Learning by Sharing: Monetary Policy and Common Knowledge

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Abstract

A common view states that central bank releases decrease central banks' own information about the economy and are harmful if about inefficient disturbances, such as cost-push shocks. This paper shows how neither is true in a micro-founded macroeconomic model in which households and firms learn from central bank releases and the central bank learns from the observation of firm prices. Central bank releases make private sector and central bank expectations closer to common knowledge. This helps transmit dispersed information between the private sector and the central bank. As a result, the release of additional central bank information decreases the central bank's own uncertainty and can be beneficial, irrespective of the efficacy of macroeconomic fluctuations. A calibrated example suggests that the benefits of disclosure are substantial.

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1 Introduction

Good policy requires accurate information about the state of the economy. To set interest rates correctly, a policymaker needs to know whether a demand or a supply shock has hit the economy, what the size of the shock was, and what the private sector thinks of it. All are important determinants of the policymaker's choices. At the same time, modern-day

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policymakers also disclose a torrent of information. For example, members of the Board of the US Federal Reserve and Senior Treasury Staff speak, on average, nine times per week publicly about their own views about the state of the economy.[1]

As a result of these disclosures, a two-sided flow of information arises. On the one hand, policymakers devote considerable resources to learning about the state of the economy from private sector actions, such as prices. On the other hand, such private sector actions themselves reflect people's imperfect information about the economy, and are often informed and influenced by policymaker announcements.

In this paper, I study the consequences of this two-sided flow of information for the social value of policymaker releases.[2] To do so, I introduce imperfect information and higher-order uncertainty between households, firms, and a central bank in an otherwise standard macroeconomic model with monopolistic competition and nominal frictions. In the model, higher-order uncertainty arises from non-nested information about common disturbances. But crucially, both firms and the central bank also learn from each other's actions: The central bank learns about the private sectors' information from the observation of firms' prices, and the private sector learns about the central bank's information from the central bank's disclosures. The central bank uses its private information and that which it learns to set monetary policy.

My contribution is to show that central bank disclosure enhances the efficacy of monetary policy within this framework. Because of private sector and the central bank uncertainty about each other's information, disclosure not only provides more information to the private sector, but also increases the amount of common information. This increases what the central bank knows about private sector expectations, what the central bank knows about private sector expectations of its own beliefs, and so on. I detail how such decreases in higher-order uncertainty increase what the central bank knows about private sector responses to shocks and simplifies the central bank's own inference problem when it learns from firms' prices. As a result, I show that disclosure improves monetary policy's capacity to achieve the first best.

My results qualify two prevalent theories of the costs of central bank disclosure: (*i*) that disclosure can be socially costly since it increases firms' responses to inefficient shocks, such as cost-push shocks (e.g. Angeletos and Pavan, 2007; Paciello and Wiederholt, 2013; Angeletos *et al.*, 2016); and (*ii*) that disclosure decreases central banks' own information about the state of the economy by decreasing the information content of prices, and hence leads to worse

[1]This is based on Bloomberg news summary data. The precise number of releases is 457 in 2016, or nine times per working week. These values include speeches, comments, and documents by the President, Federal Reserve Presidents, senior US Treasury officials, and members of the CEA and the CBOE.

[2]A considerable debate exists about the social value of public policymaker information. This includes *inter alia* Morris and Shin (2002, 2005), Hellwig (2005), Svensson (2006), Angeletos and Pavan (2007), Gosselin *et al.*, 2007, James and Lawler (2011), Paciello and Wiederholt (2013), and Angeletos *et al.* (2016). This debate has, however, mainly abstracted from the two-sided information flow that is the focus of this paper.

monetary policy (e.g. Morris and Shin, 2005; Amador and Weill, 2007 and 2010).

By contrast, in my model, where disclosure decreases higher-order uncertainty between the private sector and the central bank, these costs can be overcome. Indeed, in a calibrated, extended version of my model that introduces higher-order uncertainty into the baseline New Keynesian framework, I find that disclosure decreases welfare losses by between 27 and 33 percent relative to the complete opacity baseline.[3] This depends on whether cost-push or productivity shocks drive the economy, and it is in each case caused by an increase in the efficacy of monetary policy. Around 16 percentage points of these welfare benefits are caused solely by the increase in the informativeness of prices leading to better monetary policy.

First, imagine the economy is driven only by an inefficient cost-push shock. On the one hand, additional central bank disclosure increases firms' responses to the inefficient shock. But, on the other hand, it also increases the central bank's information about firms' expectations, as firms use the central bank's disclosure when forming their own beliefs. This, in turn, allows the central bank to better offset firms' responses to the shock, as it knows more about them. I show how the latter effect can dominate the former, and discuss the important role that the presence of nominal (non-information) frictions play for this result.

Second, my results also qualify the common concern about central bank disclosures that they crowd out private sector information from market outcomes, such as prices.[4] All else equal, this would lead to less informed monetary policy and hence to potentially worse welfare outcomes. While the baseline model allows for this mechanism, in equilibrium its effect is overcome by the capacity of disclosure to alleviate a particular identification problem faced by the central bank when it is uncertain about private sector expectations.

Consider the case in which the central bank observes constant prices from one period to the next. This observation could be either due to firms receiving private information in line with their prior, or due to all firms receiving different information but expecting the central bank to alter monetary policy in response such that prices remain constant. Disclosure solves this identification problem. By making the central bank's own information, and hence beliefs, common knowledge, disclosure offers the distinction between the two options. As a result, central bank disclosure can decrease uncertainty for everyone, even the central bank itself.

To keep my analysis tractable, the baseline model abstracts from household imperfect information, the signaling role of monetary policy, and limits higher-order uncertainty by assuming one-period perfect state verification. I relax these assumptions when I turn to a

[3] I throughout measure welfare losses in terms of life-time consumption (Lucas, 1987).

