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Why the Publication of Socially Harmful Information May Be Socially Desirable

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Volker Hahn

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Why the Publication of Socially Harmful Information May Be Socially Desirable*

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Abstract

We propose a signaling model in which the central bank and firms receive information on cost-push shocks independently from each other. If the firms' signals are rather unlikely to be informative, central banks should remain silent about their own private signals. If, however, firms are sufficiently likely to be informed, it is socially desirable for the central bank to reveal its private information. By doing so, the central bank eliminates the distortions stemming from the signaling incentives under opacity. Our model may also explain the recent trend towards more transparency in monetary policy.

Keywords: signaling games, transparency, monetary policy, central banks, communication.

JEL: D82, D83, E58.

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1 Introduction

During the last two decades, central banks' communication practices have changed dramatically. While traditionally central banks were wrapped in mystery and withheld information about their policies, their assessment of the economy, details of decision-making and the goals of monetary policy, they have gradually become substantially more open. In 1987, the then chairman of the Federal Reserve Board, Alan Greenspan, took pride in being secretive: "Since I've become a central banker," he noted, "I've learned to mumble with great incoherence."¹ Nowadays such a statement would be unthinkable. For example, the present chairman Ben Bernanke called the "increased openness" of monetary policy makers a "welcome development" in 2007.²

This paper presents a simple model with a central bank that receives private information about cost-push shocks. We also introduce the plausible assumption that firms may receive information through sources that are independent of the central bank. Using this framework, we address the question whether the publication of the central bank's private information on cost-push shocks is socially desirable. We show that withholding the central bank's information affects welfare through two channels.

First, while it is individually optimal for firms to respond to cost-push shocks, responding to these shocks is detrimental to aggregate welfare.³ Consequently, information about cost-push shocks is socially harmful. By withholding such information, central banks may eliminate its socially harmful consequences for output and inflation if the firms have received no independent information about the shock.

Second, even if the central bank does not publish its private information and the firms do not receive independent information about the shock, the firms may infer some information by observing the monetary policy conducted by the central bank. Consequently, the central bank not only has to consider the direct impact of its action on price setters, it also has to take into account the effect that its action has on their

¹Wall Street Journal, September 22, 1987.

²"Federal Reserve Communications", speech delivered at the Cato Institute 25th Annual Monetary Conference, Washington, D.C. November 14, 2007.

³We will discuss this point in more detail in Section 2.

expectations about the shock. Due to this effect, opacity reduces the central bank's flexibility in stabilizing shocks.⁴

On balance, we show that the aggregate consequences for welfare of both effects depend on the probability of firms receiving independent information. First, if there is a low likelihood of firms receiving independent information, opacity is socially desirable because it reduces the detrimental economic effects caused by cost-push shocks. The central bank can achieve this by pursuing a passive policy, thus safeguarding the secrecy of its information. Second, for a sufficiently high probability of firms' receiving independent information, the central bank would not remain inactive if it were opaque. As the central bank will thus reveal its information anyway, transparency is socially desirable because it removes the restraint imposed by the link between the central bank's actions and the firms' expectations under opacity.

Our paper may also shed some light on the observation that central banks have become more transparent. With the constant progress of information technologies, the precision of firms' direct information is likely to have been improving over time. This trend may have made transparency in monetary policy more attractive.

Our paper contributes to two strands of the literature. First, it is part of the literature on signaling games, which goes back to Spence (1973). In monetary economics, signaling games have been studied by Gersbach and Hahn (2007, 2009), Sibert (2002, 2003, 2009), and Vickers (1986). In our paper, the public will attempt to infer the central bank's private information about economic shocks from monetary policy action if the central bank keeps this information secret. This effect has been neglected in most publications on central-bank transparency,⁵ which represent the second strand of the literature to which this paper contributes.

Second, our paper thus complements the general literature on transparency in monetary policy as surveyed by Geraats (2002), Hahn (2002), and Blinder et al. (2008). This

⁴This finding is in contrast to Jensen (2002), who finds that transparency may be a “policy-distorting straitjacket.”

⁵A notable exception is Sibert (2009). In her two-period model, the central bank has an incentive to boost output by creating surprise inflation. The public may infer the central bank's private information about its goals and the temporary effectiveness of surprise inflation from a noisy signal of the central bank's action.

literature considers the economic effects of central-bank communication as well as the consequences that the publication of private central-bank information has for welfare.⁶ Cukierman and Meltzer (1986) show that central banks may prefer some degree of ambiguity about monetary control in order to be able to surprise the public at a time when this is most valuable to them. This framework has been modified to allow for normative analysis (see Lewis (1991)) and for an explicit distinction of control-error variance and the degree of transparency (Faust and Svensson (2001)). Applying a New Keynesian specification of the Phillips curve, Jensen studies the desirability of transparency with regard to the central bank's control error (Jensen (2002)) and private information about cost-push shocks (Jensen (2000)). In Jensen (2000), transparency about cost-push shocks only has an impact on how precisely price-setters can infer the central bank's output target. In our paper, transparency affects the firms' estimate of the current shock, which directly affects their assessment of the optimal price they should charge. In contrast to the existing literature, we focus on the important role of firms' independent sources of information.

Our paper is organized as follows: In the next section we outline the model. In sections 3 and 4 we derive the equilibria under transparency and opacity, respectively. We compare welfare under both transparency regimes in Section 5. The robustness of our results is considered in Section 6. Section 7 concludes.

2 Model

We consider a signaling game with a central bank (the sender) and a multitude of firms (receivers). Each firm's optimal price, p^* , is given by

$$p^* = p + \alpha y + \varepsilon', \tag{1}$$

⁶In a much-cited paper, Morris and Shin (2002) show that transparency may be socially harmful if agents find it individually optimal to coordinate their actions and if this coordination is not socially desirable *per se*. However, Svensson (2006) convincingly argues that the range of parameters for which this result holds is unlikely to be relevant in practice. Cf. also Morris et al. (2006).

where p is the aggregate price level, y is the (log) output gap, α a positive parameter, and ε' represents a shock (more on this later).⁷ This pricing equation is frequently used in the literature and can be derived from a microeconomic model with monopolistically competitive firms.⁸

It is crucial to discuss the nature of the shock ε' . If shocks to the Phillips curve leave the difference between the natural and the efficient level of output invariant, no tradeoff will arise between stabilizing output and inflation (see Blanchard and Galí (2007)). Consequently, the central bank will be able to achieve the socially optimal solution by pursuing a policy of strict inflation stabilization. However, according to Blanchard and Galí (2007), there is a wide-spread consensus that such a policy is undesirable, which led these authors to coin the term “divine coincidence” for shocks with the aforementioned characteristics.⁹ In line with the consensus view, there is an abundance of models of monetary policy with a tradeoff between inflation stabilization and output stabilization.¹⁰

Consequently, we consider cost-push shocks, which violate the “divine coincidence” and create a tradeoff between stabilizing output and inflation. For our purposes, these shocks have one important property: it is individually but not collectively optimal for economic agents to respond to them. In this sense, information about cost-push shocks is socially harmful in the hands of price-setters.

How can these shocks be justified on theoretical grounds? First, they can be associated with variations in markups. Markup shocks can be modeled by a stochastic sales tax on all goods, where revenues are used to finance lump-sum transfers to the agents.¹¹ Markup shocks can also be motivated by changes in the intensity of competition or

⁷We normalize (log) natural output to zero and thus use the terms “output” and “output gap” interchangeably.

⁸See Woodford (2003), among others.

⁹See also King (1997), who has coined the derogatory term “inflation nutter” for a central banker who is exclusively concerned about inflation stabilization.

¹⁰This includes classic papers like Rogoff (1985). Models with “cost-push shocks” also have this property; among them are Clarida et al. (1999), Clarida et al. (2002), Steinsson (2003), Woodford (2003), and Ball et al. (2005).

¹¹For a discussion of markup shocks see Ball et al. (2005), among others. Compare also the extensive discussion in Woodford (2002), pp. 44-45.

in the aggressiveness of wage bargainers. Second, alternative approaches to modeling shocks that violate the “divine coincidence” have been presented by Blanchard and Galí (2007) and Blanchard and Galí (2008).

