Years	−0.183***	*0.052*	−0.212*	*0.119*	
	Five Years	−0.169***	*0.056*	−0.180	*0.138*	
	Ten Years	−0.134**	*0.055*	−0.178	*0.113*	

(*continued*)

Table 10 (continued). Market Reactions to Macro Announcements (I): Mean Equation

	Maturity	Feb. 1994–April 1999		May 1999–April 2004		Δ
Nonfarm Payrolls	Three Months	0.026***	*0.004*	0.018***	*0.003*	
	Six Months	0.055***	*0.006*	0.023***	*0.003*	***
	One Year	0.071***	*0.011*	0.047***	*0.008*	*
	Two Years	0.078***	*0.013*	0.067***	*0.011*	
	Five Years	0.091***	*0.014*	0.061***	*0.014*	
	Ten Years	0.073***	*0.015*	0.048***	*0.012*	
CPI	Three Months	0.018	*0.012*	0.005	*0.005*	
	Six Months	0.014	*0.013*	0.017***	*0.006*	
	One Year	0.050***	*0.015*	0.029***	*0.009*	
	Two Years	0.050***	*0.017*	0.035***	*0.012*	
	Five Years	0.046**	*0.018*	0.041***	*0.013*	
	Ten Years	0.034*	*0.019*	0.022*	*0.013*	

Note: The table shows estimates for λ_1 and λ_2 in equation (1). Data for productivity are available from 1998. *, **, and *** denote significance at the 90 percent, 95 percent, and 99 percent level, respectively. Numbers in italics are standard errors. Δ denotes whether the parameters are different for the two subsamples.

Table 11. Market Reactions to Macro Announcements (II): Variance Equation

	Maturity	Feb. 1994–April 1999		May 1999–April 2004		Δ
Consumer Confidence	Three Months	0.636*	*0.352*	−1.036***	*0.334*	***
	Six Months	1.052***	*0.348*	−0.199	*0.344*	**
	One Year	2.097***	*0.250*	1.534***	*0.339*	
	Two Years	1.537***	*0.259*	1.073***	*0.318*	
	Five Years	1.479***	*0.287*	0.693*	*0.372*	*
	Ten Years	1.409***	*0.312*	0.774**	*0.380*	
ISM Survey	Three Months	0.435***	*0.114*	0.811***	*0.096*	**
	Six Months	0.444***	*0.161*	0.910***	*0.093*	**
	One Year	−0.132	*0.133*	0.329***	*0.103*	***
	Two Years	−0.265*	*0.137*	0.825***	*0.102*	***
	Five Years	−0.406**	*0.158*	1.030***	*0.135*	***
	Ten Years	−0.329**	*0.166*	0.800***	*0.163*	***
Retail Sales	Three Months	−0.697***	*0.187*	−0.153	*0.104*	**
	Six Months	−0.327**	*0.156*	0.156	*0.097*	***
	One Year	0.458***	*0.140*	0.366***	*0.103*	
	Two Years	0.373**	*0.150*	0.383***	*0.103*	
	Five Years	−0.068	*0.175*	0.358***	*0.116*	**
	Ten Years	−0.250	*0.192*	0.324***	*0.115*	**

(*continued*)

Table 11 (continued). Market Reactions to Macro Announcements (II): Variance Equation

	Maturity	Feb. 1994–April 1999		May 1999–April 2004		Δ
Industrial Production	Three Months	0.109	*0.191*	−0.717***	*0.169*	***
	Six Months	0.166	*0.132*	−0.720***	*0.151*	***
	One Year	−0.333***	*0.106*	−0.625***	*0.148*	
	Two Years	−0.323***	*0.123*	−0.439***	*0.147*	
	Five Years	−0.549***	*0.152*	−0.448***	*0.166*	
	Ten Years	−0.528***	*0.162*	−0.455***	*0.172*	
Productivity (Preliminary)	Three Months	−2.960***	*0.809*	−0.635	*0.401*	**
	Six Months	−1.819**	*0.776*	−0.700**	*0.320*	
	One Year	−3.813***	*0.756*	0.056	*0.368*	***
	Two Years	−3.593***	*1.025*	−0.156	*0.276*	***
	Five Years	−2.888**	*1.164*	0.064	*0.325*	**
	Ten Years	−1.165	*0.869*	0.749**	*0.298*	**
Unemployment Rate	Three Months	−3.314***	*0.553*	4.568***	*0.216*	***
	Six Months	−2.184***	*0.552*	5.125***	*0.245*	***
	One Year	−2.279***	*0.512*	4.812***	*0.261*	***
	Two Years	−2.266***	*0.542*	2.679***	*0.295*	***
	Five Years	−1.549***	*0.577*	0.640	*0.431*	***
	Ten Years	−1.025*	*0.570*	−0.044	*0.675*	

(*continued*)

Table 11 (continued). Market Reactions to Macro Announcements (II): Variance Equation