[4] Besides the aforementioned literature, see also, for example, Broadbent (2013), Kohn (2005), Issing (2005), and the discussion in Woodford (2005) and Reis (2013) for such concerns voiced by policymakers. The related literature section contains additional references on the learning externality of public information that exists in markets in which agents learn from prices.

calibrated, extended version of my model that attempts to provide a quantitative first pass at the strength of the aforementioned benefits of disclosure. This, in effect, renders the extended model into an amended version of the New Keynesian model studied in Lorenzoni (2009). Crucially, and in departure from Lorenzoni (2009), or its extensions in Nimark (2014) and Melosi (2016), the central bank and the private sector here have non-nested information sets.

The solution of the model poses technical difficulty due to the infinite regress of expectations that arises when agents need to "forecast the forecasts of others" (Townsend 1983). To address these difficulties, I extend the truncated state space solution method proposed in Nimark (2017) to the case with non-atomistic agents, such as a central bank. To calibrate the model, I rely on data on private sector and central bank forecast accuracy from the "Survey of Professional Forecasters" by the Philadelphia Federal Reserve Bank and the "Greenbook", respectively. I use numerical simulations to explore the quantitative implications of the model.

The calibrated model shows considerable benefits of central bank disclosure. When the economy is driven only by unobserved cost-push shocks, full disclosure decreases welfare losses by 27 percent under the optimal policy. Of this decrease, around 50 percentage points are due to the improvement in monetary policy caused by a decrease in higher-order uncertainty between the private sector and the central bank. The direct increase in firms' responses to the cost-push shock, by contrast, only increases welfare losses by 23 percentage points. The decrease in welfare losses is of a similar magnitude when the economy is instead driven only by productivity shocks. Specifically, disclosure decreases welfare losses by 33 percent under the optimal policy, of which 16 percentage points are due to improved monetary policy responses caused by an increase in the information content of prices.

My results and core informational assumptions are consistent with two salient empirical observations. First, despite substantial increases in central bank disclosure over the past two decades, there are no indications that central banks' ability to forecast the economy has deteriorated. The root mean-square error of the US Federal Reserve's one-quarter ahead inflation forecast is, for instance, 1.2 percent and 0.9 percent before and after it started to increase its transparency in February 1994 (see also Crowe, 2010).[5] Second, as documented in Blinder *et al.* (2008), among others, the increase in central bank disclosure that has occurred since the mid-1990s has substantially reduced private sector uncertainty about future interest

[5] A similar decrease occurred in the US Federal Reserve's one-year ahead GDP forecasts: the root-mean squared error fell from 1.9 to 1.6 percent. Equivalent results hold for other forecasting horizons as well as relative to an AR(1) estimated over each of the two sub-samples. Lastly, a similar increase in forecast accuracy has occurred for the private sector. The root mean-squared error of professional forecaster's one-quarter ahead inflation forecast fell from 2.2 percent before to 1.5 percent after the Federal Reserve increased its transparency in February 1994. My model is also consistent with this evidence. To compute the above numbers, I use forecast data from the Greenbook and the Survey of Professional Forecasters as well as first release realizations of the outcome variable. All are available from the Federal Reserve Bank of Philadelphia's website. The first sample extends from Jan 1970 to Jan 1994; the second from Apr 1994 to Dec 2010.

rates. This is consistent with disclosure leading to a broad-based decrease in higher-order uncertainty between the private sector and the central bank.

Finally, combined, my results illustrate the importance of private sector and policymaker uncertainty about each other's expectations for an accurate picture of the social value of policymaker releases. They, however, also hint at broader consequences of incomplete common knowledge for several macroeconomic policies which success depends on private sector knowledge of future policymaker actions. This includes among others the recent debate about the efficacy of central bank forward guidance (Werning, 2015; McKay *et al.*, 2016; Angeletos and Lian, 2018). As shown by, for example, Weale (2013), rather than decrease average future interest rate expectations *per se*, forward guidance has often simply created more common expectations between the private sector and the central bank. My results suggest that forward guidance through this mechanism increases the efficacy of subsequent monetary policy.

Related Literature: This paper is related to the recent debate about the social value of public information that has followed Morris and Shin's (2002) influential contribution. In particular, Hellwig (2005), Angeletos and Pavan (2007), and Angeletos *et al.* (2016) show that the social value of public releases depends critically on the efficacy of macroeconomic fluctuations in models with higher-order uncertainty *among* private sector agents. By contrast, this paper demonstrates that once we also account for the higher-order uncertainty that exists *between* the private sector and the policymaker, an invariable benefit of disclosure arises. One that holds irrespective of the efficacy of macroeconomic fluctuations.

Morris and Shin (2005) and Amador and Weill (2010) have relatedly proposed a stark "Paradox of Transparency".[6] This shows how central bank disclosure could be socially costly because it decreases the informativeness of prices by crowding out private information. Paradoxically, disclosure could thus end up increasing uncertainty for everyone, including the central bank itself. This paper, by contrast, demonstrates how disclosure can increase the informativeness of prices by alleviating a particular identification problem.

My paper shares the emphasis on the importance of higher-order expectations for the effects of monetary policy with Wiederholt (2017) and Angeletos and Lian (2018). Central to their respective contributions is that an absence of common knowledge *among* households and firms dampens the effects of prospective monetary policy. By contrast, I focus on how an absence of common knowledge *between* the private sector and the central bank can cause central bank disclosure to, all else equal, boost the efficacy of monetary policy.

Finally, this paper is related to the literature that studies the combined optimal use of

[6] See also Amato *et al.* (2002), Amato and Shin (2006), Wong (2008), Gaballo (2016), and the related work on the *learning externality* of public information in markets where agents also observe and learn from prices (see e.g. Vives, 1997; Amador and Weill, 2012; Gosselin *et al.*, 2008; and the summary in Veldkamp, 2011).

policymaker disclosure and the conditional use of policy instruments. Walsh (2007), Baeriswyl and Cornand (2010), and James and Lawler (2011) show how disclosure can be suboptimal since a policymaker can instead always condition his policy instrument on his information. By contrast, in this paper I show how the combined use of disclosure and instrument policy can arise as an optimal outcome. This occurs because information frictions exist alongside and interact with nominal frictions. Carlsson and Skans (2012) demonstrate the need for nominal frictions in imperfect information models to match the observed behavior of firms' prices.