In order to keep the model tractable, we assume that only four realizations of the shock are possible.¹² These realizations are $-e'_L$, $+e'_L$, $-e'_H$, $+e'_H$ with $0 < e'_L < e'_H$ (where L stands for low and H for high). The prior probabilities are ρ_L for $-e'_L$ and $+e'_L$ and ρ_H for $-e'_H$ and $+e'_H$ ($2\rho_H + 2\rho_L = 1$). Thus the shock distribution is symmetric. The restriction to a discrete set of possible shocks enables us not only to derive analytical results for separating equilibria but also to study the existence of pooling equilibria and semi-separating equilibria, where some types of central banks pool, while others choose a policy that perfectly reveals their type. By contrast, most analyses of signaling games in monetary economics are restricted to separating equilibria (see, for example, Sibert (2009)).

The central bank and the firms independently receive signals about the shock realization. The central bank receives a signal that reveals the state of the world with probability p_{CB} ($0 \leq p_{CB} \leq 1$). With the complementary probability, the central bank obtains no signal. Similarly, all firms jointly receive a signal that reveals ε with probability p_F . Otherwise they receive no signal.

The central bank chooses its instrument m (log money growth), which affects output via a quantity equation:

$$y = m - p \tag{2}$$

Prices are sticky to some extent, which we model by assuming that only a fraction λ ($0 < \lambda < 1$) of firms can adjust their prices upon observing the central bank’s decision and possibly their signals.¹³ The other firms cannot adjust their prices and are assumed to inherit a price from the beginning of the period.

¹²The mechanisms identified in this paper are likely also to hold for other shock distributions, as we will argue in Section 6.

¹³This assumption has been introduced by Calvo (1983).

Alternatively, our model can be re-interpreted as a model of sticky information rather than sticky prices.¹⁴ Then λ would correspond to the fraction of firms updating their information about ε' and m . The remaining firms would remain ignorant of ε' and m , so they would not change their prices.

The sequence of events is as follows:

- All firms choose their default prices. Without loss of generality, we assume that all firms choose a (log) default price of 0.
- Nature draws the shock ε' .
- The central bank becomes informed about the shock realization with probability p_{CB} .
- Under opacity, the central bank's signal is kept private. Under transparency, the signal is published.
- The central bank chooses its instrument m . This choice is publicly observable.¹⁵
- All firms obtain precise information on the shock with probability p_F . With the complementary probability, all firms remain ignorant of the shock.
- A fraction λ of all firms may re-adjust their prices. The other firms keep their default prices.
- Output is realized.

In line with other papers that study signaling games in monetary economics, we do not study an infinite-horizon model (see, for example, Sibert (2009)). This keeps our framework analytically tractable. We note that our results are driven by the distortions

¹⁴Sticky information as an alternative to price stickiness has been proposed by Mankiw and Reis (2002).

¹⁵In principle, one could also consider the case where the central bank's instrument is kept secret. For example, the Federal Reserve did not make its policy directive public immediately after the board meetings (see Goodfriend (1986)). However, the central bank's instrument, usually a short-term interest rate, can easily be observed. Therefore it is implausible that monetary policy makers can keep their choices of instrument secret for any considerable length of time.

created by the central bank's signaling incentives under opacity. It is plausible that these distortions would also occur in a variant of our model with multiple periods.

The equilibrium price level as a function of m can now be obtained by inserting $y = m - p$ into (1), applying the expectations operator with respect to the firms' information set (\mathbb{E}_F), and using $p = \lambda \mathbb{E}_F[p^*]$:

$$p = \lambda (p + \alpha(m - p) + \mathbb{E}_F[\varepsilon']) \quad (3)$$

Solving for p yields

$$p = \frac{\lambda}{1 - \lambda(1 - \alpha)} (\alpha m + \mathbb{E}_F[\varepsilon']). \quad (4)$$

With the help of $\sigma := (\lambda\alpha)/(1 - \lambda(1 - \alpha))$ and $\varepsilon := \lambda/(1 - \lambda(1 - \alpha))\varepsilon'$, p can be rewritten as

$$p = \sigma m + \mathbb{E}_F[\varepsilon]. \quad (5)$$

We note that the price level is identical to inflation (π) in our model because we have normalized the default price level to zero. Consequently, we obtain

$$\pi = \sigma m + \mathbb{E}_F[\varepsilon]. \quad (6)$$

It is crucial to note that $\mathbb{E}_F[\varepsilon]$ is determined by the firms' signal, if they have received one. If they have received no signal, $\mathbb{E}_F[\varepsilon]$ depends on the central bank's information under transparency and on the central bank's choice of m under opacity.

There exist five types of central banks. Four types correspond to the different possible signals. The fifth type is a central bank that has not received a signal. We will use 0 denote this type. As a consequence the set of possible types is $\mathcal{T} := \{-H, -L, 0, +L, +H\}$. This notation enables us to introduce normalized values for the shock realization in a compact manner: $e_\tau := [\lambda/(1 - \lambda(1 - \alpha))] e'_\tau \forall \tau \in \mathcal{T} \setminus \{0\}$.

The central bank's loss function, which also represents social losses, is given by

$$\mathcal{L} = \frac{1}{1 + a} \pi^2 + \frac{a}{1 + a} y^2, \quad (7)$$

where $a \geq 0$ is a parameter that measures the importance of the output target. Compared to the more standard formulation $\mathcal{L} = \pi^2 + ay^2$, we have normalized losses by

the factor $\frac{1}{1+a}$. Obviously, this does not affect our findings; however, it will simplify the analysis.¹⁶

Inserting (2) and (6) into (7) yields

$$\mathcal{L}(m, \mathbb{E}_F[\varepsilon]) = \frac{1}{1+a}(\sigma m + \mathbb{E}_F[\varepsilon])^2 + \frac{a}{1+a}((1-\sigma)m - \mathbb{E}_F[\varepsilon])^2. \quad (8)$$

Importantly, the central bank could always achieve zero losses by choosing $m = 0$ if the firms' expectations concerning the cost-push shock were zero. By contrast, the central bank can never achieve zero losses when firms' expectations are different from zero. Thus information about cost-push shocks is socially harmful.

3 Transparency

In this section we focus on the transparency scenario, i.e. if the central bank has received a signal, then it makes its information public.

In the following, we derive the optimal policy chosen by the different types of central bank under transparency. For types in $\mathcal{T} \setminus \{0\}$, we obtain $\mathbb{E}_F[\varepsilon] = \varepsilon$. It is straightforward to prove that (8) can be rewritten in the following way:

$$\mathcal{L}(m, \mathbb{E}_F[\varepsilon]) = \frac{a}{(1+a)(\sigma^2 + a(1-\sigma)^2)}(\mathbb{E}_F[\varepsilon])^2 + \frac{\sigma^2 + a(1-\sigma)^2}{1+a}(m - m_{\mathbb{E}_F[\varepsilon]}^T)^2, \quad (9)$$

where

$$m_{\mathbb{E}_F[\varepsilon]}^T = \frac{a - \sigma(1+a)}{\sigma^2 + a(1-\sigma)^2} \mathbb{E}_F[\varepsilon]. \quad (10)$$

Variable $m_{\mathbb{E}_F[\varepsilon]}^T$ can be interpreted as the optimal value of m , conditional on the fact that the firms' beliefs about ε are given by $\mathbb{E}_F[\varepsilon]$. With slight abuse of notation we will sometimes write m_τ^T for $m_{E_F[\varepsilon]}^T$ evaluated at $E_F[\varepsilon] = e_\tau$ ($\tau \in \mathcal{T}$). Then m_τ^T represents the optimal choices of central banks $\tau \in \mathcal{T} \setminus \{0\}$ under transparency.

For $a - \sigma(1+a) > 0$, $m_{\mathbb{E}_F[\varepsilon]}^T$ is a strictly monotonically increasing function of $\mathbb{E}_F[\varepsilon]$. For $a - \sigma(1+a) < 0$, it is strictly monotonically decreasing. This observation is important, as we will draw an analogy under opacity and impose monotonicity as a

¹⁶The loss function can be derived from microeconomic foundations (see Woodford (2002)).

restriction on the equilibria. To simplify the exposition, we exclude the knife-edge case $a - \sigma(1 + a) = 0$ for the remainder of the paper.

