Information Design, Signaling, and Central Bank Transparency*

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This study examines monetary policy and central bank communication when a monetary instrument signals the central bank's private information. A novel feature is that the central bank ex ante determines how much information it acquires and how much of this information it releases to the public. Using a static model with a neoclassical Phillips curve, I show that an optimal information policy is composed of the full disclosure of the bank's acquired information, eliminating the signaling effect of monetary policy. The optimal signal consists of two linear combinations of three shocks, balancing an informational tradeoff between inflation and output stabilization.

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1. Introduction

There is a long-standing and ongoing debate on central bank transparency. In the past three decades, central banks in developed economies shifted their focus to greater transparency in their objectives, policymaking procedures, and market operations.[1] Transparency in these aspects is desirable to achieve accountability, which is important to discipline monetary policy under central

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[1] Eijffinger and Geraats (2006) document changes in central bank transparency between 1998 and 2002 for major developed economies.

bank independence. Nonetheless, central banks can still be opaque with respect to internal forecasts about underlying economic conditions or short-term policy targets if opacity improves social welfare. An important aspect of economic transparency is that central banks process internal information about the economy, such as economic statistics and simulation results, under organizational policies. Therefore, the policy for economic transparency is inseparable from the collection and processing of internal information used in policymaking and communicated to the public.

In this study, I use a static monetary model to investigate the optimal policy for the acquisition and disclosure of information about the underlying state of the economy. Specifically, the central bank imperfectly controls the inflation rate by adjusting its monetary instrument, accounting for a positive relationship between inflation and real output based on the short-term expectations-augmented Phillips curve. The central bank's role is to reduce economic fluctuations due to three types of shocks, such as shocks in the monetary policy channel, labor supply, and markups, which determine the effect of a monetary policy as well as the efficient levels of output and inflation rate. A novel feature of this study is that the central bank ex ante chooses an information policy that determines how much information it acquires and how much of this information it releases to the public.

Under the information structure specified by an information policy, the central bank engages in monetary policy contingent on signal observations, and then the private sector forms a posterior belief about the state of the economy based on the disclosed information and observed monetary policy.[2] If the central bank acts in response to its private information, the private sector can at least partially infer the information from the policy action. In this sense, I examine a signaling game with an endogenous information structure in which the information policy determines the degree of informational asymmetry between the central bank and the private sector. The present study differs from those on central bank transparency or signaling games in its general framework of the information policy, which is a

[2]In this respect, the present study crucially differs from the classical framework by Barro and Gordon (1983), in which the monetary policy occurs *after* the private sector forms an expectation about inflation.

standard formulation in the recent literature on optimal information design/Bayesian persuasion.[3]

The main finding of this study is that central banks can implement an optimal information policy under the restriction that the central bank discloses all acquired information.[4] More precisely, this study shows that (i) any outcome induced by a commitment policy (e.g., a pairing of information and monetary instrument policies) can be generated under the full disclosure restriction and (ii) there is an information policy under which the discretionary monetary policy in equilibrium implements the optimal commitment policy. The former result implies that creating information asymmetries plays no role in enhancing the effectiveness of a monetary policy when the signaling effect works. The latter observation indicates that the acquisition of imperfect information serves as a commitment device, while providing enough information to make appropriate policy decisions. Therefore, greater accountability or an increased transparency requirement itself entails no conflict in monetary policy and expectations management by central banks if information acquisition is costless and subject to no constraints.[5]

These observations allow us to avoid the difficulties of policy signaling and move to investigating the optimal design of public information. In a specific monetary model, I show that the optimal public signal consists of two statistics constructed as linear combinations of the three state variables. Thus, both the central bank and private sector have imperfect information about the state of the economy. An advantage of this kind of partial revelation over full revelation is that it can generate a certain correlation between the expectations about the underlying state variables, which helps stabilize output by inducing a co-movement between expected inflation and the efficient output level (or a supply shock). In the model, output becomes

[3] See, for example, Kamenica and Gentzkow (2011) and Bergemann and Morris (2016).

[4] This result does not depend on the specification of state distribution, action space, and payoff structure, and applies to any type of signaling game in which the leader also chooses the information structure for both players. For a general framework, see Tamura (2015).

[5] The study assumes that information collection is costless. I assume this because the social costs of information acquisition are small compared with the social benefits of enhanced macroeconomic stabilization.

high when the private sector over-estimates the shock to monetary transmission (or, shortly, the monetary shock). Hence it is beneficial to make the private sector over-estimate the monetary shock in situations where the output target is high. Compared with no revelation, the optimal signal provides certain information about the state that enables a flexible monetary policy to stabilize inflation. Using a numerical example, I illustrate how the two-dimensional signal helps in the pursuit of the two policy objectives of output and inflation stabilization, and successfully reduces the welfare loss compared with benchmark information regimes.

For the optimal information policy, however, the specific weights of the two statistics are determined based on an informational tradeoff between output stabilization through expectations management and inflation stabilization through monetary policy. To improve the flexibility of monetary policy, one of the statistics must contain a certain amount of information about a monetary shock. An increase in information revelation about a monetary shock necessarily limits the scope of inducing a co-movement in expectations because it reduces the impact of another statistic on the posterior expectation about a monetary shock, and therefore on expected inflation. In other words, enhanced output stabilization requires a distortion in monetary policy wherein the monetary instrument must be less responsive to a monetary shock to avoid revealing excess information about a monetary shock. The optimal weights for the two statistics account for this informational tradeoff and result in imperfect inflation stabilization.

It is worth noting that in the present study, the central bank is a leader and the private sector is a follower. Therefore, the classical time-inconsistency problem, as Barro and Gordon (1983) highlight, among others, does not arise. In the time-inconsistency setting in which the central bank is a follower, there is an informational tradeoff wherein the central bank must refrain from acquiring information to curb ex post incentives but wishes the private sector to be aware of it.[6] By contrast, I address the policy signaling issue in which the

[6] In this case, the optimal information policy is characterized using the Bayes correlated equilibrium (BCE) approach developed by Bergemann and Morris (2013, 2016) rather than the Bayesian persuasion approach I adopt here.

central bank must respond to information but wishes to withhold it from the private sector.[7]

The monetary model in this study is based on a recent work by Frankel and Kartik (2015), who analyze a signaling game with multiple shocks and examine the welfare consequences of greater transparency about each shock. They find that greater transparency about the central bank's short-term inflation target reduces social welfare, while full revelation about a monetary shock minimizes welfare loss. In contrast, this study considers a general model of information choice and shows that providing independent signals for each shock cannot be optimal if the supply shock is introduced.

Several studies focus on the signaling role of a monetary policy under discretion and commitment. Under discretion, Faust and Svensson (2001) consider a reputation model with a privately informed central bank and investigate the relationship between transparency and the credibility of a disinflationary policy. Within a New Keynesian framework, Hahn (2012) examines the disclosure of noisy information about cost-push shocks and shows that the opacity regime is socially preferred to the transparency regime if the degree of informational frictions for price setters is strong enough.[8] A few studies investigate optimal monetary policy under commitment when the monetary instrument has a signaling effect. Baeriswyl and Cornand (2010) examine how the signaling effect of a monetary policy affects optimal responses to fundamentals by comparing several information regimes. Walsh (2007) examines the optimal degree of dissemination of public information, as in Cornand and Heinemann (2008). A recent work by Tamura (2016) characterizes the optimal commitment policy of a monetary instrument and information disclosure and investigates how informational frictions among price setters affect the informational content of an optimal public signal. Unlike these studies, I consider an optimal policy design

[7]In the monetary model in this study, the shock in the monetary policy channel plays the key role in this policy signaling tradeoff. In the New Keynesian model, Tamura (2016) argues that information on markup or cost-push shocks generates such an informational tradeoff.

[8]In contrast, Hahn (2014) considers a signaling model with a demand shock (or labor supply shock) and shows that the disclosure of a central bank's private information before taking a policy action can improve welfare only by eliminating a bad equilibrium that may arise in the opacity regime.

for information acquisition in addition to a disclosure policy, which enables a reexamination of the role of monetary policy signaling.

Within a classical Barro-Gordon framework in which the central bank is a follower, Cukierman (2001) and Gersbach (2003) examine the welfare effects of transparency about a supply shock and a monetary shock. They show that greater transparency about a supply shock increases the welfare loss, while information about the monetary shock is irrelevant. Information about a supply shock reveals the central bank's ex post incentive to adjust the inflation rate, which in turn reduces the effectiveness of monetary policy to stabilize output because the policy effect on output is based on unexpected inflation. On the other hand, information about a monetary shock does not affect the outcome, because the central bank perfectly neutralizes the monetary shock and keeps the inflation rate constant. In contrast, the present signaling framework, in which the central bank is a leader, nullifies the direct effect of monetary policy on the output and creates a need to introduce co-movement between the supply shock and expected inflation through expectations management.

A seminal work of Morris and Shin (2002) initiated the recent debate on central bank transparency. The study shows that when private agents have dispersed information about the state, strategic complementarities generate excess responses to public information, which can be the focal point in successfully coordinating actions. Depending on the payoff structure, increased precision in the public signal may have a detrimental effect on social welfare.[9] In addition, the literature examines the types of shocks in monetary economics models that induce inefficient fluctuations in market expectations. For example, public information about shocks on monetary policy (Hellwig 2005) and labor supply or productivity (Roca 2010) are harmless, while cost-push, markup, or labor-wedge shocks generate undesirable fluctuations in the economy (Angeletos, Iovino, and La'O 2011). As I highlight in section 5 below, it may be optimal to

[9]Using a Lucas-Phelps island model with dispersed information, Myatt and Wallace (2014) examine the conditions under which increased accuracy or transparency of central bank announcements reduce output gap variations. In their model, the central bank controls a correlation in privately observed signals about a common shock, thereby affecting the formation of higher-order beliefs. In contrast, the present model addresses the introduction of a correlation in the beliefs about multiple shocks held by a single representative agent.

construct and disclose economic statistics or monetary policy indexes using available information on the different types of shocks rather than disclosing an independent statistic or index for each shock.