Organization: The rest of this paper proceeds as follows. Section 2 presents the baseline model. Section 3 characterizes the equilibrium and the limit-cases in which the central bank can replicate the first best outcome. Sections 4 and 5 contain the main results that illustrate the welfare benefits of disclosure. Section 6 describes the extended version of the benchmark model, and Section 7 the numerical results that I obtain after calibrating it. I conclude in Section 8. Additional extensions and all proofs are contained in the Appendix.

2 A Baseline Model

2.1 Economic Environment

I start with a dynamic model with dispersed information and monopolistic competition. The model consists of a representative household, a continuum of firms, and a central bank. Each period is comprised of three stages. At the start of each period, firms pre-set prices based on imperfect information subject to a cost. After prices are set, the economy transitions to the second stage, where the central bank determines the money supply, in part based on its own imperfect information. The economy then transitions to the final stage, where all information that was previously unknown becomes publicly available. The representative household now meets with firms to produce what is demanded of firms' goods at stated prices. The wage adjusts to clear the labor market. Commodity markets open and the household consumes.

Households: A representative household has preferences given by the utility function,

$$\mathcal{U} = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\log\left(C_t\right) - \frac{1}{1+\eta} L_t^{1+\eta} \right], \tag{2.1}$$

where β denotes the household discount factor, C_t the consumption index at time t, L_t the number of hours worked by the household, and η parametrizes the Frisch elasticity of labor supply. The consumption index is comprised of

$$C_t = \left(\int_0^1 C_{it}^{\frac{\rho-1}{\rho}} di \right)^{\frac{\rho}{\rho-1}}, \quad P_t = \left(\int_0^1 P_{it}^{1-\rho} di \right)^{\frac{1}{1-\rho}}, \tag{2.2}$$

where C_{it} is the quantity the household consumes of the goods produced by firm $i \in [0,\, 1]$ and $\rho > 1$; P_t denotes the associated welfare-based price index and P_{it} the price set by firm i.

Because the representative household receives all profits and labor income in the economy, its per-period budget constraint is

$$\int_0^1 P_{it} C_{it} di + M_t^d \leq \int_0^1 \Pi_{it} di + W_t L_t + M_{t-1}^d + T_t^h, \tag{2.3}$$

where Π_{it} denotes the profits of firm $i \in [0, 1]$, M_t^d the household's demand for nominal balances, W_t the nominal wage, and T_t^h lump-sum nominal transfers. Household consumption is, in addition to (2.3), restricted by a cash-in-advance constraint after receiving nominal transfers,

$$\int_0^1 P_{it} C_{it} di \leq M_{t-1} + T_t^h, \quad T_t^h = M_t - M_{t-1}. \tag{2.4}$$

The representative household seeks to maximize its utility (2.1) subject to the per-period budget constraint (2.3) and the cash-in-advance constraint (2.4).

Firms: The production sector consists of a continuum of imperfectly informed firms $i \in [0,\, 1]$ that specialize in the production of differentiated goods, also indexed by $i \in [0,\, 1]$. The production function used by firms is linear,

$$Y_{it} = A_t L_{it}, \quad A_t = A_{t-1} \exp\left(\theta_t\right), \tag{2.5}$$

where L_{it} denotes the amount of labor input used and A_t common labor productivity with random innovation $\theta_t \sim \mathcal{N}\left(0, 1/\tau_\theta\right)$.

An individual firm's objective is to set its price P_{it} to maximize its own expectation of the household's valuation of its stream of profits, using the per-period discount factor $\beta\left(P_t C_t\right)^{-1}$. Profits at time t are given by

$$\Pi_{it} = \left(1 + T_t^s\right) P_{it} Y_{it} - W_t L_{it} - \frac{\psi}{2} \left(\frac{P_{it}}{P_{it-1}} - 1\right)^2 P_t Y_t, \tag{2.6}$$

where $1 + T_t^s$ is stochastic with mean $\frac{\rho}{\rho - 1}$ such that, in a symmetric equilibrium ($P_{it} = P_t$), a firm's mark-up over marginal cost $\mathcal{M}_t \equiv \frac{P_t}{W_t / A_t}$ follows[7]

$$\mathcal{M}_t = \frac{\rho}{\rho - 1} \frac{1}{1 + T_t^s} = \mathcal{M}_{t-1} \exp\left(\xi_t\right), \quad \xi_t \sim \mathcal{N}\left(0,\, 1/\tau_\xi\right). \tag{2.7}$$

I allow $\mathcal{M}_t$ to be random so as to accommodate mark-up (or cost-push) shocks.

[7]See, for example, Steinsson (2003) and Uhlig (2006).

Finally, separate from the cost associated with physical production, firms in (2.6) face a quadratic price-adjustment cost, as in Rotemberg (1982), where $\psi > 0$ denotes a parameter which measures the severity of the nominal friction.

Central Bank: Similar to an individual firm, the central bank makes its choices based on imperfect information about the state of the economy. As a starting point, I assume that it sets its policy instrument, the money supply, directly based on its own expectation about the two fundamental shocks, the productivity and the mark-up disturbance,

$$M_t^s = M_{t-1}^s \exp\left\{\phi_0 + \phi_\theta \mathbb{E}_t^{cb}\left[\theta_t\right] + \phi_\xi \mathbb{E}_t^{cb}\left[\xi_t\right]\right\}, \tag{2.8}$$

where ϕ_θ and ϕ_ξ denote the publicly known levels of policy activism and $\mathbb{E}_t^{cb}\left[\cdot\right]$ central bank expectations (described below). Monetary policy is thus characterized in terms of a commitment to a log-linear rule. This assumption by itself does not prevent policy from achieving the first best outcome because of the below log-quadratic specification of welfare. In fact, as I show in Section 3, the central bank can always attain the efficient outcome with (2.8) if it observes all shocks without error and firms do so as well.[8] Sections 4 to 7 demonstrate how my results carry over to other policy rules that also allow the central bank to replicate the efficient outcome under full information, such as when it instead responds to deviations of output from flex-price levels, or the level of the driving forces themselves. However, for the sake of brevity, I choose to adopt the simpler approach in (2.8) to start with.