It then remains to derive the optimal policy of an uninformed type $\tau = 0$. $\mathbb{E}_F[\varepsilon]$ may take five different values from this central bank's perspective, namely $-e_H$, $-e_L$, 0 , e_L , e_H , depending on whether the firms receive a signal about the shock and, if so, which realization they observe. Hence an uninformed central bank chooses m to minimize its expected losses

$$\begin{aligned} \mathcal{L}_0 := & p_F [\rho_L \mathcal{L}(m, -e_L) + \rho_L \mathcal{L}(m, +e_L) + \rho_H \mathcal{L}(m, -e_H) + \rho_H \mathcal{L}(m, +e_H)] \\ & + (1 - p_F) \mathcal{L}(m, 0). \end{aligned}$$

Importantly, $\mathcal{L}(m, -e_L) + \mathcal{L}(m, +e_L)$, $\mathcal{L}(m, -e_H) + \mathcal{L}(m, +e_H)$, and $\mathcal{L}(m, 0)$ are quadratic functions of m with minima at $m = 0$. As a consequence, the optimal policy of an uninformed central bank under transparency is given by $m_0^T := 0$.

We summarize our observations in the following proposition:

Proposition 1

Under transparency a unique equilibrium exists. Each central bank of type $\tau \in \mathcal{T}$ chooses m_τ^T .

In this equilibrium each central bank chooses m so as to optimally trade off the effect of the shock on output and inflation. Because firms receive direct information about the central bank's signal, the central bank does not have to care about its choice affecting the firms' estimate of the shock.

4 Opacity

Under opacity, the firms do not receive the central bank's signal directly. However, upon observing the central bank's choice of money growth, they may update their estimate of the central bank's type.

With probability p_F , firms learn the correct realization of ε because they receive information independently of the central bank. With probability $1 - p_F$ they obtain no

independent signal and attempt to infer the central bank's information from the central bank's choice of money growth m . We introduce $f(m)$ to denote the firms' beliefs about ε , given that they have observed m and have received no signal. Obviously, $f(m)$ must be a function that satisfies $-e_H \leq f(m) \leq e_H \forall m$. Under opacity, the model thus corresponds to a signaling game. This makes the analysis substantially more complex over and against transparency. To simplify the analysis, we focus on perfect Bayesian Nash equilibria in pure strategies that satisfy two additional, plausible assumptions.

First, we impose a monotonicity requirement on $f(m)$, as will be detailed in the following. Imposing monotonicity is intuitive, given that under transparency the central bank's choice of m is a monotonic function of its estimate about the shock. Under transparency, the equilibrium value of m is an increasing function of $E_{CB}[\varepsilon]$ for $a - \sigma(1 + a) > 0$ and a decreasing function for $a - \sigma(1 + a) < 0$. Hence we assume that firms beliefs under opacity are a monotonic function of m . In particular, we postulate that $f(m)$ is weakly increasing for $a - \sigma(1 + a) > 0$ and weakly decreasing for $a - \sigma(1 + a) < 0$.

Second, we assume that $f(m)$ is an odd function, i.e. $f(m) = -f(-m) \forall m$. This is plausible because of the model's linear-quadratic nature. Under transparency, for example, the central bank's optimal choice of m is also an odd function of the central bank's estimate about the shock.

These assumptions have several important implications. First, firms expect the shock to be zero if they have not observed an independent signal and the central bank has chosen $m = 0$. Formally, this can be stated as $f(0) = 0$. Second, and consequently, a central bank of type 0 will always choose $m = 0$. Third, the equilibrium choices of all types \mathcal{T} are a weakly monotonic function of the central bank's estimate of the shock. Formally, this implies $m_{-H}^O \leq m_{-L}^O \leq m_0^O = 0 \leq m_{+L}^O \leq m_{+H}^O$ for $a - \sigma(1 + a) > 0$ and $m_{-H}^O \geq m_{-L}^O \geq m_0^O = 0 \geq m_{+L}^O \geq m_{+H}^O$ for $a - \sigma(1 + a) < 0$, using m_τ^O to denote type τ 's equilibrium choice of m under opacity ($\tau \in \mathcal{T}$).¹⁷

¹⁷The third consequence of our assumptions can be easily explained. Suppose, for example, $a - \sigma(1 + a) > 0$. Then $f(m) \geq 0 \forall m > 0$ because $f(0) = 0$ and $f(m)$ is weakly monotonically increasing. A central bank that has observed a positive shock would never choose a negative money growth rate $m < 0$ because $-m > 0$ would yield lower losses, which is readily verified with the help of (8). As a

In the following it will prove useful to introduce the critical value of p_F , denoted by p_F^* , as follows

$$p_F^* := \frac{a}{(\sigma^2 + a(1 - \sigma)^2)(1 + a)}. \quad (11)$$

It is straightforward to derive

$$1 - p_F^* = \frac{(a - \sigma(1 + a))^2}{(\sigma^2 + a(1 - \sigma)^2)(1 + a)} > 0.$$

Hence one can conclude $0 \leq p_F^* < 1$.¹⁸

We are now in a position to describe the equilibria under opacity. In Appendix A we prove an important proposition:

Proposition 2

For $p_F < p_F^$, a unique¹⁹ equilibrium exists. In this equilibrium, all types of central banks $\tau \in \mathcal{T}$ choose $m = 0$. If they have not received direct information about ε , the firms' beliefs about the shock are $f(0) = 0$. For $a - \sigma(1 + a) > 0$, $f(m) = e_H \forall m > 0$ and $f(m) = -e_H \forall m < 0$. For $a - \sigma(1 + a) < 0$, $f(m) = -e_H \forall m > 0$ and $f(m) = +e_H \forall m < 0$.*

The proof is given in Appendix A. Intuitively, if the chances of the firms receiving information directly are rather low, it is profitable for the central bank to remain completely passive. As the firms are unlikely to learn about the shock, the expected losses incurred by not stabilizing the shock are low. Importantly, by not responding to its own private information, the central bank can prevent the firms from inferring this information.

For $p_F > p_F^*$, no unique equilibrium exists in general. In the following we will characterize several different equilibria. With the help of

$$\hat{p}_F = \frac{e_H + e_L}{e_H + (2p_F^* - 1)e_L} p_F^*, \quad (12)$$

consequence, H and L choose positive values of m . Analogously, $-H$ and $-L$ choose negative values of m . Monotonicity of $f(m)$ then requires $m_H \geq m_L$ (otherwise the firms' beliefs would be incorrect). In a similar vein, $m_{-H} \leq m_{-L}$ follows from the monotonicity of $f(m)$.

¹⁸Recall that we have excluded the knife-edge case $a - \sigma(1 + a) = 0$.

¹⁹To be more precise, the equilibrium is unique in the sense that no additional equilibrium exists in which the equilibrium choices for the five central bank types \mathcal{T} are different. However, the equilibrium is not unique with respect to out-of-equilibrium beliefs.

it is possible to describe the circumstances under which the same outcome as under transparency can prevail under opacity:

Proposition 3

If and only if $p_F \geq \hat{p}_F$, there is an equilibrium under opacity in which all types of central bankers $\tau \in \mathcal{T}$ choose the money growth rates they would find optimal under transparency (m_τ^T).

For the proof, see Appendix B. Intuitively, for high values of p_F the firms are likely to be informed about the shock directly. As a consequence, it is optimal for the central bank to behave in the same manner as under transparency.

We note that $\hat{p}_F < 1$. Thus the range of values of p_F for which the fully separating equilibria described in Proposition 3 exist is always non-empty.

Additionally, we note that $\hat{p}_F > p_F^*$. Consequently, for the interval $p_F^* < p_F < \hat{p}_F$ neither pooling equilibria, which are described in Proposition 2, nor separating equilibria with the same choices as under transparency exist. Intuitively, separating equilibria with the same choices as under transparency do not exist, as there would be strong incentives for central banks of type H to mimic L . By mimicking the L -type, type H can reduce the firms' expectations about the shock, which leads to lower losses if the firms do not receive an independent signal. However, if H could successfully mimic L , this would be harmful to L as the firms might mistake it for H . This, in turn, would lead to high losses due to the firms' beliefs that the shock is very large. Thus type L tends to choose an m farther away from m_H^T in order to make mimicking more costly for H .

One example of such behavior is given in the following proposition, proven in Appendix C:

Proposition 4

There is a critical value for p_F , denoted by \tilde{p}_F , such that the following semi-separating equilibrium exists under opacity for $p_F \in [p_F^, \tilde{p}_F]$. Central banks of types $\tau \in \{-L, 0, +L\}$ choose $m = 0$. Central banks of types $\tau \in \{-H, +H\}$ choose m_τ^T . If firms have not received direct information about ε , their beliefs about the shock are*

$f(0) = 0$. For $a - \sigma(1 + a) > 0$, $f(m) = e_H \forall m > 0$ and $f(m) = -e_H \forall m < 0$. For $a - \sigma(1 + a) < 0$, $f(m) = -e_H \forall m > 0$ and $f(m) = +e_H \forall m < 0$.