The remainder of this paper proceeds as follows. Section 2 specifies the basic monetary model and section 3 defines the equilibrium and optimal policy for two commitment setups. Section 4 presents the main results. Section 5 examines the optimal information policy for a specific monetary model. Section 6 discusses the commitment assumption. Section 7 concludes. The appendixes contain proofs and derivations.

2. A Monetary Model

2.1 A Setup

This section presents a simple static model of a monetary economy.[10] The economy consists of a central bank and a representative private sector. The central bank (imperfectly) controls the inflation rate by setting its monetary instrument $m \in M \equiv \mathbb{R}$. The monetary instrument m and the shock on a monetary policy channel $\eta \in \mathbb{R}$ determine the inflation rate:

$$\pi = m - \eta. \tag{1}$$

The expectations-augmented Phillips curve determines real output:

$$y = \pi - \hat{\pi}, \tag{2}$$

where $\hat{\pi} \equiv \mathbb{E}[\pi|\mathcal{I}_{PS}]$ is the expected inflation rate given the private sector's information set $\mathcal{I}_{PS}$. Suppose that the private sector perfectly observes monetary instrument m. This assumption implies that if the central bank has information superior to that of the private sector, the choice of m may have a signaling effect. In this case, the central bank should control its monetary instrument while accounting for both the direct impact on the inflation rate and the indirect effect of the changes on the private sector's expectations.

[10]This model is based on a slight modification of the specification of Frankel and Kartik (2015), who develop a static signaling model with multiple state variables.

The central bank's objective is to minimize the welfare loss function defined by

$$L = (y - y^*)^2 + \lambda(\pi - \pi^*)^2, \tag{3}$$

where y^* and π^* are the efficient levels of output and inflation rate, which may reflect shocks in the labor supply, productivity, and aggregate demand and shocks in distortionary taxes and efficient markups.[11,12]

I denote the state of the economy (e.g., a vector of shocks) by $\theta \equiv (\eta, y^*, \pi^*) \in \Theta \equiv \mathbb{R}^3$. Assume that the state is distributed according to the distribution function $F(\theta)$ with density $f(\theta)$. When I present a specific solution to the optimal policy problem in section 5, I assume that the state variables are independent and normally distributed according to $\eta \sim N(0, \sigma_\eta^2)$, $y^* \sim N(0, \sigma_{y^*}^2)$, and $\pi^* \sim N(0, \sigma_{\pi^*}^2)$.

The central bank reduces welfare losses by choosing (i) an information policy (a combination of information acquisition and public announcement), which determines the information structures of the central bank and private sector and (ii) an instrument policy, which is a rule for the monetary policy instrument. The private sector forms expectations for the state of the economy based on the observed monetary instrument and public announcement. Specifically, an information policy $\varphi : \Theta \to \Delta(R \times S)$ is a mapping that determines the joint distribution of the private signal $r \in R$ and public signal $s \in S$ for each state realization $\theta \in \Theta$, where R and S are any arbitrary measurable sets.[13,14] The signal r is privately observed by the central bank, while the signal s is publicly observed.[15] The central bank's information set is $\mathcal{I}_{CB} = \{r, s\}$ and

[11] Note that it is essentially equivalent to consider an alternative specification with labor supply shock e instead of y^*, where the output gap is $y = \pi - \hat{\pi} + e$. Thus, y^* is interpreted as a negative labor supply shock.

[12] It is straightforward to introduce the central bank's inflation bias by modifying the output loss, as in $(y - y^* - b)^2$ or $(y - y^*)^2 - by$ for some constant $b > 0$, although it does not affect the optimal information policy characterized in proposition 3.

[13] Here, $\Delta(X)$ denotes the set of distributions over set X.

[14] Therefore, the information policy should be formally defined as (R, S, φ).

[15] Alternatively, I can represent an information policy as a combination of an information acquisition policy (experiment) φ^e, which determines the central

that of the private sector is $\mathcal{I}_{PS} = \{s, m\}$. I denote the central bank's mixed strategy or instrument policy as $\sigma : R \times S \to \Delta(M)$. In an abuse of notation, I also denote a pure strategy by $m = \sigma(r, s)$.

An advantage of the Bayesian persuasion approach is that it enables a researcher to deal with a general class of information policies. Below are a few examples common in the literature. A *full revelation policy* is an information policy in which the central bank acquires full information of the state and discloses it to the private sector. I formally define this policy as φ^F such that (i) R is a singleton, (ii) $S = \Theta$, and (iii) $\varphi(r, s|\theta) = 1$ for $s = \theta$. A *private revealing policy* is an information policy in which the central bank acquires full information of the state and discloses no information to the private sector. This policy corresponds to a standard information structure for signaling games formally defined by φ^P such that (i) $R = \Theta$, (ii) S is a singleton, and (iii) $\varphi(r, s|\theta) = 1$ for $r = \theta$. A *noisy communication policy* is an information policy in which the central bank receives imperfect signals about the state and discloses signals with additional noise. This is usually expressed as

$$r = \theta + \epsilon_r \equiv \begin{bmatrix} \eta + \epsilon_{r,\eta} \\ y^* + \epsilon_{r,y^*} \\ \pi^* + \epsilon_{r,\pi^*} \end{bmatrix}, \ s \equiv r + \epsilon_s = \begin{bmatrix} \eta + \epsilon_{r,\eta} + \epsilon_{s,\eta} \\ y^* + \epsilon_{r,y^*} + \epsilon_{s,y^*} \\ \pi^* + \epsilon_{r,\pi^*} + \epsilon_{s,\pi^*} \end{bmatrix}, \quad (4)$$

where $\epsilon_r = (\epsilon_{r,\eta}, \epsilon_{r,y^*}, \epsilon_{r,\pi^*})$ and $\epsilon_s = (\epsilon_{s,\eta}, \epsilon_{s,y^*}, \epsilon_{s,\pi^*})$ are noise in the central bank's and private sector's signals. A typical setup for central bank communication assumes that these noise terms are independent and normally distributed.

Although the general formulation of information policies allows the central bank to create a wide variety of information asymmetries against the private sector, it is useful to focus on a class of information policies in which the central bank and private sector have symmetric information about the state of the economy. Specifically, a *symmetric information policy* or full disclosure policy is an information policy in which the central bank discloses all acquired information. This class of information policies corresponds to the

bank's information set as a function of the state, and a disclosure policy φ^d, which specifies the information available to the private sector as a function of the central bank's information set.

case in which R is a singleton, so the central bank and private sector observe only the realization of the public signal. For a symmetric information policy, I also state that an information policy satisfies the *full disclosure restriction*.

2.2 Benchmark Information Regimes

I now illustrate the basic mechanism of the present model within two benchmark information regimes. In the full information regime (or the full revelation policy φ^F), in which the central bank and private sector perfectly observe the realization of the state, a monetary policy cannot affect the real output because unexpected inflation does not arise:

$$y^F = \pi - \hat{\pi} = (m - \eta) - (m - \hat{\eta}) = 0. \tag{5}$$

Then, the loss function reduces to

$$L^F = (-y^*)^2 + \lambda(m - \eta - \pi^*)^2. \tag{6}$$

Hence, the equilibrium monetary policy must focus only on stabilizing inflation:

$$m^F = \eta + \pi^*. \tag{7}$$

Although a monetary policy can reduce the inflation loss to zero, the remaining output gap arises from fluctuations in the efficient output level due to the supply or employment shock that cannot be absorbed. Hence, the equilibrium welfare loss under the full information regime is

$$\mathcal{L}^F = \mathbb{E}[L^F] = \mathrm{var}(y^*). \tag{8}$$

In the signaling equilibrium regime (or the privately revealing policy φ^P), in which the central bank perfectly observes the realization of the state but discloses no information directly to the private sector, a monetary policy can affect output by changing expected inflation. Suppose that in equilibrium, the private sector's expectations of the monetary shock is $\hat{\eta} = \phi m$ for some $\phi > 0$. Then, the central bank's loss function is

$$L^P = (\phi m - \eta - y^*)^2 + \lambda(m - \eta - \pi^*)^2. \tag{9}$$

This signaling effect generates the central bank's incentive to adjust its monetary instrument in response to the supply shock $-y^*$ because it reduces the output gap loss by inducing a co-movement between output and the efficient output level. Indeed, the first-order condition for the sequentially optimal monetary policy is

$$m^P = \frac{\phi + \lambda}{\phi^2 + \lambda}\eta + \frac{\phi}{\phi^2 + \lambda}y^* + \frac{\lambda}{\phi^2 + \lambda}\pi^*. \tag{10}$$

If there is no signaling effect (e.g., $\phi = 0$), the monetary policy rule becomes $m^P = \eta + \pi^*$, which leads to zero inflation loss. In the signaling equilibrium $\phi > 0$, the signaling incentive distorts the policy responses to the state variables. Anticipating this type of discretionary behavior, the private sector rationally forms expectations of the state based on the observed monetary policy, which in turn exacerbates the incentive distortion caused by policy signaling. Although the closed-form solution for the equilibrium strategy is not available, I present some numerical exercises to examine the equilibrium policy responses to shocks and the expected loss in section 5.3.

The benchmark analyses above suggest two distinct approaches to reducing welfare losses. One is to reduce the distortion in monetary policy to stabilize inflation. If m is set close to $\eta + \pi^*$, the inflation loss is small. The other is to induce a co-movement between the output target y^* and output $y = \hat{\eta} - \eta$. Indeed, the output gap loss is

$$\mathbb{E}[(\hat{\eta} - \eta - y^*)^2] = \text{var}(\eta + y^*) - \text{var}(\hat{\eta}) - 2\text{cov}(\hat{\eta}, \hat{y}^*). \tag{11}$$

Hence, the output gap is small if the private sector is better informed of η and has correlated expectations about η and y^*.