Information Structure: At the start of each period, all firms and the central bank publicly observe previous period's realization of the driving forces of the economy $\mu_{t-1} \equiv \log \mathcal{M}_{t-1}$ and a_{t-1}, as well as previous period's money supply m_{t-1}.[9] In addition, firms and the central bank also observe noisy type-specific and public information about the innovations to these.

As a first pass, I assume that all firms observe the same firm-specific information, unknown to the central bank, which I refer to as firms' *private sector information*. I then later address the case in which each firm observes individual-specific signals. Firms' private sector information is summarized by the two noisy signals x_t^θ and x_t^ξ,

$$x_t^\theta = \theta_t + \epsilon_{xt}^\theta : \quad \epsilon_{xt}^\theta \sim \mathcal{N}\left(0, 1/\tau_x^\theta\right), \qquad x_t^\xi = \xi_t + \epsilon_{xt}^\xi : \quad \epsilon_{xt}^\xi \sim \mathcal{N}\left(0, 1/\tau_x^\xi\right), \tag{2.9}$$

where ϵ_{xt}^θ and ϵ_{xt}^ξ are independent of all other disturbances.[10]

[8] When the central bank can respond to all shocks within each period, then it can always accommodate (or offset) each shock perfectly. This, in turn, ensures that the economy in each period can track its flex-price, first best counterpart from a time-less perspective (see Section 3). A similar result would, of course, hold if the central bank were to respond directly to the level of the driving forces instead.

[9] As is standard, lower-case letters denote the logarithm of their uppercase counterparts.

[10] Notice that, because of one-period perfect state verification, observing signals of the *innovations* to the

In addition to their private sector information, firms observe two (potentially noisy) public signals ω_t^θ and ω_t^ξ sent by the central bank of its own private information about the innovations to labor productivity and price mark-ups,

$$\omega_t^\theta = z_t^\theta + \epsilon_{\omega t}^\theta : \quad \epsilon_{\omega t}^\theta \sim \mathcal{N}\left(0, 1/\tau_\omega^\theta\right), \qquad \omega_t^\xi = z_t^\xi + \epsilon_{\omega t}^\xi, \quad \epsilon_{\omega t}^\xi \sim \mathcal{N}\left(0, 1/\tau_\omega^\xi\right), \tag{2.10}$$

where z_t^θ and z_t^ξ denote the central bank's noisy private signals,

$$z_t^\theta = \theta_t + \epsilon_{zt}^\theta : \quad \epsilon_{zt}^\theta \sim \mathcal{N}\left(0, 1/\tau_z^\theta\right), \qquad z_t^\xi = \xi_t + \epsilon_{zt}^\xi : \quad \epsilon_{zt}^\xi \sim \mathcal{N}\left(0, 1/\tau_z^\xi\right). \tag{2.11}$$

The case of *full disclosure* is here equal to the limit $\tau_\omega^j \to \infty$ with $j = \{\theta, \xi\}$, while *complete opacity* is equivalent to the situation where the central bank's communication contains no valuable information, $\tau_\omega^j \to 0$. *Partial disclosure* refers to the interim case, $\tau_\omega^j \in \mathbb{R}_+$.[11]

Turning to the central bank, besides its own private information, the central bank also observes a noisy public signal of the economy-wide price level,

$$\bar{p}_t = p_t + \epsilon_{pt}, \quad \epsilon_{pt} \sim \mathcal{N}\left(0, 1/\tau_p\right), \tag{2.12}$$

where ϵ_{pt} is independent of all other disturbances for all t.

We can summarize the information structure by the following information sets:

$$\Omega_t^f = \{x_{t-j}, \, \omega_{t-j}, \, \bar{p}_{t-j}, \, a_{t-j-1}, \, \mu_{t-j-1}, \, m_{t-j-1}\}_{j=0}^{\infty} \tag{2.13}$$

$$\Omega_t^{cb} = \{z_{t-j}, \, \omega_{t-j}, \, \bar{p}_{t-j}, \, a_{t-j-1}, \, \mu_{t-j-1}, \, m_{t-j-1}\}_{j=0}^{\infty}, \tag{2.14}$$

where $x_t' \equiv \begin{bmatrix} x_t^\theta & x_t^\xi \end{bmatrix}$, $z_t' \equiv \begin{bmatrix} z_t^\theta & z_t^\xi \end{bmatrix}$, and $\omega_t' \equiv \begin{bmatrix} \omega_t^\theta & \omega_t^\xi \end{bmatrix}$. I denote firm and central bank expectations based on (2.13) and (2.14) by $\mathbb{E}_t^f[\cdot]$ and $\mathbb{E}_t^{cb}[\cdot]$, respectively.

2.2 Remarks on the Environment

The above economy includes three central features that differentiate it from workhorse models of monopolistic competition and imperfect information.

First, the central bank uses its noisy private information to set *both* monetary and disclosure policy. This differentiates the above economy from those in Angeletos and Pavan (2009),

driving forces θ_t and ξ_t is equivalent to observing signals of the *levels* of these a_t and $\mu_t = \log \mathcal{M}_t$.

[11] My chosen approach to model communication policy in (2.10) follows that of Cukierman and Meltzer (1986) and has been used extensively since. An advantage of this approach is that it allows for a meaningful discussion of different, intermediate levels of disclosure. This advantage, of course, rests on the central bank committing to a disclosure rule such as (2.10). Absent this commitment, the central bank could communicate anything following the realization of its private information, and the only values that would be consistent with equilibrium would be full or zero disclosure. I show below how my main results still remain valid in this case.

Paciello and Wiederholt (2013), Angeletos *et al.* (2016), among others. As I argue below, accounting for both means to use a central bank's noisy information is important, because it provides the basis for the two-sided informational interaction between the private sector and the central bank that is at the center of my analysis. On the one hand, it allows private sector firms to learn from the central bank's communication and use this information to better set prices. But, on the other hand, the central bank also itself has scope to learn from the observation of firms' prices and use this information to better set monetary policy.