We have shown that, for sufficiently large values of p_F ($p_F \geq \hat{p}_F$), separating equilibria exist where all central-bank types display the same behavior under opacity as under transparency. Moreover, for sufficiently small values of p_F ($p_F \leq p_F^*$), pooling equilibria exist. For somewhat larger p_F ($p_F^* \leq p_F \leq \tilde{p}_F$), semi-separating equilibria occur in which central banks of types $-L$ and L mimic the behavior of 0. We note that $\tilde{p}_F < \hat{p}_F$ cannot be ruled out, as can be readily verified. Thus it now remains to describe equilibria for the interval $p_F \in]\tilde{p}_F; \hat{p}_F[$. This gap is filled by the following proposition:

Proposition 5

Suppose $\tilde{p}_F < \hat{p}_F$. For all $p_F \in]\tilde{p}_F; \hat{p}_F[$, values $\underline{\phi}$ and $\overline{\phi}$ with $0 < \underline{\phi} < \overline{\phi} < 1$ exist such that for all $\phi \in [\underline{\phi}; \overline{\phi}]$ separating equilibria exist under opacity that satisfy the following properties: Central banks of types $-H$ and $+H$ choose m_{-H}^T and m_H^T , respectively. Central banks of types $-L$ and $+L$ choose ϕm_{-L}^T and ϕm_L^T , respectively. Type 0 chooses $m_0^T = 0$.

The proof is given in Appendix D. These equilibria are particularly interesting as they represent fully separating equilibria where the behavior of types $-L$ and L is distorted by the factor ϕ over and against the equilibria under transparency. This distortion is the result of the incentives of types $-H$ and H to mimic the behavior of the types with moderate shock realizations, i.e. $-L$ and L . As successful imitation may increase the firms' shock estimate, types $-L$ and L choose the distorted money growth rates ϕm_{-L}^T and ϕm_L^T respectively, which makes mimicking less attractive for $-H$ and H .

5 Comparison

In this section we compare the central bank's losses and thus also social losses under transparency with the losses under opacity. The following proposition, proved in Appendix E, contains the major finding of this paper:

Proposition 6

For $p < p_F^$, transparency is inferior to opacity. For $p > p_F^*$, transparency is superior.*

Accordingly, whether transparency is desirable depends on the quality of the firms' direct information. If firms are unlikely to be well-informed, transparency is harmful. If there is a high probability of their being well-informed, then central-bank transparency is desirable.²⁰

The intuition for this finding is as follows. If the central bank publishes its private information, it provides the firms with information that may be unknown to them. As it is individually optimal for firms, albeit socially harmful, to respond to the shock, publishing information is costly to society. On the other hand, transparency eliminates the signaling costs the central bank incurs if the money growth rate it would like to choose under transparency were to signal the wrong information under opacity.

For low-quality information available to firms (or low levels of p_F), the costs incurred by transparency outweigh the benefits. Loosely speaking, it is better to remain inactive in this case and to speculate that firms will not discover the shock realization. By contrast, if the firms' information is high in quality, the firms are probably informed anyhow. By publishing its private information the central bank can avoid the signaling costs.

6 Robustness

In this section we discuss some issues related to the robustness of our findings. In particular, we focus on the specification of shocks, different types of shocks, the additional restrictions on equilibrium we have introduced under opacity, and the quality of the central bank's information.

²⁰Transparency is strictly desirable for $p_F \in]p_F^*; \hat{p}_F[$. For $p_F \geq \hat{p}_F$, transparency and opacity lead to equivalent results with respect to welfare if the equilibria specified in Proposition 3 materialize. Transparency is strictly superior for all other equilibria.

Specification of shocks In this paper we have focused on four different shock realizations. This number is sufficiently high to identify the important signaling incentives in our framework and at the same time low enough to permit analytical results. If we considered only one possible realization of a positive and a negative shock (as opposed to the two in our model), we would ignore the crucial incentive of type H to mimic type L , which leads to the distortions under opacity driving our results regarding welfare. By contrast, if we considered more possible realizations of positive and negative shocks, the signaling incentives and thus the distortions would remain, but the analysis would be substantially more complex. In particular, with a continuum of potential shock realizations it is possible to show that pooling equilibria exist under opacity for small values of p_F and fully separating equilibria occur for large values of p_F , which is in line with the analysis in this paper. For intermediate values of p_F , equilibria corresponding to the semi-pooling equilibria in our paper are plausible. However, these would be extremely laborious to characterize for infinitely many central-bank types.

Other types of shocks In our paper we deliberately focus on cost-push shocks because we intend to demonstrate that even with these shocks transparency can be socially desirable. We could introduce demand shocks into our framework, but transparency regarding these shocks would never be socially harmful. Under opacity, separating equilibria are likely to exist that would perfectly reveal the central bank's information. Then transparency and opacity would be equivalent with respect to welfare. Moreover, additional equilibria may exist under opacity, which would definitely entail lower welfare levels.²¹ Consequently, transparency would be desirable from a welfare point of view.

Quality of the central bank's information Interestingly, the quality of the central bank's information, which is associated with parameter p_{CB} in our model, is irrelevant for the relative performance of transparency and opacity. Consequently, our findings extend to the case where central banks are always informed about cost-push shocks.

²¹For a detailed analysis, see Hahn (2009).

Restrictions on equilibrium In Section 4, where we analyze the opacity scenario, we have introduced two important restrictions on the equilibria under opacity, namely that $f(m)$ is monotonic and odd. Relaxing these assumptions might allow for additional equilibria. Although a complete characterization of all additional equilibrium candidates is beyond the scope of this paper, it is plausible that these equilibria would lead to higher losses under opacity. For example, an equilibrium where type L chooses negative values of m under opacity despite $m_L^T > 0$ is likely to be less desirable than equilibria satisfying our restrictions. Hence relaxing the restrictions on equilibria might make transparency more attractive over and against opacity.

7 Conclusions

In this paper we have considered the impact that the publication of the central bank's private information regarding shocks has on welfare. Information about these shocks induces price-setters to adjust their prices in a socially detrimental way. Consequently, transparency is harmful from a social welfare perspective if the probability of firms' receiving information through alternative sources is low. However, if this probability is sufficiently high, transparency is beneficial. Transparency eliminates the signaling incentives of different types of central banks and hence, in turn, the policy distortions prevalent under opacity.

Interestingly, our model can also be used to rationalize the current trend towards increased transparency in monetary policy. As improvements in information technologies plausibly raise the probability of economic agents receiving information on the economy independently of the central bank, it may be increasingly important for central banks to become more open about their private assessments of the economy.

A Proof of Proposition 2

A.1 Existence

To show that the proposed equilibrium exists, we have to demonstrate that there is no profitable deviation for all types $\tau \in \mathcal{T}$. Before we show this, we note that central-bank losses can be written in a compact manner with the help of p_F^* (see (11)). Using (9) and (10), we obtain

$$\mathcal{L}(m_e^T, \mathbb{E}_F[\varepsilon]) = p_F^*(\mathbb{E}_F[\varepsilon])^2 + (1 - p_F^*)(e - \mathbb{E}_F[\varepsilon])^2. \quad (13)$$

This expression gives the losses the central bank incurs if firms believe the shock to be $\mathbb{E}_F[\varepsilon]$ and if the central bank chooses the money growth rate m_e^T , which is the choice that would be optimal under transparency given that firms would believe the shock to be e .

Deviations for 0 It is obvious that there is no profitable deviation for 0, as $m = 0$ is its preferred choice under transparency as well and any other choice would imply that the public believes a large shock has occurred, which would increase losses further. It thus remains to show whether profitable deviations exist for the other types. For simplicity, we focus on the case $a - \sigma(1 + a) > 0$. In this case, $f(m) = e_H \forall m > 0$ and $f(m) = -e_H \forall m < 0$ hold. The case with $a - \sigma(1 + a) < 0$ is completely analogous and is therefore omitted.