3. Equilibrium Concepts and Optimal Policy Definitions

In this section, I define optimal policies in two commitment environments. One is a benchmark case in which the central bank can commit to both an instrument policy and an information policy. Second is a setting with a discretionary monetary policy in which the central bank and private sector play a signaling game under the information structure specified by the information policy.

3.1 Monetary Policy under Commitment

I first consider the benchmark case in which a central bank implements a monetary policy under commitment. The timing of the game is as follows. First, the central bank chooses a pair (σ^c, φ^c) of monetary and information policies, referred to as a *commitment policy.* Second, the state is realized and the signals are delivered to the central bank and private sector according to φ^c. Third, the central bank chooses its monetary instrument m contingent on (r, s) according to the predetermined instrument policy σ^c. Finally, the private sector forms expectations of the state, $\hat{\theta} = \mathbb{E}[\theta|\mathcal{I}_{PS}]$, based on $\mathcal{I}_{PS} = \{r, m\}$.

In this benchmark case, the central bank is non-strategic at the third stage of choosing m.[16] Therefore, the condition for the perfect Bayesian equilibrium reduces to the belief consistency for the private sector. Let $\mu : S \times M \to \Delta(\Theta)$ denote the private sector's belief function, which specifies a posterior belief $\mu(\cdot|s, m) \in \Delta(\Theta)$ as a function of public signal s and observed monetary instrument m. Then, the optimal commitment policy $(\sigma^{c*}, \varphi^{c*})$ is a solution to the following problem:

$$\begin{aligned} &\min_{\sigma^c, \varphi^c} \ \mathcal{L}(\mu; \sigma^c, \varphi^c) \\ &\text{s.t. } \mu \in \mathcal{B}(\sigma^c, \varphi^c), \end{aligned}$$

where $\mathcal{L}(\mu; \sigma^c, \varphi^c)$ is the expected loss function given $(\mu, \sigma^c, \varphi^c)$ and $\mathcal{B}(\sigma^c, \varphi^c)$ is the set of belief functions consistent with Bayes's rule under (σ^c, φ^c). In the specific monetary model in section 2, the central bank's problem is as follows:

$$\begin{aligned} \min_{\sigma^c, \varphi^c} \ \int_{\theta \in \Theta} \int_{(r,s) \in R \times S} \int_{m \in M} &\left\{ (\hat{\eta}(s, m) - \eta - y^*)^2 + \lambda(m - \eta - \pi^*)^2 \right\} \\ &\times d\sigma^c(m|r, s) d\varphi^c(r, s|\theta) dF(\theta) \\ \text{s.t. } \hat{\eta}(s, m) = &\int_{\theta \in \Theta} \eta d\mu(\theta|s, m) \end{aligned}$$

[16]Note that the central bank strategically chooses the rule of monetary policy σ^c at the first stage.

$$\mu(\theta|s,m) = \frac{\int_{r\in R} \sigma^c(m|r,s)\varphi^c(r,s|\theta)drf(\theta)}{\int_{\theta\in\Theta}\int_{r\in R} \sigma^c(m|r,s)\varphi^c(r,s|\theta)drf(\theta)d\theta}.$$

The first expression in the program above is the expectation of the loss function, where the random variables are (m, r, s, θ). The commitment policy determines the conditional distribution of (m, r, s) given θ. The second expression is the private sector's expectation of the state computed by the posterior belief $\mu(\theta|s,m)$, which is in turn defined in the third expression. Alternatively, I can simplify the expression of the program using the expectation operators:

$$\min_{\sigma^c,\varphi^c} \mathbb{E}_{(\sigma^c,\varphi^c)}\left[(\hat{\eta}(s,m) - \eta - y^*)^2 + \lambda(m - \eta - \pi^*)^2\right]$$
$$\text{s.t. } \hat{\eta}(s,m) = \mathbb{E}_{(\sigma^c,\varphi^c)}\left[\eta|s,m\right].$$

3.2 Monetary Policy under Discretion

In the case in which a central bank conducts monetary policy under discretion, the timing of the game is as follows. First, the central bank chooses an information policy φ. Second, the state is realized and the signals are delivered to players according to φ. Third, the central bank strategically chooses m given the signal realizations (r, s). Finally, the private sector forms an expectation $\hat{\theta} = (\hat{\eta}, \hat{y}^*, \hat{\pi}^*)$ given $\mathcal{I}_{PS} = \{s, m\}$.

Unlike in the commitment benchmark case, the central bank's strategy (or discretionary instrument policy) is determined in equilibrium. Hence, the optimal information policy φ^* is a solution to the following problem:

$$\min_{\varphi} \mathcal{L}(\mu,\sigma;\varphi)$$
$$\text{s.t. } (\mu,\sigma) \in \mathit{PBE}(\varphi),$$

where $\mathit{PBE}(\varphi)$ is the set of perfect Bayesian equilibriums under information policy φ.[17] In the specific monetary model, the optimal information policy is

[17] A pair (μ, σ) constitutes a perfect Bayesian equilibrium under φ if (i) σ is optimal given μ and (ii) μ is consistent with (σ, φ), at least on the equilibrium path.

$$\min_{\varphi} \int_{\theta\in\Theta}\int_{(r,s)\in R\times S}\left\{(\hat{\eta}(s,\sigma(r,s))-\eta-y^*)^2+\lambda(\sigma(r,s)-\eta-\pi^*)^2\right\}$$
$$\times\, d\varphi(r,s|\theta)dF(\theta)$$
$$\text{s.t. } \sigma(r,s)=\arg\min_{\tilde{m}}\int_{\theta\in\Theta}\left\{(\hat{\eta}(s,\tilde{m})-\eta-y^*)^2+\lambda(\tilde{m}-\eta-\pi^*)^2\right\}$$
$$\times\, dq(\theta|r,s)$$
$$q(\theta|r,s)=\frac{\varphi(r,s|\theta)f(\theta)}{\int_{\theta\in\Theta}\varphi(r,s|\theta)f(\theta)d\theta}$$
$$\hat{\eta}(s,m)=\int_{\theta\in\Theta}\eta d\mu(\theta|s,m)$$
$$\mu(\theta|s,m)=\frac{\int_{r\in\{\tilde{r}:m=\sigma(\tilde{r},s)\}}\varphi(r,s|\theta)drf(\theta)}{\int_{\theta\in\Theta}\int_{\tilde{r}\in\{r:m=\sigma(r,s)\}}\varphi(r,s|\theta)drf(\theta)d\theta}.$$

The first expression in the program is the expectation of the loss function where the random variables are (r,s,θ). The second expression defines the central bank's (pure strategy) best response to the private sector's equilibrium belief formation. The third expression is the central bank's posterior belief $q(\theta|r,s)$. The third and fourth expressions define the condition for the consistency of the private sector's posterior belief with respect to the state distribution, information policy, and equilibrium strategy. Alternatively, the optimal information policy problem with a discretionary monetary policy is expressed simply using the following expectation operators:

$$\min_{\varphi}\ \mathbb{E}_{\varphi}\left[(\hat{\eta}(s,\sigma(r,s))-\eta-y^*)^2+\lambda(\sigma(r,s)-\eta-\pi^*)^2\right]$$
$$\text{s.t. } \sigma(r,s)=\arg\min_{\tilde{m}}\mathbb{E}_{\varphi}\left[(\hat{\eta}(s,\tilde{m})-\eta-y^*)^2+\lambda(\tilde{m}-\eta-\pi^*)^2|r,s\right]$$
$$\hat{\eta}(s,m)=\mathbb{E}_{(\sigma,\varphi)}\left[\eta|s,m\right].$$

3.3 Monetary Policy under the Full Disclosure Restriction

In this subsection, I reformulate the equilibrium concept and optimal policy under the full disclosure restriction. When R is a singleton, the private signal r has no informational value. This implies that the signaling issue disappears because the players have symmetric beliefs $\mathbb{E}[\theta|\mathcal{I}_{CB}] = \mathbb{E}[\theta|\mathcal{I}_{PS}] = \mathbb{E}[\theta|s]$. Therefore, it is reasonable to replace $PBE(\varphi)$ in the optimal policy problem with the set of subgame perfect equilibriums denoted by $SPE(\varphi)$ when the information policy φ satisfies the full disclosure restriction.[18]

Suppose that $\tilde{\varphi} : \Theta \to \Delta(S)$ is a symmetric information policy under which the central bank and private sector observe only the realization of public signal s. Under the full disclosure restriction, the optimal information policy is a solution to the following problem:

$$\begin{aligned} \min_{\tilde{\varphi}:\Theta\to\Delta(S)} \ & \mathcal{L}(\mu, \sigma; \tilde{\varphi}) \\ \text{s.t. } & \sigma \in SPE(\tilde{\varphi}) \\ & \mu \in \mathcal{B}(\tilde{\varphi}). \end{aligned}$$

The second expression indicates that the central bank must choose a best response given the information structure $\tilde{\varphi}$, while the third expression indicates that the private sector's belief must depend only on $\tilde{\varphi}$ and be independent of σ. This program in the specific monetary model is

$$\begin{aligned} \min_{\tilde{\varphi}:\Theta\to\Delta(S)} \int_{\theta\in\Theta}\int_{s\in S} & \left\{(\hat{\eta}(s)-\eta-y^*)^2 + \lambda(\sigma(s)-\eta-\pi^*)^2\right\} \\ & \times d\tilde{\varphi}(s|\theta)dF(\theta) \\ \text{s.t. } \sigma(s) = \arg\min_{\tilde{m}} \int_{\theta\in\Theta} & \left\{(\hat{\eta}(s)-\eta-y^*)^2 + \lambda(\tilde{m}-\eta-\pi^*)^2\right\} \\ & \times d\mu(\theta|s) \\ \hat{\eta}(s) &= \int_{\theta\in\Theta} \eta d\mu(\theta|s) \\ \mu(\theta|s) &= \frac{\tilde{\varphi}(s|\theta)f(\theta)}{\int_{\theta\in\Theta}\tilde{\varphi}(s|\theta)f(\theta)d\theta}. \end{aligned}$$

[18] These arguments implicitly assume that the belief function $\mu : S\times M \to \Delta(\Theta)$ is independent of the policy action m if the central bank chooses a symmetric information policy. In other words, it requires that the private sector's belief be consistent with Bayes's rule regardless of whether m is off the equilibrium path. Otherwise, there may exist multiple perfect Bayesian equilibriums in which the private sector has an inconsistent belief off the equilibrium path, even if players receive a common public signal that is common knowledge.