Second, to start with, all firms in (2.13) observe the same firm-specific information, in contrast to the dispersed information assumption that is common in the literature. Following Svensson and Woodford (2003), (2.13) condenses all of firms' private sector information into one, common signal. This allows me to focus on the welfare consequences of the two-sided informational interaction between firms and the central bank, and abstract from the welfare consequences that dispersed information among firms itself causes (e.g. Hellwig, 2005). Although central bank disclosure has important consequences for the dispersion of firms' information, the mechanisms behind my result do not rest upon these. What is central for my results is only that firms observe *some information* (dispersed or common) that the central bank does not know but instead needs to learn from firms' prices.[12] As documented in e.g. Rudebusch and Williams (2008), central banks track private sector developments closely, to learn more about the driving forces of the economy. Section 4 to 7 show how my main results extend to the case in which each firm observes individual-specific information.

Finally, unlike models in the spirit of Lucas (1972), in which imperfect information serves as the only basis for the "stickinesss" of prices, the above economy features an additional nominal friction: the price adjustment cost ψ in (2.6). Carlsson and Skans (2012) document the need for nominal frictions in models of imperfect information to match the observed behavior of firms' prices (see also Auclert *et al.*, 2020). Lorenzoni (2009), Nimark (2008), and Melosi (2016) likewise study economies that feature both imperfect information and nominal frictions. I discuss the importance of this assumption for my results in Section 4 and 5, and in particular how it allows monetary policy to have real effects under full disclosure.[13]

[12] Models with a common noise component are also analyzed in Myatt and Wallace (2011), Hellwig *et al.* (2012), and Colombo *et al.* (2014). Although (2.9) is only imposed for tractability purposes, there are at least two reasons to expect a common noise component in agents' private information: (i) the observation of common, delegated news sources (Nimark and Pitschner, 2019); and (ii) commonalities in the cognitive mistakes that agents make when observing new information (e.g. Vives and Yang, 2017).

[13] As in Woodford (2002a), Hellwig (2005), Angeletos *et al.* (2016), and others, firms in (2.13) also *do not* observe the current value of the central bank's policy instrument. Firm prices are pre-set and made before the realization of the money supply. Section 7 demonstrates that my results are robust towards this assumption. All that is required is that the central bank's disclosure provides some truly new information about the central bank's private signals beyond what firms can learn from the observation of the central bank's policy instrument.

3 Equilibrium, Prices, and Social Welfare

I proceed to study the equilibrium of the economy. I focus on two equilibrium objects: firms' prices and the central bank's money supply. These are the same two equilibrium objects for which imperfect information, and hence the presence of two-sided informational interactions, matters directly. The remaining equilibrium quantities as well as wages are straightforward to derive and can be computed from (2.1), (2.2), (2.5), and (A.5) in the Appendix.

3.1 Characterization of Prices

To characterize firms' prices, I first solve the representative household's problem, imposing market clearing, to derive a relationship between the wage rate, output, and productivity in the economy. I then use this relationship to derive a simple expression for firms' prices. Throughout, I focus on log-linear approximations of agents' decision rules around the full-information non-stochastic steady state. Proposition 1 details firm's optimal prices.

Proposition 1. *Let ϕ_0 be set such that $\delta = \beta \mathbb{E}_t \left[\frac{M_t}{M_{t+1}} \right] < 1$. Then, the cash-in-advance constraint always binds, $m_t - p_t = y_t$,*[14] *and the linear equilibrium price for all $i \in [0, 1]$ is*

$$p_t = \nu_{-1} p_{t-1} + \nu_0 \mathbb{E}_t^f \left[m_t - a_t \right] + \nu_1 \mathbb{E}_t^f \left[\mu_t \right] \tag{3.1}$$

$$m_t = m_{t-1} + \phi_0 + \phi_\theta \mathbb{E}_t^{cb} \left[\theta_t \right] + \phi_\xi \mathbb{E}_t^{cb} \left[\xi_t \right], \tag{3.2}$$

where $\{\nu_{-1}, \nu_0\} \in [0, 1]$ with $\nu_{-1} = 0$, $\nu_0 = 1$ iff. $\psi = 0$, and $\frac{\partial \nu_0}{\partial \psi} < 0$ and $\frac{\partial \nu_{-1}}{\partial \psi} > 0$.

Proposition 1 provides an intuitive result. On the one hand, because of nominal frictions, firms' prices depend upon previous period's prices. On the other hand, because of their direct influence on firms' real marginal cost, firms' prices also depend upon firms' expectations about labor productivity, in addition to firms' expectations about current nominal demand (because of its influence on output and wages through the cash-in advance constraint).

3.2 Social Welfare Loss

We can use the characterization of firms' prices in Proposition 1 to study the normative properties of our economy. I take my criterion to be utilitarian welfare and analyze the *ex ante* utility of the representative household before knowledge of period zero shocks.

A second-order approximation around the flex-price full information steady state shows that the welfare losses obtained relative to the first-best frictionless case can be approximated

[14] Since the real resource cost of inflation is of second-order, the log-linearized resource constraint is simply $y_t = c_t$ (see Appendix A). As a result, the cash-in-advance constraint entails that $m_t - p_t = c_t = y_t$.

by $\mathcal{W} = \mathbb{E}_{-1} \sum_{t=0}^{\infty} \beta^t (y_t - a_t)^2$ (Appendix A). This shows how standard welfare expressions familiar from workhorse New Keynesian models with nominal frictions (e.g. Woodford, 2002b; Nistico, 2007; and Galí, 2008) extend almost immediately to the above economy.

We can further simplify $\mathcal{W}$, using the Law of Iterated Expectations combined with that $\mathbb{E}_{t-1} (y_t - a_t)^2$ is constant over time.[15]

Proposition 2. *Equilibrium welfare losses relative to the first best, frictionless case can be approximated by* $\mathcal{W} = \frac{1}{1-\beta}\mathbb{E}_{t-1} [y_t - a_t]^2$, *where* $y_t = m_t - p_t$ *and* $a_t = a_{t-1} + \theta_t$.