Deviations for H and -H Now we focus on possible deviations for H . In equilibrium, type H 's losses are

$$p_F \mathcal{L}(0, \mathbb{E}_F[\varepsilon] = e_H) + (1 - p_F) \mathcal{L}(0, \mathbb{E}_F[\varepsilon] = 0) = p_F e_H^2, \quad (14)$$

where we have utilized (13). It is straightforward to see that for $a - \sigma(1 + a) > 0$ any deviation $m < 0$ is strictly inferior to $-m > 0$. Thus we consider only deviations with $m > 0$ in the following. A deviation $m > 0$ always results in beliefs $\mathbb{E}_F[\varepsilon] = e_H$. Consequently, the most profitable of these deviations is m_H^T . In line with (13), losses

for this deviation are

$$\mathcal{L}(m_H^T, \mathbb{E}_F[\varepsilon] = e_H) = p_F^* e_H^2. \quad (15)$$

There is no profitable deviation for H if $p_F^* e_H^2 \geq p_F e_H^2$ (compare (14) and (15)) or, equivalently, $p_F \leq p_F^*$. Due to the symmetry of the firms' optimization problem, this also implies that no profitable deviation exists for $-H$ in this case.

Deviations for L and -L We show next that no profitable deviation exists for L . Again it suffices to examine deviations with $m > 0$, as any deviation $m < 0$ is strictly inferior to $-m > 0$ for $a - \sigma(1 + a) > 0$. Type L 's equilibrium losses are $p_F \mathcal{L}(0, e_L) + (1 - p_F) \mathcal{L}(0, 0) = p_F e_L^2$, while a deviation m with $m > 0$ entails losses $p_F \mathcal{L}(m, e_L) + (1 - p_F) \mathcal{L}(m, e_H)$. The most profitable of all deviations is $m_{\mathcal{E}}^T$ with $\mathcal{E} := p_F e_L + (1 - p_F) e_H$.²²

This deviation will not be attractive if the equilibrium losses are smaller than the losses incurred by choosing $m_{\mathcal{E}}^T$

$$p_F e_L^2 < p_F \mathcal{L}(m_{\mathcal{E}}^T, e_L) + (1 - p_F) \mathcal{L}(m_{\mathcal{E}}^T, e_H),$$

which, utilizing (13), can be expressed as

$$p_F e_L^2 < p_F [p_F^* e_L^2 + (1 - p_F^*)(\mathcal{E} - e_L)^2] + (1 - p_F) [p_F^* e_H^2 + (1 - p_F^*)(\mathcal{E} - e_H)^2].$$

This inequality always holds, because $p_F e_L^2 < p_F p_F^* e_L^2 + (1 - p_F) p_F^* e_H^2$ for $p_F \leq p_F^*$. Hence there is no profitable deviation for L . The demonstration that a profitable deviation does not exist for $-L$ is completely analogous.

To sum up, no type $\tau \in \mathcal{T}$ has a profitable deviation, and the equilibrium outlined in the proposition exists.

A.2 Uniqueness

Next, we show that no other equilibria exist. Again we focus on the case $a - \sigma(1 + a) > 0$ and omit the case with $a - \sigma(1 + a) < 0$, which is completely analogous. In line with

²²This fact can be easily checked by solving the respective first-order condition for m .

our additional assumptions about $f(m)$, L and H will choose weakly positive values of m in any equilibrium. Moreover, $-L$ and $-H$ will choose weakly negative values of m . In addition, the monotonicity of $f(m)$ implies the monotonicity of the central bank's decisions as a function of its private estimate of the shock, which can be formally stated as $0 = m_0^O \leq m_L^O \leq m_H^O$ (and $m_{-H}^O \leq m_{-L}^O \leq m_0^O = 0$).

These considerations entail that three constellations are possible with regard to L and H , in addition to the constellation we have already considered ($m = 0$ for both). First, L may choose 0, and H may choose a strictly positive m ($0 = m_L^O < m_H^O$). Second, L may choose a strictly positive value for m that is strictly lower than H 's choice ($0 < m_L^O < m_H^O$). Third, both types may pool ($0 < m_L^O = m_H^O$). Therefore uniqueness can be established by ruling out all three additional constellations.

First we demonstrate that no equilibrium with $0 = m_L^O < m_H^O$ exists. As H separates itself from the other types, $f(m_H^O) = e_H$ must hold. We have already demonstrated that H could profitably deviate to $m = 0$ if $m_H^O = m_H^T$ and $p_F < p_F^*$. If m_H^O were different from m_H^T , deviating would be even more profitable for $p_F < p_F^*$ because m_H^T is the value of m that minimizes H 's losses under the restriction that $f(m) = e_H$.

Second, we consider $0 < m_L^O < m_H^O$. In a fully separating equilibrium, $f(m_L^O) = e_L$ and $f(m_H^O) = e_H$ must hold. Again, H could profitably deviate if $p_F < p_F^*$. Thus no separating equilibrium exists.

Third, it remains to be shown that semi-separating equilibria with $0 < m_L^O = m_H^O$ can be ruled out. For such an equilibrium $f(m_L^O) = (\rho_L e_L + \rho_H e_H) / (\rho_L + \rho_H) = 2(\rho_L e_L + \rho_H e_H) =: \hat{\mathcal{E}} > e_L$ must hold. We introduce e_L^O as the solution to $m_{e_L^O}^T = m_L^O$ (compare (10)), i.e. $e_L^O := [(\sigma^2 + a(1 - \sigma)^2) / (a - \sigma(1 + a))] m_L^O$. In line with (13), type L 's losses in the semi-separating equilibrium would amount to

$$\begin{aligned} \mathcal{L}_{L,1} &:= p_F \mathcal{L}(m_L^O, e_L) + (1 - p_F) \mathcal{L}(m_L^O, \hat{\mathcal{E}}) \\ &= p_F (p_F^* e_L^2 + (1 - p_F^*) (e_L^O - e_L)^2) + (1 - p_F) (p_F^* \hat{\mathcal{E}}^2 + (1 - p_F^*) (e_L^O - \hat{\mathcal{E}})^2) \end{aligned}$$

For the deviation to $m = 0$, type L 's losses would be

$$p_F \mathcal{L}(m = 0, \mathbb{E}_F[\varepsilon] = e_L) = p_F e_L^2.$$

The equilibrium does not exist if $\mathcal{L}_{L,1} > p_F e_L^2$ holds $\forall e_L^O$. To show this condition, we note that $p_F e_L + (1 - p_F) \hat{\mathcal{E}}$ is the value of e_L^O that minimizes $\mathcal{L}_{L,1}$. Evaluating $\mathcal{L}_{L,1}$ at $e_L^O = p_F e_L + (1 - p_F) \hat{\mathcal{E}}$ yields

$$\begin{aligned}\mathcal{L}_{L,1} &= p_F^* (p_F e_L^2 + (1 - p_F) \hat{\mathcal{E}}^2) \\ &\quad + (1 - p_F^*) (p_F (p_F e_L + (1 - p_F) \hat{\mathcal{E}} - e_L)^2 + (1 - p_F) (p_F e_L + (1 - p_F) \hat{\mathcal{E}} - \hat{\mathcal{E}})^2) \\ &= p_F^* (p_F e_L^2 + (1 - p_F) \hat{\mathcal{E}}^2) \\ &\quad + (1 - p_F^*) (p_F (1 - p_F)^2 (e_L - \hat{\mathcal{E}})^2 + (1 - p_F) p_F^2 (e_L - \hat{\mathcal{E}})^2) \\ &= p_F^* (p_F e_L^2 + (1 - p_F) \mathcal{E}^2) + (1 - p_F^*) p_F (1 - p_F) (e_L - \hat{\mathcal{E}})^2.\end{aligned}$$

The difference between $\mathcal{L}_{L,1}$, evaluated at $e_L^O = p_F e_L + (1 - p_F) \hat{\mathcal{E}}$, and the losses incurred by deviating to $m = 0$, $p_F e_L^2$, can be readily computed as

$$\mathcal{L}_{L,1} - p_F e_L^2 = p_F^* (1 - p_F) \hat{\mathcal{E}}^2 + (1 - p_F^*) \left[p_F (1 - p_F) (\hat{\mathcal{E}} - e_L)^2 - p_F e_L^2 \right].$$

This expression is always positive for $\hat{\mathcal{E}} > e_L$ and $p_F \leq p_F^*$. Consequently, for type L a profitable deviation always exists, and semi-separating equilibria with $0 < m_L^O = m_H^O$ can be ruled out.

Hence we have established existence and uniqueness of the equilibrium outlined in the proposition.