The second expression defines the central bank's best response given the realization of s. The third and fourth expressions define the posterior expectations of the state under $\tilde{\varphi}$. In the alternative expression, the optimal policy problem is

$$\begin{aligned} &\min_{\tilde{\varphi}} \ \mathbb{E}_{\tilde{\varphi}}\left[(\hat{\eta}(s)-\eta-y^*)^2+\lambda(\sigma(s)-\eta-\pi^*)^2\right] \\ \text{s.t. } &\sigma(s)=\arg\min_{\tilde{m}} \mathbb{E}_{\tilde{\varphi}}\left[(\hat{\eta}(s)-\eta-y^*)^2+\lambda(\tilde{m}-\eta-\pi^*)^2|s\right] \\ &\hat{\eta}(s)=\mathbb{E}_{\tilde{\varphi}}\left[\eta|s\right]. \end{aligned}$$

An important implication of the full disclosure restriction is that the monetary instrument cannot affect the output loss $(y-y^*)^2$, because the private sector's expectation is independent of m (i.e., no signaling effect). Therefore, in the subgame perfect equilibrium, the monetary instrument must focus only on its direct effect on the inflation loss, even if the central bank is biased to induce unexpected inflation.

4. Transparency Principle

This section shows that the full disclosure obligation generates no additional losses, regardless of the commitment environment for an instrument policy when the central bank ex ante commits to an information policy. This result, called the transparency principle, emerges from two observations formally stated in propositions 1 and 2 below.

I first focus on a setting with a monetary policy under commitment, wherein the central bank ex ante determines the information to make public and the monetary instrument to be used depending on each state realization. Therefore, the central bank need not acquire the information that it does not use for public announcements or monetary policies. In other words, any commitment policy can be replicated under the restriction that the central bank and private sector always receive the same information about the state. This observation is formally stated as follows.

Proposition 1. *For any commitment policy (σ^c, φ^c), there is an alternative policy pair $(\tilde{\sigma}^c, \tilde{\varphi}^c)$ that induces identical outcomes for every state realization and satisfies the full disclosure restriction.*

Although proposition 1 is independent of the state and action spaces or the payoff specification, it may be helpful to illustrate the argument using a specific example. Suppose that shocks (η, y^*, π^*) are independent and normally distributed according to $\eta \sim N(0, \sigma_\eta^2)$, $y^* \sim N(0, \sigma_{y^*}^2)$, and $\pi^* \sim N(0, \sigma_{\pi^*}^2)$. Fix a commitment policy (σ^c, φ^c) such that (i) the information policy φ^c reveals full information to the central bank (e.g., $\mathcal{I}_{CB} = \{\eta, y^*, \pi^*\}$) and no information to the private sector (e.g., S is a singleton) and (ii) the monetary instrument policy σ^c is a linear combination of the shocks defined by

$$\sigma^c(r) = \alpha\eta + \beta y^* + \gamma\pi^*. \tag{12}$$

Under this commitment policy, I compute the private sector's posterior expectations as follows:

$$\hat{\eta} = \mathbb{E}_{(\sigma^c,\varphi^c)}[\eta \,|\, m] = \frac{\mathrm{cov}(\eta,\ m)}{\mathrm{var}(m)}m = \frac{\alpha\sigma_\eta^2}{\alpha^2\sigma_\eta^* + \beta^2\sigma_{y^*}^2 + \gamma^2\sigma_{\pi^*}^2}m \tag{13}$$

$$\hat{y}^* = \mathbb{E}_{(\sigma^c,\varphi^c)}[y^*|m] = \frac{\mathrm{cov}(y^*, m)}{\mathrm{var}(m)}m = \frac{\beta\sigma_{y^*}^2}{\alpha^2\sigma_\eta^* + \beta^2\sigma_{y^*}^2 + \gamma^2\sigma_{\pi^*}^2}m \tag{14}$$

$$\hat{\pi}^* = \mathbb{E}_{(\sigma^c,\varphi^c)}[\pi^*|m] = \frac{\mathrm{cov}(\pi^*, m)}{\mathrm{var}(m)}m = \frac{\gamma\sigma_{\pi^*}^2}{\alpha^2\sigma_\eta^* + \beta^2\sigma_{y^*}^2 + \gamma^2\sigma_{\pi^*}^2}m. \tag{15}$$

Since the monetary instrument responds to the central bank's private information, the private sector's posterior expectations depend on the observed policy action. Now, consider a symmetric information policy $\tilde{\varphi}$, which reveals a public signal $\tilde{s}$ according to

$$\tilde{s} = \alpha\eta + \beta y^* + \gamma\pi^*, \tag{16}$$

and an instrument policy $\tilde{\sigma}$ such that $\tilde{\sigma}(\tilde{s}) = \tilde{s}$. That is, $\tilde{s}$ is interpreted as a planned policy action, and the central bank indeed chooses the announced policy action $m = \tilde{s}$. Under this commitment policy, the posterior expectations are exactly same as those induced by policy (σ^c, φ^c). Specifically, for every realization (η, y^*, π^*), the expectations computed by $\tilde{\varphi}$ coincide with those computed by (σ^c, φ^c):

$$\mathbb{E}_{\tilde{\varphi}}[\eta \mid \tilde{s}] = \frac{\alpha\sigma_\eta^2}{\alpha^2\sigma_\eta^* + \beta^2\sigma_{y^*}^2 + \gamma^2\sigma_{\pi^*}^2}(\alpha\eta + \beta y^* + \gamma\pi^*)$$
$$= \mathbb{E}_{(\sigma^c,\varphi^c)}[\eta \mid m] \tag{17}$$
$$\mathbb{E}_{\tilde{\varphi}}[y^* \mid \tilde{s}] = \frac{\beta\sigma_{y^*}^2}{\alpha^2\sigma_\eta^* + \beta^2\sigma_{y^*}^2 + \gamma^2\sigma_{\pi^*}^2}(\alpha\eta + \beta y^* + \gamma\pi^*)$$
$$= \mathbb{E}_{(\sigma^c,\varphi^c)}[y^*|m] \tag{18}$$
$$\mathbb{E}_{\tilde{\varphi}}[\pi^*|\tilde{s}] = \frac{\gamma\sigma_{\pi^*}^2}{\alpha^2\sigma_\eta^* + \beta^2\sigma_{y^*}^2 + \gamma^2\sigma_{\pi^*}^2}(\alpha\eta + \beta y^* + \gamma\pi^*)$$
$$= \mathbb{E}_{(\sigma^c,\varphi^c)}[\pi^*|m]. \tag{19}$$

Moreover, for every state realization, the monetary instrument chosen under $(\tilde{\sigma}, \tilde{\varphi})$ coincides with that chosen under (σ^c, φ^c):

$$\tilde{\sigma}(\tilde{s}) = \alpha\eta + \beta y^* + \gamma\pi^* = \sigma^c(r). \tag{20}$$

Using the same argument, any commitment policy disclosing s to the private sector can be implemented by a commitment policy with the full disclosure restriction in which the public signal $\tilde{s}$ also contains the planned policy action m and signal s.

The second key observation is that commitment to an information policy alone obviates the need for a commitment to an instrument policy. Here, suppose that $(\tilde{\sigma}^{c*}, \tilde{\varphi}^{c*})$ is an optimal commitment policy that satisfies the full disclosure restriction. Then, $\tilde{\sigma}^{c*}$ must specify the monetary instrument as sequentially optimal given every possible realization $\tilde{s} \in \tilde{S}$. Thus, $\tilde{\sigma}^{c*}$ constitutes a subgame perfect equilibrium strategy under $\tilde{\varphi}^{c*}$. In other words, the equilibrium discretionary policy under $\tilde{\varphi}^{c*}$ coincides with the optimal instrument policy under commitment.