A convenient benchmark to compare subsequent optimal policies to is the special case in which firms and the central bank observe all fundamental shocks without error.[16] Combined, Proposition 1 and 2 show that welfare losses under full information equal[17]

$$\mathcal{W}^{full} = \frac{1}{1-\beta} \left\{ (1-\nu_0)^2 (\phi_\theta - 1)^2 \frac{1}{\tau_\theta} + [(1-\nu_0)\phi_\xi - \nu_1] \frac{1}{\tau_\xi} \right\}. \tag{3.3}$$

It follows that the optimal policy under full information is to set $\phi_\theta = \phi_\theta^{\star,full} = 1$ and $\phi_\xi = \phi_\xi^{\star,full} = \frac{\nu_1}{1-\nu_0} > 0$, and that the central bank under this optimal policy replicates the first best, flex-price outcome ($\mathcal{W}^{full} = 0$). This shows how one tenet of optimal monetary policy carries over to our economy. The central bank accommodates the efficient productivity shock and offsets the inefficient mark-up disturbance. However, unlike economies with price dispersion, due to for example dispersed information, the central bank here chooses to completely offset the mark-up shock under full information. By contrast, price dispersion would require the central bank to trade-off output and price stabilization, and thus to only partially offset the mark-up shock. Section 4 to 7 show how my main results also extend to this case.

Equipped with Proposition 1 and 2, we are now ready to turn to the costs and benefits of central bank disclosure.

4 Disclosure about Inefficient Disturbances

I start with a much discussed cost that arises from increased responses to *inefficient disturbances*, such as cost-push (or mark-up) shocks (e.g. Angeletos and Pavan, 2007; Paciello and Wiederholt, 2013; Angeletos *et al.*, 2016). In this section, I show how private sector and central bank uncertainty about each other's expectations can substantially modify this cost.

[15] Notice that both output $y_t = m_t - p_t$ and productivity a_t follow a Markov process of order one with white noise innovations (see 2.5, 3.1, and 3.2). As a result, all second-order moments based upon $t-1$ information are constant in equilibrium (Appendix A). See also footnote 17 for the derivation of the output gap.

[16] That is, the special case in which $\tau_x^j \to \infty$ and $\tau_z^j \to \infty$ for both $j = \{a, \mu\}$

[17] This follows immediately from the output gap being equal to $y_t - a_t = m_t - p_t - a_t = (1 - \nu_0)(\phi_\theta \theta_t + \phi_\xi \xi_t - \theta_t) - \nu_1 \xi_t + l.p.t$, where $l.p.t$ denotes previous period's $(t-1)$ terms.

4.1 Preliminaries

I consider the special case in which $\tau_\theta \to \infty$ and $\tau_p \to 0$. The former assumption allows me to focus on the inefficient fluctuations caused by the mark-up disturbance without having to also account for the efficient productivity shock. The latter assumption ensures that the central bank does not learn about firms' private sector information from the noisy observation of the price level. This simplifies the analysis. I extend my results to positive values of τ_p further below, while Section 5 deals with the productivity shock case.

4.2 The Cost of Disclosure

I start with the welfare cost of disclosure that arises from increased responses to inefficient disturbances. To see a stark example of this cost, suppose that the money supply is held fixed ($\phi_\xi = 0$). Proposition 1 shows that the output gap, the determinant of social welfare, in this case takes a particularly simple form,

$$\begin{aligned} y_t - a_t = m_t - p_t &= \phi_\xi \mathbb{E}_t^{cb}[\xi_t] - \nu_0 \mathbb{E}_t^f \left[\phi_\xi \mathbb{E}_t^{cb} \xi_t + \frac{\nu_1}{\nu_0}\xi_t\right] + l.p.t. && (4.1) \\ &= -\nu_1 \mathbb{E}_t^f[\xi_t] + l.p.t., && (4.2) \end{aligned}$$

where I abstract from last period terms ($l.p.t.$) irrelevant to current welfare and productivity is held constant at its steady state value ($a_t = 0$).[18] We conclude from Proposition 2 that the associated welfare losses are $\mathcal{W} = \frac{1}{1-\beta}\nu_1^2 \mathbb{V}\left[\mathbb{E}_t^f \xi_t\right]$. Equation (4.2) illustrates how additional central bank disclosure can be harmful for social welfare. Increases to τ_ω^ξ always increase $\mathbb{V}\left[\mathbb{E}_t^f \xi_t\right]$ and thus $\mathcal{W}$. Additional central bank disclosure increases firms' responses to the inefficient mark-up shock, causing further fluctuations in output, despite constant productivity. Indeed, as in Hellwig (2005) and Angeletos *et al.* (2016), because welfare losses of (4.2) increase monotonically in disclosure, complete opacity is optimal when the money supply is held fixed.

4.3 The Benefit of Disclosure

An increased responsiveness is a natural consequence of disclosure. However, despite this cost, disclosure can still be beneficial when the central bank is uncertain about firms' expectations, and hence their responses to the mark-up shock. A sharp example of this insight can be seen from the special case in which the central bank's private signal z_t^ξ perfectly reveals the mark-up disturbance ($\tau_z^\xi \to \infty$). Notice that the central bank in this case is still uncertain about firms' expectations, and thus their responses to the mark-up shock, because of the private

[18] I will henceforth abstract from last period terms in all derivations of welfare.

sector signal x_t^ξ. The output gap equation (4.1) now becomes

$$
\begin{aligned}
y_t - a_t &= \phi_\xi \mathbb{E}_t^{cb}\left[\xi_t\right] - \nu_0 \phi_\xi \mathbb{E}_t^f \left[\mathbb{E}_t^{cb} \xi_t\right] - \nu_1 \mathbb{E}_t^f \left[\xi_t\right] + l.p.t. \\
&= \phi_\xi \mathbb{E}_t^{cb}\left[\xi_t\right] - \left(\nu_0 \phi_\xi + \nu_1\right) \mathbb{E}_t^f \left[\xi_t\right] + l.p.t., \qquad (4.3)
\end{aligned}
$$

where I have used that $\mathbb{E}_t^f \left[\mathbb{E}_t^{cb} \xi_t\right] = \mathbb{E}_t^{cb}\left[\xi_t\right] = \xi_t$, because the central bank's private signal perfectly reveals the mark-up shock. (It will be useful to keep the remaining central bank expectation in 4.3 in terms of $\mathbb{E}_t^{cb}\xi_t$ rather than to collapse it to the fundamental ξ_t).