□

B Proof of Proposition 3

As a first step, we specify beliefs and, in particular, out-of-equilibrium beliefs. We have to distinguish between $a - \sigma(1 + a) > 0$ and $a - \sigma(1 + a) < 0$. For $a - \sigma(1 + a) > 0$ beliefs are

$$f(m) = \begin{cases} -e_H & \text{for } m < m_{-L}^T \\ -e_L & \text{for } m_{-L}^T \leq m < 0 \\ 0 & \text{for } m = 0 \\ +e_L & \text{for } 0 < m \leq m_L^T \\ +e_H & \text{for } m > m_L^T \end{cases} \quad (16)$$

and for $a - \sigma(1 + a) < 0$ they are

$$f(m) = \begin{cases} e_H & \text{for } m < m_L^T \\ e_L & \text{for } m_L^T \leq m < 0 \\ 0 & \text{for } m = 0 \\ -e_L & \text{for } 0 < m \leq m_{-L}^T \\ -e_H & \text{for } m > m_{-L}^T. \end{cases}$$

For the remainder of the proof we assume $a - \sigma(1 + a) > 0$. Adapting the proof to $a - \sigma(1 + a) < 0$ is straightforward. In the following, we have to show that no profitable deviation exists for all types $\tau \in \mathcal{T}$.

Deviations for 0 It is easy to show that 0 cannot profitably deviate from $m = 0$. Even if $f(m) = 0 \forall m$ held, $m = 0$ would be preferable over and against all $m \neq 0$. For all m with $f(m) \neq 0$, type 0's losses would be even higher than in the case where $f(m) = 0$ would hold. Thus $m = 0$ represents the optimal choice for the beliefs defined in (16).

Deviations for -H and H It suffices to consider only possible deviations of H , as the analysis of type $-H$'s deviations is completely analogous. It is important to note that a deviation with $m < 0$ always leads to higher losses than $-m > 0$. Thus we focus on deviations with $m > 0$.

According to (16), all deviations m with $m > m_L^T$ entail $f(m) = e_H$. As m_H^T is H 's optimal choice, conditional on $f(m) = e_H$, these deviations are not profitable.

A deviation to 0 implies $f(0) = 0$. We note that $\hat{p}_F > p_F^*$. Thus $p_F > \hat{p}_F$ implies $p_F > p_F^*$. According to the proof of Proposition 2, type H therefore prefers m_H^T with $f(m_H^T) = e_H$ to 0 with $f(m_H^T) = 0$. Hence $m = 0$ never represents a profitable deviation.

Finally, we have to check whether deviating to a value of m with $0 < m \leq m_L^T$ might yield lower losses to H . For such a deviation, $f(m) = e_L$ according to (16). The most profitable of these deviations is m_L^T .²³ Thus we need to compare type H 's losses for m_H^T

²³Conditional on $f(m) = e_L$, $m = p_F m_H^T + (1 - p_F) m_L^T$ would minimize losses. Because this value

with its losses for m_L^T . If a central bank of type H chooses m_H^T , losses can be computed using (13):

$$\mathcal{L}(m_H^T, e_H) = p_F^* e_H^2$$

By contrast, if H chooses m_L^T , its losses will amount to

$$\begin{aligned} \mathcal{L}_{H,3} &:= p_F \mathcal{L}(m_L^T, e_H) + (1 - p_F) \mathcal{L}(m_L^T, e_L) \\ &= p_F^* (p_F e_H^2 + (1 - p_F) e_L^2) + p_F (1 - p_F^*) (e_H - e_L)^2. \end{aligned} \tag{17}$$

Thus there is no profitable deviation if $\mathcal{L}_{H,3} \geq \mathcal{L}(m_H^T, e_H)$ or

$$p_F^* (p_F e_H^2 + (1 - p_F) e_L^2) + p_F (1 - p_F^*) (e_H - e_L)^2 \geq p_F^* e_H^2.$$

This inequality can be reformulated as

$$p_F [p_F^* (e_H^2 - e_L^2) + (1 - p_F^*) (e_H - e_L)^2] \geq p_F^* e_H^2 - p_F^* e_L^2.$$

Rearranging terms and applying $e_H^2 - e_L^2 = (e_H - e_L)(e_H + e_L)$ yields

$$p_F \geq \frac{p_F^* e_H^2 - p_F^* e_L^2}{p_F^* (e_H^2 - e_L^2) + (1 - p_F^*) (e_H - e_L)^2} = \frac{e_H + e_L}{e_H + (2p_F^* - 1)e_L} p_F^* = \hat{p}_F.$$

Hence, if $p_F \geq \hat{p}_F$, there is no profitable deviation for H . Otherwise a profitable deviation exists.

Deviations for -L and L Again we focus on deviations of L with $m \geq 0$. According to the proof of Proposition 2, deviating to $m = 0$ is not profitable if $p_F > p_F^*$, which holds because of $p_F > \hat{p}_F$ and $\hat{p}_F > p_F^*$. Choosing a value of m from the interval $]0; m_L^T[$ is never profitable, as this would entail $f(m) = e_L$ and m_L^T is the value of m that minimizes type L 's losses contingent on $f(m) = e_L$. It remains to be shown that L cannot lower its losses by choosing $m > m_L^T$. Such a choice implies $f(m) = e_H$. The deviation with $m > m_L^T$ that yields the lowest losses can be easily computed as $m_{\mathcal{E}}^T$ with $\mathcal{E} = p_F e_L + (1 - p_F) e_H$. Following (13), this deviation implies losses

$$\begin{aligned} \mathcal{L}_{L,3} &:= p_F \mathcal{L}(m_{\mathcal{E}}^T, e_L) + (1 - p_F) \mathcal{L}(m_{\mathcal{E}}^T, e_H) \\ &= p_F [p_F^* e_L^2 + (1 - p_F^*) (e_L - \mathcal{E})^2] + (1 - p_F) [p_F^* e_H^2 + (1 - p_F^*) (e_H - \mathcal{E})^2] \\ &= p_F [p_F^* e_L^2 + (1 - p_F^*) (1 - p_F)^2 (e_H - e_L)^2] + (1 - p_F) [p_F^* e_H^2 + (1 - p_F^*) p_F^2 (e_H - e_L)^2] \\ &= p_F^* (p_F e_L^2 + (1 - p_F) e_H^2) + p_F (1 - p_F) (1 - p_F^*) (e_H - e_L)^2. \end{aligned} \tag{18}$$

of m is strictly larger than m_L^T , $\operatorname{argmin}_{m \in]0; m_L^T]} \{p_F \mathcal{L}(m, e_H) + (1 - p_F) \mathcal{L}(m, e_L)\} = m_L^T$.

In equilibrium, L 's losses are

$$\mathcal{L}(m_L^T, e_L) = p_F^* e_L^2.$$

Thus from L 's perspective deviating is not desirable if $\mathcal{L}_{L,3} \geq \mathcal{L}(m_L^T, e_L)$, which is equivalent to

$$p_F^*(1 - p_F)(e_H^2 - e_L^2) + p_F(1 - p_F)(1 - p_F^*)(e_H - e_L)^2 > 0.$$

As this inequality always holds, all deviations lead to higher losses for L over and against the equilibrium losses. Consequently, we have demonstrated that the proposed equilibrium exists for $p_F \geq \hat{p}_F$. For $p_F < \hat{p}_F$, the equilibrium does not exist because $-H$ and H can profitably deviate to m_L^T in this case.

□

C Proof of Proposition 4

As in previous proofs, we focus on $a - \sigma(1 + a) > 0$. The analysis of the case with $a - \sigma(1 + a) < 0$, which is completely analogous, is omitted.

Deviations for 0 Again, no profitable deviation exists for type 0, because $m = 0$ is the money growth this type of central bank would also choose under transparency and any deviation results in beliefs $f(m) = e_H$, which involves even higher costs than the same deviation would entail for $f(m) = 0$.

Deviations for H and -H We focus on type H and note that it is straightforward to extend the analysis to $-H$. As m_H^T is the optimal choice, given that $f(m) = e_H$, no deviation with $m > 0$ can ever be profitable. Moreover, we do not have to examine deviations with $m < 0$ because $-m > 0$ would always be strictly more desirable in these cases. Consequently, we only have to check the deviation $m = 0$, which involves $f(m) = 0$. In the proof of Proposition 2 we have already demonstrated that choosing $m = 0$ is not profitable compared to $m = m_H^T$ if $f(0) = 0$, $f(m_H^T) = e_H$, and $p_F \geq p_F^*$.