PROPOSITION 2. *There is a symmetric information policy $\tilde{\varphi}^*$ under which the equilibrium discretionary policy implements an optimal commitment policy.*

I illustrate proposition 2 using a specific monetary model presented in section 2. Suppose that $(\tilde{\sigma}^{c*}, \tilde{\varphi}^{c*})$ is an optimal commitment policy such that $\tilde{\varphi}^{c*} : \Theta \to \Delta(\tilde{S})$ satisfies the full disclosure restriction. Then, for any other instrument policy $m = \sigma(\tilde{s})$, the following inequality must hold:

$$\begin{aligned}
&\mathbb{E}_{\tilde{\varphi}^{c*}} \left[(\hat{\eta}(\tilde{s}) - \eta - y^*)^2 + \lambda(\tilde{\sigma}^{c*}(\tilde{s}) - \eta - \pi^*)^2 \right] \\
&\quad \leq \mathbb{E}_{\tilde{\varphi}^{c*}} \left[(\hat{\eta}(\tilde{s}) - \eta - y^*)^2 + \lambda(\sigma(\tilde{s}) - \eta - \pi^*)^2 \right]. \qquad (21)
\end{aligned}$$

This inequality implies that the expected loss under optimal policy $(\tilde{\sigma}^{c*}, \tilde{\varphi}^{c*})$ is not greater than the expected loss under $(\sigma, \tilde{\varphi}^{c*})$. Since both $\hat{\eta}$ and σ are functions of $\tilde{s}$, the following inequality almost surely holds:

$$\begin{aligned}
&\mathbb{E}_{\tilde{\varphi}^{c*}} \left[(\hat{\eta}(\tilde{s}) - \eta - y^*)^2 + \lambda(\tilde{\sigma}^{c*}(\tilde{s}) - \eta - \pi^*)^2 | \tilde{s} \right] \\
&\quad \leq \mathbb{E}_{\tilde{\varphi}^{c*}} \left[(\hat{\eta}(\tilde{s}) - \eta - y^*)^2 + \lambda(\sigma(\tilde{s}) - \eta - \pi^*)^2 | \tilde{s} \right]. \qquad (22)
\end{aligned}$$

This inequality implies that $\tilde{\sigma}^{c*}$ achieves the lowest conditional expectation of the loss function for all signal realizations $\tilde{s}$. In other words, $\tilde{\sigma}^{c*}$ must be sequentially rational given the information policy $\tilde{\varphi}^{c*}$. Thus, $\tilde{\sigma}^{c*} \in SPS(\tilde{\varphi}^{c*})$ and $\tilde{\varphi}^{c*}$ are an optimal information policy under a discretionary monetary policy.

Proposition 2 implies that when the central bank determines the information to acquire, there is no gain from withholding private information from the public and conveying additional information through the implicit signaling of policy actions. In this case, the more important question is what information the central bank should gather and process, rather than whether greater transparency improves social welfare.

The observations in the propositions themselves might be straightforward from the model structure in which the central bank moves first and the private sector observes its policy action. However, they make sense only when the optimal public signal is available. In other words, if the information policy available to the central bank is restricted to a specific class of signals, it may be optimal to generate information asymmetry and reveal private information through signaling. Thus, the observations would be analogous to the revelation principle in mechanism design because it applies when the class of mechanisms available to the designer is general enough.

5. Solving the Optimal Information Policy Problem

This section presents a specific solution to the optimal information policy problem for the model in section 2. From the results of the previous section, I focus on the class of information policies that satisfy the full disclosure restriction. The derivation proceeds as follows.[19] First, compute the expected loss or the gain from the information policy in the subgame perfect equilibrium under an arbitrary public signal (section 5.1). Then, determine the optimal public signal that minimizes the computed expected loss (section 5.2). Throughout this section, I assume that the state variables are independent and normally distributed.

5.1 Benefits of Correlated Expectations

Suppose, without loss of generality, that the central bank is obliged to disclose all acquired information and chooses a symmetric information policy, $\varphi : \Theta \to \Delta(S)$, where S is the set of public signal realizations. Then, the central bank and private sector share information about the state perfectly and have the same posterior belief. Given realization $s \in S$, the equilibrium strategy or optimal instrument policy solves the following loss-minimization problem:

$$\min_{m} \ \mathbb{E}\,[\,\underbrace{(\hat{\eta} - \eta - y^*)^2}_{\text{Output gap loss}} + \lambda \underbrace{(m - \eta - \pi^*)^2}_{\text{Inflation loss}} |s\,]\,. \tag{23}$$

Due to the observability of policy action m, the direct effect of monetary policy is limited only to the inflation loss. In addition, because there is no signaling effect under the symmetric information policy, the output gap loss is independent of m. This implies that a monetary policy must focus only on inflation loss, although it is constrained by the information contained in the signal. I characterize the equilibrium strategy simply by the first-order condition:

$$m = \hat{\eta} + \hat{\pi}^*. \tag{24}$$

[19] Tamura (2016) considers a similar approach within a static New Keynesian model.

Given this equilibrium strategy, the central bank's expected loss is

$$\mathcal{L} = \mathbb{E}[L] = \mathbb{E}\,[\,\underbrace{(\hat{\eta} - \eta - y^*)^2}_{\text{Output gap loss}} + \lambda \underbrace{(\hat{\eta} + \hat{\pi}^* - \eta - \pi^*)^2}_{\text{Inflation loss}}\,]. \tag{25}$$

The central bank's objective is to minimize this loss function by choosing a symmetric information policy.

To understand the benefits of inducing correlated expectations, I now examine a limitation of a noisy public signal defined by

$$s = \begin{bmatrix} s_\eta \\ s_{y^*} \\ s_{\pi^*} \end{bmatrix} = \begin{bmatrix} \eta + \epsilon_\eta \\ y^* + \epsilon_{y^*} \\ \pi^* + \epsilon_{\pi^*} \end{bmatrix}, \tag{26}$$

where $\epsilon = (\epsilon_\eta, \epsilon_{y^*}, \epsilon_{\pi^*})$ are independent noise terms in the signal. In this class of public signals, the central bank controls the precision of each signal (or the variance of each noise term). If the underlying state variables are independent of each other, the loss function (25) is independent of the precision of s_{y^*} and decreasing in the precision of s_η and s_{π^*}. This observation implies that the full revelation policy, which leads to $\hat{\eta} = \eta$ and $\hat{\pi}^* = \pi^*$, achieves the lowest expected loss in the class of noisy public signals. When the signal reveals η and π^*, the inflation loss is reduced to zero by (24), while the output gap loss remains positive (e.g., $\mathbb{E}[L] = \mathbb{E}[(y^*)^2] = \sigma_{y^*}^2 > 0$). Reducing the output gap loss further, it is necessary to induce a co-movement between real output $y = \hat{\eta} - \eta$ and the output target y^*. In terms of the distribution of posteriors, it is important to induce a positive correlation between $\hat{\eta}$ and $\hat{y}^*$. This correlation structure in expectations, which cannot be induced by noisy public signals, should be a notable property of the optimal information policy presented below.

5.2 Characterization

Given the equilibrium strategy (24), the expected equilibrium loss under any symmetric information policy is expressed by the expected loss under no information minus the gain from the information policy:

$$\mathbb{E}[L] = \underbrace{\mathbb{E}\left[(\eta + y^*)^2 + \lambda(\eta + \pi^*)^2\right]}_{\text{Loss under no information}} - \underbrace{\mathbb{E}\left[\hat{\eta}^2 + 2\hat{\eta}\hat{y}^* + \lambda(\hat{\eta} + \hat{\pi}^*)^2\right]}_{\text{Gain from information policy}}. \tag{27}$$

The role of an information policy here is to determine the distribution of posterior beliefs (e.g., posterior expectations). Although the first term in (27) is exogenously determined by the underlying distribution of the state, the second term varies by the choice of information policy. Thus, the central bank's problem is a quadratic Bayesian persuasion problem:

$$\max_{\varphi} \mathbb{E}[V(\hat{\eta}, \hat{y}^*, \hat{\pi}^*)],$$

where

$$V(\hat{\eta}, \hat{y}^*, \hat{\pi}^*) = (1+\lambda)\hat{\eta}^2 + 2\hat{\eta}\hat{y}^* + 2\lambda\hat{\eta}\hat{\pi}^* + \lambda(\hat{\pi}^*)^2. \tag{28}$$

Tamura (2018) shows that if the objective function is quadratic in conditional expectations and the underlying distribution of the state is Gaussian, the optimal signal is given by a linear function of the state. The dimension of the optimal signal depends on the Hessian matrix of function V defined above. I provide the derivation of the following result in appendix 1.

PROPOSITION 3. *Suppose that the state variables are independent and normally distributed.*

- *The optimal symmetric information policy φ^* publicly reveals two statistics $(s_1, s_2) \in R^2$, which are constructed by the linear combinations of the state:*

$$\begin{aligned} s_1 &= \alpha_1\eta + \beta_1 y^* + \gamma_1\pi^* \\ s_2 &= \alpha_2\eta + \beta_2 y^* + \gamma_2\pi^*. \end{aligned}$$

- *Under the optimal public signal, the equilibrium instrument policy is expressed as a linear function of the signal realizations:*

$$m = \delta_1 s_1 + \delta_2 s_2. \tag{29}$$

The first part of proposition 3 is a solution to the Bayesian persuasion problem in which the weights for the two statistics nontrivially depend on policy weight λ and the variance matrix of the state.[20] Because the dimension of the optimal signal is less than

[20]Note that the number of statistics for disclosure do not change, even if the state variables are correlated. For details, see the proof of proposition 3.

that of the state space, the players cannot identify the change in each state variable from the signal observation. As such, the induced posterior expectations $(\hat{\eta}, \hat{y}^*, \hat{\pi}^*)$ can show correlations.[21] The second part of the proposition is computed from (24) with the standard property of the normal distribution that the conditional expectations are linear functions of Gaussian signals.

I now discuss the intuition behind the structure of the optimal information policy. To see this, first consider a suboptimal information policy φ' (parameterized by $\beta \in \mathbb{R}$), which releases two statistics (s_1', s_2') defined by

$$s_1' = \eta + \pi^* \tag{30}$$

$$s_2' = \eta + \beta y^*. \tag{31}$$

Under this information structure, the central bank and private sector are perfectly informed of the realization of $(\eta + \pi^*)$, and therefore, the optimal instrument policy should target zero inflation loss by setting $m = \eta + \pi^*$. Then, the expected loss becomes independent of λ and is a non-monotonic function of parameter β. When $\beta = 0$, the signal reveals η and π^* such that it generates the same loss as in the full information regime. For $\beta > 0$, the signal induces a positive correlation in $\hat{\eta}$ and $\hat{y}^*$, which helps to reduce the output gap loss. For example, if the state variables are normally distributed with the same variance σ^2, the expected loss is $\mathbb{E}[L] = \sigma^2$ at $\beta = 0$ and is minimized at $\beta = 0.5$, which leads to $\mathbb{E}[L] = 0.5\sigma^2$. As β goes to infinity, the expected loss in this numerical example converges to $\mathbb{E}[L] = 1.5\sigma^2$.