Because the central bank discloses a noisy version of its signal, we can further decompose firms' expectations in (4.3) into the associated central bank expectation and an error term,[19]

$$
\mathbb{E}_t^f\left[\xi_t\right] = b \mathbb{E}_t^{cb}\left[\xi_t\right] + e_t, \quad e_t \sim \mathcal{N}\left(0, \frac{\tau_x^\xi + \tau_\omega^\xi}{\left(\tau_\xi + \tau_x^\xi + \tau_\omega^\xi\right)^2}\right), \qquad (4.4)
$$

where $b \equiv \frac{\tau_x^\xi + \tau_\omega^\xi}{\tau_\xi + \tau_x^\xi + \tau_\omega^\xi} \in (0,1)$ measures *the commonality of expectations*, and e_t denotes a convex combination of the noise terms ϵ_{xt}^ξ and $\epsilon_{\omega t}^\xi$. Importantly, the commonality of expectations b increases in the precision of central bank disclosure τ_ω^ξ, while the variance of the error term e_t eventually vanishes. Inserting (4.4) into (4.3), we arrive at a key equation for the output gap:

$$
y_t - a_t = \left[\phi_\xi - \left(\nu_0 \phi_\xi + \nu_1\right) b\right] \mathbb{E}_t^{cb}\left[\xi_t\right] - \left(\nu_0 \phi_\xi + \nu_1\right) e_t + l.p.t. \qquad (4.5)
$$

Combined, (4.4) and (4.5) show that the central bank can always offset firms' increased responses to the mark-up shock that are caused by the central bank's own disclosure, by modifying the conditional use of its policy instrument. This is important.

Suppose the central bank sets $\phi_\xi = \frac{\nu_1}{1-\nu_0} b$ in (4.5). Then, all of firms' increased responses to the mark-up shock are fully offset by monetary policy (the term in brackets in 4.5 equals zero). Additional disclosure, in this case, only decreases the portion of firms' responses to the mark-up shock that are caused by information that is not spanned by the central bank's own, captured by the error term e_t in (4.5), and which the central bank hence cannot offset.[20] Additional disclosure as a result always improves welfare. Indeed, in the full disclosure limit, in

[19] We have that (Appendix B)

$$
\mathbb{E}_t^f\left[\xi_t\right] = w_x x_t + w_\omega \omega_t = \left(w_x + w_\omega\right) \xi_t + w_x \epsilon_{xt}^\xi + w_\omega \epsilon_{\omega t}^\xi,
$$

where $w_x = \frac{\tau_x^\xi}{\tau_\xi + \tau_x^\xi + \tau_\omega^\xi}$, $w_\omega = \frac{\tau_\omega^\xi}{\tau_\xi + \tau_x^\xi + \tau_\omega^\xi}$. It follows that $b = \frac{\tau_x^\xi + \tau_\omega^\xi}{\tau_\xi + \tau_x^\xi + \tau_\omega^\xi}$, $e_t \equiv w_x \epsilon_{xt}^\xi + w_\omega \epsilon_{\omega t}^\xi$, since we also have that $\mathbb{E}_t^{cb}\left[\xi_t\right] = \xi_t$. Finally, notice that the variance of the shock e_t equals $\mathbb{V}\left[e_t\right] = \frac{\tau_x^\xi + \tau_\omega^\xi}{\left(\tau_\xi + \tau_x^\xi + \tau_\omega^\xi\right)^2}$

[20] The next subsection discusses how my results extend to the important case in which the central bank's money supply also responds to the noise in the central bank's own disclosure $\epsilon_{\omega t}$.

which $\tau_\omega^\xi \to \infty$ and thus $\phi_\xi = \frac{\nu_1}{1-\nu_0}$ (b increases towards one as $\tau_\omega^\xi \to \infty$), this policy attains the first best outcome ($\mathcal{W} = \frac{1}{1-\beta}\mathbb{E}_{t-1}\left[y_t - a_t\right]^2 = 0$). We conclude that the optimal policy equals full disclosure $\tau_\omega^{\xi,\star} \to \infty$ combined with monetary policy set to its optimal full-information value $\phi_\xi^\star = \frac{\nu_1}{1-\nu_0} = \phi_\xi^{\star,full}$.

Using the dual approach to optimal policy, Proposition 3 extends these results to the general case, in which the central bank's signal is imperfect $\tau_z^\xi \in \mathbb{R}_+$.

Proposition 3. *The combined optimal policy with mark-up shocks is full disclosure $\tau_\omega^{\xi,\star} \to \infty$ and a monetary policy that undoes the nominal friction $\phi_\xi^\star = \frac{\nu_1}{1-\nu_0} > 0$. Increases in central bank disclosure increase the commonality of expectations between firms and the central bank.*

Proposition 3 states the first of our two main results. The proposition shows that full disclosure about an inefficient mark-up disturbance is optimal, irrespective of the precision of central bank and private sector information ($\tau_z^\xi \in \mathbb{R}_+$, $\tau_x^\xi \in \mathbb{R}_+$).

We can summarize the economic intuition behind this result, based on our previous discussion, as follows: On the one hand, the more precisely the central bank discloses its information, the more firms will respond to the mark-up shock. However, on the other hand, the more precisely the central bank discloses its information, the more firms will also use the central bank's disclosure to form their own expectations. This increases the commonality of expectations between firms and the central bank. This is crucial. The central bank can only counter the portion of firms' responses that are spanned by its own information; the portion that it knows about. Full disclosure allows the central bank to best offset firms' responses to the mark-up shock by maximizing this component. Put simply, by sharing its information, the central bank knows the most about private sector responses. This, in turn, makes disclosure optimal.

The above example in (4.4) and (4.5), in which the central bank's information is perfectly accurate $\tau_z^\xi \to \infty$, provides a sharp illustration of this insight. Indeed, the optimal policy in this case replicates the first best outcome. Clearly, with imperfect central bank information $\tau_z^\xi \in \mathbb{R}_+$ the optimal policy can no longer attain the unconstrained first best. But as Section 7 shows, even in such cases, full disclosure can meaningfully decrease welfare losses.