Deviations for L and -L Again we omit the analysis of type $-L$'s deviations. For type L , deviations with $m < 0$ are never desirable. The most profitable of all deviations with $m > 0$ is $p_F m_L^T + (1 - p_F) m_H^T$. This choice leads to losses $\mathcal{L}_{L,3}$ (see (18)). In equilibrium, L 's losses are

$$p_F \mathcal{L}(0, e_L) + (1 - p_F) \mathcal{L}(0, 0) = p_F e_L^2.$$

Deviating is not attractive if $\mathcal{L}_{L,3} > p_F e_L^2$ or

$$p_F^* (p_F e_L^2 + (1 - p_F) e_H^2) + p_F (1 - p_F) (1 - p_F^*) (e_H - e_L)^2 > p_F e_L^2. \quad (19)$$

This inequality holds for $p_F = p_F^*$ and is violated for $p_F = 1$. Moreover, we note that the difference between the left-hand side and the right-hand side of the inequality is quadratic in p_F . Consequently, there is a unique value of p_F , denoted by \tilde{p}_F ($p_F^* < \tilde{p}_F < 1$) such that (19) holds with equality. Hence the proposed equilibrium exists for $p_F^* \leq p_F \leq \tilde{p}_F$.

□

D Proof of Proposition 5

As a first step, we specify beliefs and, in particular, out-of-equilibrium beliefs. We have to distinguish between $a - \sigma(1 + a) > 0$ and $a - \sigma(1 + a) < 0$. For $a - \sigma(1 + a) > 0$ beliefs are

$$f(m) = \begin{cases} -e_H & \text{for } m < \phi m_{-L}^T \\ -e_L & \text{for } \phi m_{-L}^T \leq m < 0 \\ 0 & \text{for } m = 0 \\ +e_L & \text{for } 0 < m \leq \phi m_L^T \\ +e_H & \text{for } m > \phi m_L^T \end{cases} \quad (20)$$

and for $a - \sigma(1 + a) < 0$ they are

$$f(m) = \begin{cases} e_H & \text{for } m < \phi m_L^T \\ e_L & \text{for } \phi m_L^T \leq m < 0 \\ 0 & \text{for } m = 0 \\ -e_L & \text{for } 0 < m \leq \phi m_{-L}^T \\ -e_H & \text{for } m > \phi m_{-L}^T. \end{cases}$$

For the remainder of the proof we assume $a - \sigma(1 + a) > 0$. Adapting the proof to $a - \sigma(1 + a) < 0$ is straightforward. In the following, we examine the conditions under which no profitable deviation exists for all types.

Deviations of -L and L It again suffices to study only possible deviations of L , as the extension of the analysis to type $-L$'s deviations is straightforward. In equilibrium, L chooses ϕm_L^T , and the firms' beliefs amount to e_L , irrespective of whether they have received direct information or have inferred the size of the shock from the central bank's policy. Applying (13) yields the losses in equilibrium:

$$\mathcal{L}_{L,4} := p_F^* e_L^2 + (1 - p_F^*)(1 - \phi)^2 e_L^2 \quad (21)$$

We note that no deviations with $0 < m < \phi m_L^T$ are ever profitable, as $\phi m_L^T < m_L^T$ holds and m_L^T is the most profitable choice if $f(m) = e_L$. Given $f(m) = e_H$, $m_{\mathcal{E}}^T$ with $\mathcal{E} = p_F e_L + (1 - p_F) e_H$ is the most profitable option. Hence it is sufficient to check only two candidate deviations, namely 0 and $m_{\mathcal{E}}^T$.

According to (13), deviation 0 involves losses

$$\mathcal{L}_{L,5} := p_F \mathcal{L}(0, e_L) + (1 - p_F) \mathcal{L}(0, 0) = p_F e_L^2$$

and, in line with (18), deviation $m_{\mathcal{E}}^T$ results in

$$\mathcal{L}_{L,3} = p_F^* (p_F e_L^2 + (1 - p_F) e_H^2) + p_F (1 - p_F) (1 - p_F^*) (e_H - e_L)^2. \quad (22)$$

Interestingly, $\mathcal{L}_{L,5} > \mathcal{L}_{L,3}$ follows from the fact that (19) is violated for $p_F > \tilde{p}_F$. Thus $m_{\mathcal{E}}^T$ represents the most profitable of all deviations, and condition $\mathcal{L}_{L,3} \geq \mathcal{L}_{L,4}$ alone guarantees that L cannot profitably deviate.

As a next step, we examine the range of ϕ for which $\mathcal{L}_{L,3} \geq \mathcal{L}_{L,4}$ holds. For $\phi = 0$, this inequality is violated due to $(\mathcal{L}_{L,4} = e_L^2 > \mathcal{L}_{L,5} > \mathcal{L}_{L,3})$, and for $\phi = 1$ it holds strictly. Consequently, there is a unique value of $\phi \in]0; 1[$ that satisfies $\mathcal{L}_{L,3} = \mathcal{L}_{L,4}$. We use $\underline{\phi}$ to denote this value. If and only if $\phi \geq \underline{\phi}$, no profitable deviation exists for L .

Deviations of -H and H In equilibrium, H 's losses are $\mathcal{L}(m_H^T, e_H) = p_F^* e_H^2$. For H , $m = 0$ cannot represent a profitable deviation, because $p_F \geq p_F^*$ (compare the

proof of Proposition 2). No deviation to $m > \phi e_L$ can be profitable. These deviations imply $f(m) = e_H$, and m_H^T is the optimal choice in this case. Given $f(m) = e_L$, $p_F m_H^T + (1 - p_F) m_L^T$ would be optimal, which is larger than ϕm_L^T . Consequently, ϕm_L^T is the most profitable of all deviations $m \in]0; \phi m_L^T]$. If H deviates to ϕm_L^T , losses will be

$$\mathcal{L}_{H,4} := p_F [p_F^* e_H^2 + (1 - p_F^*)(e_H - \phi e_L)^2] + (1 - p_F) [p_F^* e_L^2 + (1 - p_F^*)(e_L - \phi e_L)^2]. \quad (23)$$

No profitable deviation for H exists if $\mathcal{L}_{H,4} \geq \mathcal{L}(m_H^T, e_H)$. We note that $\mathcal{L}_{H,4} = p_F e_H^2 + (1 - p_F) e_L^2 > p_F^* e_H^2 = \mathcal{L}(m_H^T, e_H)$ for $\phi = 0$ and $\mathcal{L}_{H,4} < \mathcal{L}(m_H^T, e_H)$ for $\phi = 1$ (which follows from $p_F < \hat{p}_F$). As a result, there is a value of $\phi \in]0; 1[$ with $\mathcal{L}_{H,4} = \mathcal{L}(m_H^T, e_H)$, which will be denoted by $\bar{\phi}$. For every $\phi \leq \bar{\phi}$ type H cannot profitably deviate.

Does $\underline{\phi} < \bar{\phi}$ hold? Finally, we have to show $\underline{\phi} < \bar{\phi}$ for all $p_F \in]\tilde{p}_F, \hat{p}_F[$. For this purpose, we demonstrate $\mathcal{L}_{H,4} > \mathcal{L}(m_H^T, e_H)$ at $\phi = \underline{\phi}$.

Recall that $\underline{\phi}$ is defined by $\mathcal{L}_{L,3} = \mathcal{L}_{L,4}$. Applying (21) yields

$$\mathcal{L}_{L,3} = p_F^* e_L^2 + (1 - p_F^*)(1 - \underline{\phi})^2 e_L^2. \quad (24)$$

With the help of (17) and (24), $\mathcal{L}_{H,4}$ (in (23)) can be written as

$$\begin{aligned} \mathcal{L}_{H,4} &= p_F \left[p_F^* e_H^2 + (1 - p_F^*) (e_H - e_L + (1 - \underline{\phi}) e_L)^2 \right] \\ &\quad + (1 - p_F) [p_F^* e_L^2 + (1 - p_F^*)(1 - \underline{\phi})^2 e_L^2] \\ &= p_F [p_F^* e_H^2 + (1 - p_F^*) \{ (e_H - e_L)^2 + 2(e_H - e_L)(1 - \underline{\phi}) e_L + (1 - \underline{\phi})^2 e_L^2 \}] \\ &\quad + (1 - p_F) [p_F^* e_L^2 + (1 - p_F^*)(1 - \underline{\phi})^2 e_L^2] \\ &= \mathcal{L}_{H,3} + 2p_F(1 - p_F^*)(e_H - e_L)(1 - \underline{\phi}) e_L + (1 - p_F^*)(1 - \underline{\phi})^2 e_L^2 \\ &= \mathcal{L}_{H,3} + 2p_F(1 - p_F^*)(e_H - e_L)(1 - \underline{\phi}) e_L + \mathcal{L}_{L,3} - p_F^* e_L^2. \end{aligned}$$

Hence $\mathcal{L}_{H,4} > \mathcal{L}(m_H^T, e_H) = p_F^* e_H^2$ holds at $\phi = \underline{\phi}$ if $\mathcal{L}_{H,3} + \mathcal{L}_{L,3} > p_F^*(e_H^2 + e_L^2)$. Using (17) and (22), this condition can be easily verified.