This example highlights an advantage of a two-dimensional signal to pursue two objectives: to reduce the output gap loss by inducing a positive correlation between $\hat{\eta}$ and $\hat{y}^*$, and to reduce the inflation loss by making the monetary instrument flexible to stabilize inflation. Indeed, in the limiting case in which λ goes to infinity, the optimal information policy in proposition 3 converges to φ'.

PROPOSITION 4. *Suppose that the state variables are independent and normally distributed. As λ goes to infinity, the optimal*

[21] Formally, the players can identify from the two-dimensional signal a subspace of dimension 1 on which the state is realized. Consequently, the posterior expectations of the state are distributed over a subspace of dimension 2 in $\mathbb{R}^3$.

symmetric information policy converges to φ', where β is chosen to minimize the remaining output gap loss $E[(\hat{\eta} - \eta - y^*)^2]$.

When λ is at a finite value, however, φ' is not optimal. The tradeoff the central bank faces comes from the "budget constraint" of information flows about the monetary shock η. Under φ', signal s'_1 contains a certain amount of information about η, and it limits the scope of variability and co-movement in expectations that an additional signal s'_2 can generate. To illustrate this informational tradeoff, consider the following information policy $\bar{\varphi}$ parameterized by $(\bar{\alpha}, \bar{\beta})$:

$$\bar{s}_1 = \bar{\alpha}\eta + \pi^* \tag{32}$$

$$\bar{s}_2 = \eta + \bar{\beta}y^*. \tag{33}$$

The previous policy φ' is a special case of $\bar{\alpha} = 1$, and the optimal signal structure in proposition 3 can be normalized with some parameter values $(\bar{\alpha}^*, \bar{\beta}^*)$. When $\bar{\alpha} \in (0, 1)$, $\bar{s}_1$ reveals less about η than s'_1 (e.g., $\text{var}(\eta|\bar{s}_1) > \text{var}(\eta|s'_1)$), which increases the degree of freedom to introduce a preferred distribution of posteriors for output stabilization. In this case, however, the inflation loss cannot be zero because the central bank is not informed of $(\eta + \pi^*)$. Thus, the optimal weight $(\bar{\alpha}^*, \bar{\beta}^*)$ should be based on the tradeoff between output and inflation stabilization.

Figure 1 illustrates how the policy weight λ affects the optimal signal structure $(\bar{\alpha}^*, \bar{\beta}^*)$. In this numerical example, the state variables are independent and identically distributed with variance σ^2. When the policy weight on inflation loss (λ) is zero, $\bar{\alpha}^*$ equals zero to save the informational budget and $\bar{\beta}^* = 2/(1 + \sqrt{5}) \approx 0.618$, which leads to the expected loss of $\mathbb{E}[L] = \sigma^2(3 - \sqrt{5})/2 \approx 0.382\sigma^2$. As λ increases, $\bar{\alpha}^*$ increases and converges to 1 to improve the scope of monetary policy against inflation loss, while $\bar{\beta}^*$ decreases and goes to 0.5 to keep the co-movement between $\hat{\eta}$ and $\hat{y}^*$.

Figure 2 presents the distribution of the conditional expectations by the variances (panel A) and the correlation coefficients (panel B) as functions of policy weight.[22] When λ equals zero,

[22] In this numerical example, I normalize the variances of the underlying state variables to one.

Figure 1. Weights in the Optimal Public Signals

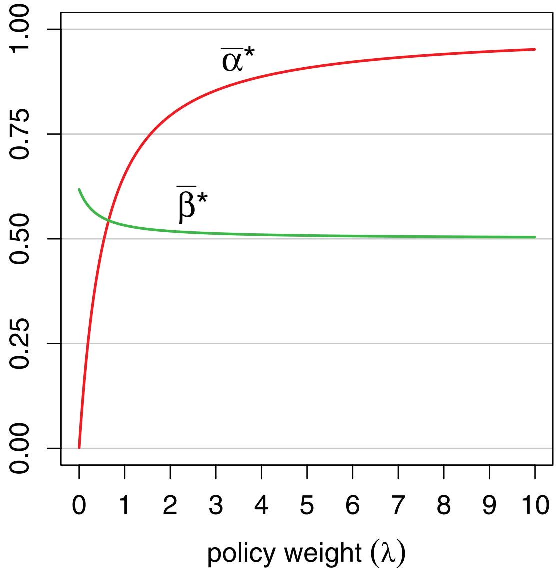
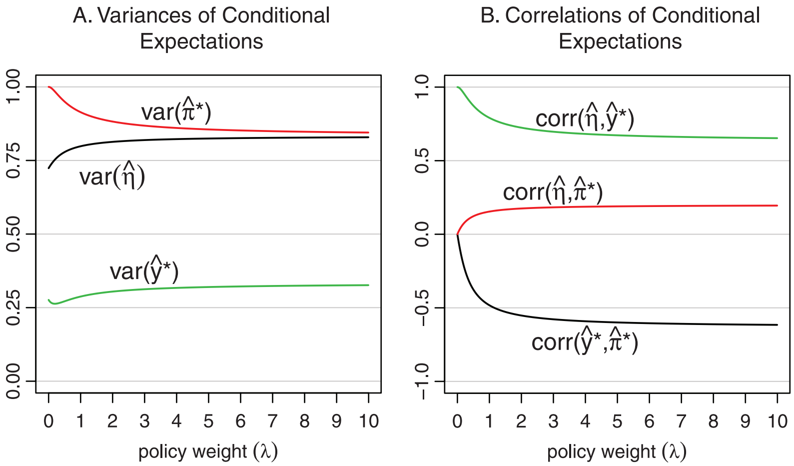


Figure 2. Distribution of Conditional Expectations



$\mathrm{var}(\hat{\pi}^*)$ converges to $\mathrm{var}(\pi^*)$, which implies that the public signal reveals π^*. This is consistent with the observation in figure 1 that $\bar{\alpha}^* \to 0$ as $\lambda \to 0$. Consequently, $\mathrm{corr}(\hat{\eta}, \hat{y}^*) = 1$ and $\mathrm{corr}(\hat{\eta}, \hat{\pi}^*) = \mathrm{corr}(\hat{y}^*, \hat{\pi}^*) = 0$. When λ is positive, the players cannot identify any state variables from the public signal. As λ increases, the signal for π^*, such as $\bar{s}_1$ in (32), is contaminated by η, such that the conditional expectation $\hat{\pi}^*$ has a positive correlation with $\hat{\eta}$ and a negative correlation with $\hat{y}^*$.[23]

5.3 Incentives and Distortions in Monetary Policy

This subsection examines the incentives and distortions in monetary policy under an optimal information policy. To this end, I compare three different policy regimes in terms of equilibrium monetary policy responses to shocks and expected losses (figure 3).

The first is the full information regime (or the full revelation policy φ^F). As in subsection 2.2, the equilibrium instrument policy under full information is $m^F = \eta + \pi^*$, which leads to zero inflation loss, while the output gap is $y - y^* = \pi - \hat{\pi} - y^* = -y^*$. Thus, the expected loss is $\mathbb{E}[L] = \mathbb{E}[(y^*)^2]$.

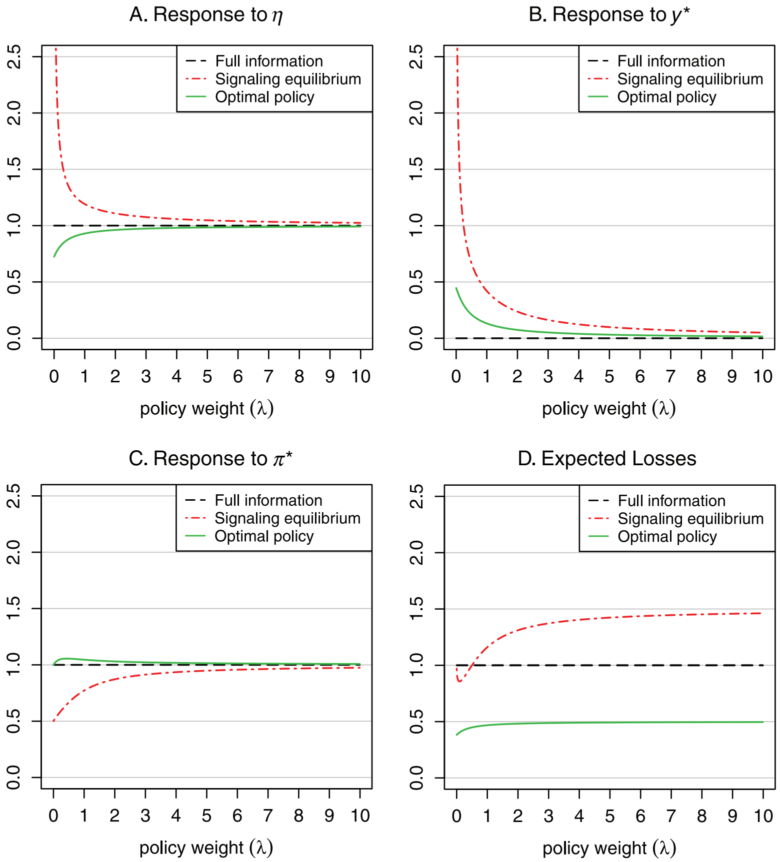
The second is the signaling equilibrium regime (or the privately revealing policy φ^P). This is a typical information structure in a signaling model in which the private sector forms expectations based on the observed policy action and the central bank has an incentive to distort its policy instrument to manipulate the private sector's expectations through signaling. For this case, I focus on a perfect Bayesian equilibrium of a signaling game in which the central bank's strategy is linear in the state variables:[24]

$$m^P = \tilde{c}_\eta \eta + \tilde{c}_{y^*} y^* + \tilde{c}_{\pi^*} \pi^*.$$

[23]The negative correlation between $\hat{y}^*$ and $\hat{\pi}^*$ is due to the structure of $\bar{\varphi}$, in which expectation $\hat{y}^*$ is negatively related to realization π^* (because $\mathbb{E}[\hat{y}^* \pi^*] = \mathbb{E}[\hat{y}^* \hat{\pi}^*]$). For example, suppose that $\eta = y^* = 0$ and $\pi^* > 0$. Then, $\bar{\varphi}$ generates a realization such that $\bar{s}_1 > 0$ and $\bar{s}_2 = 0$. Given this, the players cannot identify the following three possibilities: (i) $\pi^* > 0$ and $\eta = -y^* > 0$, (ii) $\pi^* > 0$, $\eta = -y^* < 0$, or (iii) $\pi^* < 0$, $\eta = -y^* > 0$. Case (i) is more likely than cases (ii) or (iii), and the players form $\hat{y}^* < 0$ in response to $\pi^* > 0$.