	Maturity	Feb. 1994–April 1999		May 1999–April 2004		Δ
Nonfarm Payrolls	Three Months	0.588***	*0.070*	0.070	*0.079*	***
	Six Months	0.756***	*0.067*	0.066	*0.069*	***
	One Year	1.062***	*0.049*	0.006	*0.085*	***
	Two Years	1.074***	*0.049*	−0.052	*0.086*	***
	Five Years	1.019***	*0.058*	0.000	*0.093*	***
	Ten Years	1.005***	*0.063*	0.005	*0.105*	***
CPI	Three Months	0.759***	*0.193*	0.214*	*0.110*	**
	Six Months	0.395**	*0.165*	0.236*	*0.126*	
	One Year	0.321**	*0.147*	0.005	*0.130*	
	Two Years	0.502***	*0.160*	0.063	*0.125*	**
	Five Years	0.717***	*0.172*	−0.234*	*0.132*	***
	Ten Years	0.825***	*0.183*	−0.041	*0.141*	***

Note: The table shows estimates for τ_1 and τ_2 in equation (2). Data for productivity are available from 1998. *, **, and *** denote significance at the 90 percent, 95 percent, and 99 percent level, respectively. Numbers in italics are standard errors. Δ denotes whether the parameters are different for the two subsamples.

informative about the future path of monetary policy in the medium run (as reflected by the fact that it is primarily the intermediate maturities that react to these releases), such that markets consider them important to update their expectations beyond the horizon of the next FOMC statements.

5. Conclusions

The objective of the paper has been to assess whether the change in the Federal Reserve's disclosure practice of 1999 was successful in enhancing the effectiveness and transparency of U.S. monetary policy. This regime change entailed the publication of a statement, immediately after each FOMC meeting, that not only explains its monetary policy decision but also contains a forward-looking element—initially in the form of an outlook for the monetary policy stance and, later, in the form of a balance-of-risks assessment concerning inflationary pressures and economic conditions in the "foreseeable future."

The empirical approach taken in the paper has been to compare both the market's reaction to FOMC decisions and its ability to anticipate and predict the future course of monetary policy under the new regime as compared to the previous regime. First, we find that markets have anticipated monetary policy decisions equally well under both regimes, when comparing the expectations just before each meeting with the actual decisions. Second, the reactions of financial markets to monetary policy are strikingly different across the two regimes. Not only do they have a larger effect on the level of interest rates if they are accompanied by an asymmetric risk assessment, but also the conditional volatility induced by FOMC meetings has been significantly lower since 1999. Third, markets anticipate the next monetary policy decision earlier under the new disclosure regime, such that market interest rates move by a smaller magnitude over the whole intermeeting period under the new regime.

Taken together, these three pieces of evidence suggest that under the old regime, markets were capable of compensating their lack of information from FOMC announcements by extracting information from other sources in the intermeeting period. We show that markets reacted more strongly to other types of Federal Reserve communication—such as testimonies, interviews, and speeches by

FOMC members—in the intermeeting periods. In this sense, markets may merely have shifted their attention from other types of information to the statements and balance-of-risks assessments of the FOMC decisions themselves to obtain the relevant information.

How shall one assess this regime change? On the one hand, the change in the disclosure regime may be interpreted as an increase in transparency, as markets are provided with relevant information at an earlier stage and in a more-transparent manner. This makes it easier and less costly for markets to obtain the information, and helps reduce market uncertainty about the future course of monetary policy. On the other hand, our finding that markets attach such a strong importance to the statements by the FOMC is contrary in spirit to King (2000), who argues that, with a transparent monetary-policy reaction function, news should not be in the announcements of central banks but should entirely arise in the development of the economy.

Several major issues are left unanswered, as the scope and objective of the paper has been limited to the analysis of the change in the FOMC disclosure regime. In particular, while we have provided evidence that the market's anticipation of monetary policy has improved in some ways, a verdict is still out on whether the approach adopted by the FOMC is optimal or whether alternative communication strategies are superior in providing transparency and in enhancing the efficiency of monetary policy. What constitutes an "optimal" communication strategy is hotly debated and very much depends on one's understanding of the concepts of transparency and effectiveness of monetary policy. Some phrase their view in the same manner as William Poole (2003, 7):

> Some will regard this approach [of choosing among a relatively few standard phrases] as providing "boilerplate" language with little real meaning. My own judgment is that it is better to provide boilerplate with clear meaning than rich language with a multiplicity of possible meanings. It just is not true that lots of words equals lots of disclosure and greater transparency.

By contrast, others, such as Issing (2005, 70), argue that the use of simple language and code words bears some serious dangers:

> However, with the use of such code words, the central bank puts itself under pressure to honour a quasi-promise. If, in the meantime, its assessment of the situation has changed, owing

> to new developments, the central bank will be faced with the dilemma of triggering market disturbances if they “disappoint” expectations, even though they may have convincing arguments to justify their reassessment of the circumstances. For this reason, indications about future decisions must always be seen only as conditional commitments. In practice, however, it is likely to prove extremely difficult to communicate this proviso with sufficient clarity. The more straightforward the “announcement” and the simpler the code, the more difficult it will be to explain its conditionality ex ante.

In order to assess these claims, one would need to compare the consequences of the different ways of communication chosen by different central banks. We leave this for future research.

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