□

E Proof of Proposition 6

E.1 Case $p_F < p_F^*$

For $p_F < p_F^*$, the statement of the proposition is a direct consequence of the proof of Proposition 2. There we have shown that each type of bank $\tau \in \mathcal{T} \setminus \{0\}$ prefers 0 with $f(0) = 0$ to m_τ^T with $f(m_\tau^T)$, provided that $p_F < p_F^*$. Thus each of these central-bank types has lower losses under opacity than under transparency. Moreover, type 0's losses are unaffected by the transparency regime. Consequently, expected social losses are lower under opacity for $p_F < p_F^*$.

E.2 Case $p_F > p_F^*$

The case with $p_F > p_F^*$ is more intricate, because the equilibria under opacity are not unique in general. We proceed by showing that any potential equilibrium under opacity yields higher losses compared to the transparency solution. While it is unclear for which parameter constellations these potential equilibria exist (if they exist at all), we show that, if they existed, they would definitely lead to higher social losses over and against the equilibrium under transparency.

First we show that semi-separating equilibria with $m_L^O = 0$ and $m_H^O > 0$ can never be superior to the transparency solution. In the proof of Proposition 2, we have shown that type L 's losses are lower for m_L^T than for 0 if $f(m_L^T) = e_L$, $f(0) = 0$, and $p_F > p_F^*$. Type H 's losses can never be lower in a semi-separating equilibrium with $m_L^O = 0$ compared to transparency, as the money growth chosen under transparency minimizes losses, given that $f(m) = e_H$. Obviously, losses for type 0 are identical under transparency and opacity. As losses are weakly higher under opacity for all types and strictly higher for some, expected social losses are strictly lower under transparency.

Second, we note that the fully separating equilibrium where all central banks choose the same money growth rates as under transparency is the fully separating equilibrium with the lowest social losses. Consequently, social losses under transparency are weakly lower over and against opacity under any fully separating equilibrium. For $p_F^* < p_F < \hat{p}_F$,

they are strictly lower under transparency irrespective of which equilibrium is chosen under opacity. This is a consequence of Proposition 3, which states that equilibria where all types make the same choices as under transparency do not exist under opacity for $p_F < \hat{p}_F$.

Third, it remains to be shown that semi-separating equilibria with $0 < m_L^O = m_H^O$ would yield higher losses compared to the transparency solution. For such a semi-separating equilibrium $f(m_L^O) = f(m_H^O) = (\rho_L e_L + \rho_H e_H)/(\rho_L + \rho_H) = 2(\rho_L e_L + \rho_H e_H) = \hat{\mathcal{E}}$, where we have utilized $\rho_H + \rho_L = 1/2$. In equilibrium, type L 's losses would amount to

$$\mathcal{L}_{L,1} = p_F \mathcal{L}(m_L^O, e_L) + (1 - p_F) \mathcal{L}(m_L^O, \hat{\mathcal{E}})$$

and type H 's losses would be

$$\mathcal{L}_{H,1} := p_F \mathcal{L}(m_L^O, e_H) + (1 - p_F) \mathcal{L}(m_L^O, \hat{\mathcal{E}}).$$

Under transparency, type L 's losses are

$$\mathcal{L}_{L,2} := \mathcal{L}(m_L^T, e_L) = p_F^* e_L^2$$

and type H 's losses are given by

$$\mathcal{L}_{H,2} := \mathcal{L}(m_H^T, e_H) = p_F^* e_H^2.$$

A semi-separating equilibrium where L and H pool would yield higher expected social costs than the transparency solution, if $\rho_L(\mathcal{L}_{L,1} - \mathcal{L}_{L,2}) + \rho_H(\mathcal{L}_{H,1} - \mathcal{L}_{H,2}) > 0 \forall m$. It is straightforward to verify that the value of m_L^O that minimizes the left-hand side of this inequality is $m_{\hat{\mathcal{E}}}^T$. Evaluating the left-hand side of the above inequality for this value,

we obtain

$$\begin{aligned}
& \rho_L(\mathcal{L}_{L,1} - \mathcal{L}_{L,2}) + \rho_H(\mathcal{L}_{H,1} - \mathcal{L}_{H,2}) \\
&= \rho_L \left[p_F \left(p_F^* e_L^2 + (1 - p_F^*) (e_L - \hat{\mathcal{E}})^2 \right) + (1 - p_F) p_F^* \hat{\mathcal{E}}^2 - p_F^* e_L^2 \right] \\
&\quad + \rho_H \left[p_F \left(p_F^* e_H^2 + (1 - p_F^*) (e_H - \hat{\mathcal{E}})^2 \right) + (1 - p_F) p_F^* \hat{\mathcal{E}}^2 - p_F^* e_H^2 \right] \\
&= \frac{1}{2} (1 - p_F) p_F^* \hat{\mathcal{E}}^2 + \rho_L \left[p_F (1 - p_F^*) (e_L - \hat{\mathcal{E}})^2 - (1 - p_F) p_F^* e_L^2 \right] \\
&\quad + \rho_H \left[p_F (1 - p_F^*) (e_H - \hat{\mathcal{E}})^2 - (1 - p_F) p_F^* e_H^2 \right] \\
&= \frac{1}{2} (1 - p_F) p_F^* \hat{\mathcal{E}}^2 + \rho_L \left[p_F (1 - p_F^*) (e_L^2 - 2e_L \hat{\mathcal{E}} + \hat{\mathcal{E}}^2) - (1 - p_F) p_F^* e_L^2 \right] \\
&\quad + \rho_H \left[p_F (1 - p_F^*) (e_H^2 - 2e_H \hat{\mathcal{E}} + \hat{\mathcal{E}}^2) - (1 - p_F) p_F^* e_H^2 \right] \\
&= \frac{1}{2} (1 - p_F) p_F^* \hat{\mathcal{E}}^2 + (p_F - p_F^*) [\rho_L e_L^2 + \rho_H e_H^2] \\
&\quad + p_F (1 - p_F^*) \left[\frac{1}{2} \hat{\mathcal{E}}^2 - 2(\rho_L e_L + \rho_H e_H) \hat{\mathcal{E}} \right] \\
&= \frac{1}{2} (1 - p_F) p_F^* \hat{\mathcal{E}}^2 + (p_F - p_F^*) [\rho_L e_L^2 + \rho_H e_H^2] - \frac{1}{2} p_F (1 - p_F^*) \hat{\mathcal{E}}^2 \\
&= (p_F - p_F^*) [\rho_L e_L^2 + \rho_H e_H^2 - 2\rho_H^2 e_H^2 + 4\rho_L \rho_H e_L e_H - 2\rho_L^2 e_L^2] \\
&= (p_F - p_F^*) [\rho_L (1 - 2\rho_L) e_L^2 + \rho_H (1 - 2\rho_H) e_H^2 + 4\rho_L \rho_H e_L e_H] \\
&= 2(p_F - p_F^*) \rho_H \rho_L (e_H + e_L)^2,
\end{aligned}$$

where we have applied (13), $\hat{\mathcal{E}} = 2(\rho_L e_L + \rho_H e_H)$, and $\rho_L + \rho_H = \frac{1}{2}$. $2(p_F - p_F^*) \rho_H \rho_L (e_H + e_L)^2$ is positive if $p_F > p_F^*$. Consequently, transparency yields strictly lower losses than any semi-separating equilibrium that might exist.

To sum up, transparency is strictly superior to opacity for $p_F^* < p_F < \hat{p}_F$. For $p_F \geq \hat{p}_F$, transparency and opacity will be equivalent with regard to welfare if the equilibrium outlined in Proposition 3 is chosen. If another equilibrium is chosen, transparency will be strictly more desirable than opacity from the aggregate welfare perspective.

□

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