[24]Here, I focus on a unique linear equilibrium in which $\hat{\eta}$ is increasing in m because it exists for any parameter values. Other linear equilibriums exist for some parameter values, in which $\hat{\eta}$ is decreasing in m. I provide the details in appendix 2.

Figure 3. Response to Shocks and Welfare Losses



Note: I set $\sigma_\eta^2 = \sigma_{y^*}^2 = \sigma_{\pi^*}^2 = 1$.

When the private sector's posterior expectation is $\hat{\eta} = \phi m$, the first-order condition for the signaling equilibrium strategy is

$$m^P = \frac{\lambda}{\lambda + \phi^2}(\eta + \pi^*) + \underbrace{\frac{\phi}{\lambda + \phi^2}(\eta + y^*)}_{\text{Signaling incentive}}. \tag{34}$$

In appendix 2, it is shown that $\phi \in (0, 1)$ in the unique linear equilibrium in which $\hat{\eta}$ is increasing in m. Thus, in equilibrium, the monetary policy responses to η and y^* are more sensitive than those in the full information regime (i.e., $\tilde{c}_\eta > 1$ and $\tilde{c}_{y^*} > 0$), while the response to π^* is less than that in the full information regime (i.e., $\tilde{c}_{\pi^*} < 1$). Although ϕ is endogenously determined in equilibrium and depends on λ, the signaling incentive diminishes and the equilibrium strategy converges to $m = \eta + \pi^*$ as λ goes to infinity.

The third case is the optimal symmetric policy φ^* in proposition 3. As I show in (24), the equilibrium monetary policy is $m = \hat{\eta} + \hat{\pi}^*$, which is in turn a linear function of the state variables. In the notation of proposition 3, it is expressed as

$$\begin{aligned} m &= \delta_1 s_1 + \delta_2 s_2 \\ &= (\delta_1 \alpha_1 + \delta_2 \alpha_2)\eta + (\delta_1 \beta_1 + \delta_2 \beta_2) y^* + (\delta_1 \gamma_1 + \delta_2 \gamma_2)\pi^* \\ &= c_\eta \eta + c_{y^*} y^* + c_{\pi^*} \pi^*. \end{aligned}$$

Unlike in the other two regimes, the optimal monetary policy responses to η and π^* are lower than one and higher than one, respectively (figure 3, panels A and C). Although this distortion in monetary policy generates an inflation loss, it reduces the information flow of η through signaling, thereby improving the scope of expectations management to stabilize output.

Panel D of figure 3 presents a comparison of expected losses in the three regimes. The expected loss under the optimal policy is substantially lower than those under the benchmark regimes. Moreover, the differences in expected losses do not converge to zero as λ goes to infinity, even though the instrument policy converges to $m = \eta + \pi^*$ in all policy regimes. This observation indicates that significant differences in welfare losses are determined mainly by expectations management rather than monetary policy.

6. Commitment Assumption

Thus far, I investigated the optimal policy under a strong assumption that the central bank can commit to an information policy that specifies the information to acquire and make public. In particular, it must be able to inform the central bank and private sector of only two linear combinations of the three underlying state variables. A straightforward way to implement this policy is to delegate data collection, information processing, and the public release of statistics to an independent statistical agency. If the statistics to disclose are optimally chosen, the equilibrium with a discretionary monetary policy coincides with the optimal commitment policy. Below, I discuss the extent to which the commitment assumption is justifiable and, if not, the other commitment devices necessary when it is not feasible to delegate information processing.

First, it might be reasonable to suppose that the central bank can commit to constructing and disclosing specific indexes for policy targets or statistics related to market conditions. Indeed, many government sectors, including central banks, regularly publicize a number of statistics. It is difficult to consider that they withhold or manipulate those statistics after observing internal information.

Even when the construction and disclosure of statistics are credible without delegation to a third party, the commitment problem remains if the central bank or, more precisely, the committee members cannot refrain from acquiring information superior to that held by the public. In this case, implementing the optimal policy requires additional commitment devices to prevent two types of deviations. One is a discretionary instrument policy based on private information. Recall that the public can predict the optimal instrument policy perfectly from the publicized indexes; hence, the public easily detects any deviation from the optimal policy. Therefore, reputational concerns would prevent the central bank from such potential deviations.

The other type of possible deviation is revealing excess information through public announcements or information disclosures. Although most existing studies on central bank transparency assume that the central bank credibly commits to providing public information, including noisy signals, it would be important to consider an institutional design to reduce incentives for deviations from a predetermined communication policy. According to the literature on communication games, multiple informed senders tend to reveal more information in equilibrium than a single sender does.[25] This observation suggests that restricting the number of committee members and clarifying who is responsible for communication to the market might have the advantage of sustaining the optimal communication policy. Given that the discussions above are still informal,

[25]For example, Battaglini (2002) considers a cheap talk setup and Gentzkow and Kamenica (2017) consider a Bayesian persuasion setup.

a public disclosure of optimally constructed indexes would be useful to discipline the conduct of monetary policies and central bank communication.

7. Conclusion

This study examined the optimal policy design for the acquisition and disclosure of information about the state of the economy in a simple signaling model with multiple shocks. The main finding is that the central bank can be obliged to account for the conduct of monetary policy fully without any loss if information acquisition is endogenous. In a neoclassical monetary model with a Phillips curve, the optimal public signal consists of two linear combinations of three different shocks, considering an informational tradeoff between output and inflation stabilization.

In practice, however, the process of information acquisition and public disclosure is subject to a number of constraints. For example, acquiring precise information may be costly and technologically limited, and disclosing statistics may generate unpredictable fluctuations in market outcomes. Thus, it would be interesting to investigate the effects of such frictions in the information process and expectation formation on the optimal policy design I consider in this study.

Appendix 1. Proofs

Proof of Proposition 1

Suppose that the central bank can commit to an instrument policy σ^c. I will show that for any (σ^c, φ^c), there exists a pair $(\tilde{\sigma}^c, \tilde{\varphi}^c)$ such that $\tilde{\varphi}^c : \Theta \to \Delta(\tilde{S})$ is a symmetric information policy, $\tilde{\sigma}^c : \tilde{S} \to M$ is a pure strategy, and two policy pairs generate the same outcome for every state realization.

Fix (σ^c, φ^c). Define $(\tilde{\sigma}^c, \tilde{\varphi}^c)$ as follows:

$$\tilde{S} \equiv S \times M \text{ with typical element } \tilde{s} = (s, m)$$
$$\tilde{\varphi}^c(\tilde{s}|\theta) \equiv \int \sigma^c(m|r, s)\varphi^c(r, s|\theta)dr$$
$$\tilde{\sigma}^c(\tilde{s}) \equiv m.$$

Intuitively, $\tilde{\varphi}^c$ reveals both the explicit and implicit information provided to the public under (σ^c, φ^c), and $\tilde{\sigma}^c$ chooses the same level of monetary instrument as specified under (σ^c, φ^c). Pick any $\mu \in \mathcal{B}(\sigma^c, \varphi^c)$, a belief function that is consistent with (σ^c, φ^c). On the equilibrium path, the private sector's belief function $\tilde{\mu}$ given below is consistent with Bayes's rule under $(\tilde{\sigma}^c, \tilde{\varphi}^c)$:

$$\tilde{\mu}(\tilde{s}, m) \equiv \mu(s, m) \qquad \text{for } \tilde{s} = (s, m).$$

Note that under the commitment policy setting, we do not have to specify the belief function at the probability zero event such as $\tilde{\mu}(\tilde{s}, m')$ where $\tilde{s} = (s, m)$.

Proof of Proposition 2

Let $(\tilde{\sigma}^*, \tilde{\varphi}^*)$ be an optimal commitment policy that satisfies the full disclosure restriction and $\tilde{\mu}^* \in \mathcal{B}(\tilde{\sigma}^*, \tilde{\varphi}^*)$ be the belief function that is consistent with $(\tilde{\sigma}^*, \tilde{\varphi}^*)$. The following arguments show that $(\tilde{\mu}^*, \tilde{\sigma}^*)$ constitutes an equilibrium under $\tilde{\varphi}^*$.

First, note that under the full disclosure restriction, $\tilde{\mu}^* \in \mathcal{B}(\tilde{\sigma}', \tilde{\varphi}^*)$ for any instrument policy $\tilde{\sigma}' : \tilde{S} \to \Delta(M)$, since $\tilde{\varphi}^*$ eliminates the signaling role of the monetary instrument. Second, any deviation from $\tilde{\sigma}^*$ cannot be profitable for the central bank. This is because by the optimality of $(\tilde{\sigma}^*, \tilde{\varphi}^*)$ under commitment, $\mathcal{L}(\tilde{\mu}^*, \tilde{\sigma}', \tilde{\varphi}^*) \geq \mathcal{L}(\tilde{\mu}^*, \tilde{\sigma}^*, \tilde{\varphi}^*)$ for any $\tilde{\sigma}'$.

Proof of Proposition 3

Let H be the Hessian matrix of $\frac{1}{2}V(\hat{\eta}, \hat{y}^*, \hat{\pi}^*)$:

$$H \equiv \begin{bmatrix} 1+\lambda & 1 & \lambda \\ 1 & 0 & 0 \\ \lambda & 0 & \lambda \end{bmatrix}. \tag{35}$$

Then, the gain from information policy is written as

$$\mathbb{E}[V(\hat{\eta}, \hat{y}^*, \hat{\pi}^*)] = \mathrm{tr}(H\hat{\Sigma}),$$

where $\hat{\Sigma}$ is the variance-covariance matrix of $(\hat{\eta}, \hat{y}^*, \hat{\pi}^*)$.

Suppose that $\theta \sim N(0, \Sigma)$, where Σ is a diagonal matrix with diagonal entries $(\sigma_\eta^2, \sigma_{y^*}^2, \sigma_{\pi^*}^2)$. The optimal symmetric information policy is characterized as follows:

- Compute eigenvalues and eigenvectors of $W \equiv \Sigma^{\frac{1}{2}} H \Sigma^{\frac{1}{2}}$. Define the characteristic polynomial

$$\begin{aligned} f(\omega) &= \det(\omega I - W) \\ &= \omega^3 - [(1+\lambda)\sigma_\eta^2 + \lambda\sigma_{\pi^*}^2]\omega^2 + \sigma_\eta^2(\sigma_{\pi^*}^2\lambda - \sigma_{y^*}^2)\omega \\ &\quad + \sigma_\eta^2\sigma_{y^*}^2\sigma_{\pi^*}^2\lambda. \end{aligned}$$

  From the observations that $f(0) > 0$ and $f(\sigma_{\pi^*}^2\lambda) < 0$, there are two positive eigenvalues and one negative eigenvalue such that

$$\omega_1 < 0 < \omega_2 < \sigma_{\pi^*}^2\lambda < \omega_3$$

  with associated eigenvectors $q_j = (q_{j\eta}, q_{jy^*}, q_{j\pi^*})$: for $j = 1, 2, 3$,

$$\begin{cases} \sigma_\eta \sigma_{y^*} q_{j\eta} = \omega_j q_{jy^*} \\ \lambda \sigma_\eta \sigma_{\pi^*} q_{j\eta} = (\omega_j - \lambda\sigma_{\pi^*}^2) q_{j\pi^*}. \end{cases}$$

  It is worth noting that whenever Σ is non-singular, $\Sigma^{\frac{1}{2}} H \Sigma^{\frac{1}{2}}$ has the same number of positive eigenvalues as H (Sylvester's law of inertia). This implies that as long as the variance matrix of the state is positive definite, the optimal signal must be two-dimensional even if the state variables are correlated.
- The optimal public signal is given by

$$s = Q_+' \Sigma^{-\frac{1}{2}} \theta, \tag{36}$$

  where $Q_+ \equiv [q_2 \;\; q_3]$ is a 3×2 matrix constructed from the eigenvectors associated with positive eigenvalues $\omega_2, \omega_3 > 0$. From the property of the normal distribution, the conditional expectation of the state is

$$\begin{aligned} \hat{\theta} &= \Sigma^{\frac{1}{2}} Q_+ (Q_+' Q_+)^{-1} s \\ &= \Sigma^{\frac{1}{2}} Q_+ (Q_+' Q_+)^{-1} Q_+' \Sigma^{-\frac{1}{2}} \theta. \end{aligned}$$

- The equilibrium discretionary policy under the optimal signal is

$$\begin{aligned} m &= \hat{\eta} + \hat{\pi}^* \\ &= \begin{bmatrix}1 & 0 & 1\end{bmatrix} \Sigma^{\frac{1}{2}} Q_+ (Q_+' Q_+)^{-1} s \end{aligned} \tag{37}$$

- The effective responses to the state are given by the combination of (36) and (37):

$$\begin{aligned} m &= \begin{bmatrix}1 & 0 & 1\end{bmatrix} \Sigma^{\frac{1}{2}} Q_+ (Q_+' Q_+)^{-1} Q_+' \Sigma^{-\frac{1}{2}} \begin{bmatrix}\eta \\ y^* \\ \pi^*\end{bmatrix} \\ &= c_\eta \eta + c_{y^*} y^* + c_{\pi^*} \pi^*. \end{aligned}$$

Proof of Proposition 4

Let $\mathcal{L}^*$ be the expected loss under the optimal information policy and $\mathcal{L}^F$ be the expected loss under full information. For any $\lambda > 0$, $\mathcal{L}^* \leq \mathcal{L}^F$. Note that, as shown in subsection 5.1, $\mathcal{L}^F$ is independent of λ. These observations imply that $\mathbb{E}[(m - \eta - \pi^*)^2]$ must converge to zero as λ goes to infinity. Thus, under the optimal policy, m must converge in mean square toward $\eta + \pi^*$.

Let $s_1^\infty = \eta + \pi^*$ be an element of the optimal signal in the limit. From proposition 3, there must be another signal to be disclosed to the public, which is a linear combination of the state. The proof completes if the other signal is written as $s_2^\infty = \alpha\eta + \beta y^*$ for some $\alpha \neq 0$. First, for any linear combination of the state, say $s_2' = \alpha'\eta + \beta' y^* + \gamma'\pi^*$, there is an alternative signal $s_2'' = \alpha''\eta + \beta'' y^*$ such that (s_1^∞, s_2') brings the same information as (s_1^∞, s_2'').[26] Second, the signal (s_1^∞, y^*) yields a strictly higher loss than (s_1^∞, η) for all λ. This implies that the optimal signal converges to (s_1^∞, s_2^∞), where β/α is chosen to minimize $\mathbb{E}[(\hat{\eta} - \eta - y^*)^2]$ because the inflation loss is eliminated by s_1^∞.

[26] This is because $s_2' = \alpha'\eta + \beta' y^* + \gamma'(s_1^\infty - \eta) = (\alpha' - \gamma')\eta + \beta' y^* + \gamma' s_1^\infty$. Thus, (s_1^∞, s_2') is equivalent to (s_1^∞, s_2''), where $s_2'' = (\alpha' - \gamma')\eta + \beta' y^*$.

Appendix 2. A Linear Equilibrium under the Signaling Equilibrium Regime

This section derives the equilibrium properties of the signaling regime (i.e., privately revealing and no disclosure) in figure 3. Formally, I analyze a perfect Bayesian equilibrium under the information structure such that the central bank is informed of the state and the private sector receives no public signal. In particular, I focus on the linear strategy equilibrium in which the central bank's strategy is written as a linear function of the state:

$$m = \tilde{c}_\eta \eta + \tilde{c}_{y^*} y^* + \tilde{c}_{\pi^*} \pi^*. \tag{38}$$

I solve the equilibrium by the guess-and-verify method. Suppose that the private sector's posterior expectation on η is given by

$$\hat{\eta} = \phi m. \tag{39}$$

Then, the central bank minimizes, under discretion, the loss function

$$L = (\phi m - \eta - y^*)^2 + \lambda(m - \eta - \pi^*)^2.$$

The first-order condition is

$$m = \frac{\phi + \lambda}{\phi^2 + \lambda}\eta + \frac{\phi y^* + \lambda \pi^*}{\phi^2 + \lambda}. \tag{40}$$

Given (40), the private sector's conditional expectation is

$$\mathbb{E}[\eta|m] = \frac{\sigma_\eta^2}{\sigma_\eta^2 + \sigma_e^2}\frac{\phi^2 + \lambda}{\phi + \lambda}m,$$

where $\sigma_e^2 \equiv (\phi^2\sigma_{y^*}^2 + \lambda^2\sigma_{\pi^*}^2)/(\phi + \lambda)^2$. Thus, the equilibrium condition is

$$\phi = \frac{\sigma_\eta^2}{\sigma_\eta^2 + \sigma_e^2}\frac{\phi^2 + \lambda}{\phi + \lambda},$$

or $g(\phi) = 0$, where

$$g(\phi) = \sigma_{y^*}^2\phi^3 + \lambda\sigma_\eta^2\phi^2 + \lambda[\lambda(\sigma_{\pi^*}^2 + \sigma_\eta^2) - \sigma_\eta^2]\phi - \lambda^2\sigma_\eta^2.$$

Since $g(0) < 0$ and $g'''(\phi) > 0$, there is a positive value $\phi^* > 0$ such that $g(\phi^*) = 0$. From the observation that $g''(0) > 0$, this positive solution is unique. Moreover, $g(1) = \sigma_{y^*}^2 + \lambda^2\sigma_{\pi^*}^2 > 0$ implies that $0 < \phi^* < 1$. Unfortunately, for some parameter values, there can be other solutions which take negative values. I focus on the positive solution because the central bank's incentive to accommodate η comes from inflation stabilization. In other words, the negative solution is sustained solely by the self-fulfilling of the private sector's expectations. By substituting for solution ϕ^* into (40), I obtain the equilibrium responses $(\tilde{c}_\eta, \tilde{c}_{y^*}, \tilde{c}_{\pi^*})$, which satisfy $\tilde{c}_\eta > 1$, $\tilde{c}_{y^*} > 0$, and $0 < \tilde{c}_{\pi^*} < 1$.

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