Finally, notice that by continuity full disclosure is not only beneficial at the optimal level of monetary policy $\phi_\xi^\star$. Indeed, similar steps to those that lead to Proposition 3 show that full disclosure is optimal as long as monetary policy responds sufficiently to central bank expectations. This will be important later to interpret the results of the quantitative model.

Corollary 1. *Let $\bar{\phi}_\xi \equiv \frac{\nu_1}{2-\nu_0}\frac{\tau_x^\xi+\tau_z^\xi}{\tau_\xi+\tau_x^\xi+\tau_z^\xi} < \phi_\xi^\star$. Then, if $\phi_\xi > \bar{\phi}_\xi$, full disclosure $\tau_\omega^\xi \to \infty$ is uniquely optimal. By contrast, complete opacity $\tau_\omega^\xi \to 0$ is optimal if $\phi_\xi \in \left(0, \bar{\phi}_\xi\right)$.*

4.4 Discussion

A stark feature of Proposition 3 is that the optimal monetary policy $\phi_\xi^\star$ is independent of the information friction. This follows from how monetary policy does not affect the prediction errors that firms make under full disclosure. Consider the output gap equation in (4.1):

$$\begin{aligned} y_t - a_t &= \left[\phi_\xi (1-\nu_0) - \nu_1\right] \mathbb{E}_t^{cb}[\xi_t] + \nu_0 \phi_\xi \left(\mathbb{E}_t^{cb}\xi_t - \mathbb{E}_t^f \mathbb{E}_t^{cb}\xi_t\right) \\ &+ \nu_1 \left(\mathbb{E}_t^{cb}\xi_t - \mathbb{E}_t^f \xi_t\right) + l.p.t., \end{aligned} \tag{4.6}$$

where I have subtracted and added $\nu_1 \mathbb{E}_t^{cb}[\xi_t]$ from the right-hand side. Equation (4.6) shows that for any partial disclosure $\tau_\omega^\xi \in \mathbb{R}_+$, the value of monetary policy ϕ_ξ that minimizes welfare losses $\mathcal{W} = \frac{1}{1-\beta}\mathbb{E}_{t-1}[y_t - a_t]^2$ differs from its full-information value ($\phi_\star^{full} = \frac{\nu_1}{1-\nu_0}$). This is because of the second term in (4.6), and is consistent with monetary policy responding to the extent of imperfect information. But now notice that, when the central bank fully discloses its information, $\mathbb{E}_t^f\left[\mathbb{E}_t^{cb}\xi_t\right]$ equals $\mathbb{E}_t^{cb}[\xi_t]$. With full disclosure, firms do not commit any prediction errors about future monetary policy. As a result, monetary policy becomes divorced from the information friction. We can therefore apply the certainty-equivalence result in Svensson and Woodford (2004), which show that monetary policy should be set to its full-information value.

This discussion also hints at the central role played by the price-adjustment cost $\psi > 0$ in Proposition 3. Notice that if we set ψ to zero, the important coefficient ν_0, determining the responsiveness of firms' prices to their expectations of the money supply in (3.1), tends toward one (Proposition 1). This, in turn, implies that the output gap in (4.6) becomes

$$\begin{aligned} y_t - a_t = m_t - p_t &= \left(\phi_\xi \mathbb{E}_t^{cb}\xi_t - \phi_\xi \mathbb{E}_t^f\left[\mathbb{E}_t^{cb}\xi_t\right]\right) - \nu_1 \mathbb{E}_t^f[\xi_t] + l.p.t. \\ &= m_t - \mathbb{E}_t^f[m_t] - \nu_1 \mathbb{E}_t^f[\xi_t] + l.p.t.. \end{aligned}$$

Thus, absent the price friction, full disclosure re-introduces classical dichotomy ($\mathbb{E}_t^f[m_t] = m_t$ since $\mathbb{E}_t^f\left[\mathbb{E}_t^{cb}\xi_t\right] = \mathbb{E}_t^{cb}[\xi_t]$). With $\psi = 0$ and full disclosure, changes to the money supply have no real effects on the economy, as prices fully adjust to the money supply in advance.

By contrast, for any non-zero nominal friction $\psi > 0$, full disclosure instead allows the central bank to best stabilize the economy. Because firms do not fully adjust their prices when $\psi > 0$, even under full disclosure, changes to the money supply always have real effects. This, in turn, allows the central bank to counter firms' responses to the mark-up shock in the case in which it knows the most about them, the case of full disclosure. In this sense, the bite of the nominal friction ψ is that it allows monetary policy to have real effects under disclosure.

This also highlights why Proposition 3 differs from several previous results in the literature (e.g. Hellwig, 2005; Angeletos *et al.*, 2016). In these papers, nominal frictions besides imperfect information are absent. This implies that additional disclosure only increases firms' responses to the inefficient shock and decreases the efficacy of prospective monetary policy. Complete opacity is thus optimal. Proposition 3 illustrates the sensitivity of such results to the presence of nominal frictions. Any nominal friction $\psi > 0$ instead makes full disclosure optimal. Carlsson and Skans (2012), among others, document the need for nominal frictions in models of imperfect information to match micro-data on firms' prices.[21]

4.5 Extensions

Dispersed Information: A noticeable feature of the economy considered so far is the absence of dispersed information. All firms observe the same firm-specific signal x_t^ξ. This simplifies my analysis by abstracting from the welfare consequences of dispersed firm information.

To see how Proposition 3 extends to the dispersed information case, consider the economy in which each firm instead observes the private signal $x_{it}^\xi = \xi_t + \epsilon_{ixt}^\xi$, where $\epsilon_{ixt}^\xi \sim \mathcal{N}\left(0, 1/\bar{\tau}_x^\xi\right)$ and $\mathbb{E}\left[\epsilon_{ixt}^\xi \epsilon_{jxs}^\xi\right] = 0$ for all $j \neq i$ and $s \neq t$. Furthermore, for tractability purposes, suppose that the share $\alpha \in (0,1)$ of all firms faces fixed prices indefinitely, while the share $1-\alpha$ can set their prices freely without paying the price adjustment cost.

Appendix B.4 shows that the price level for this economy equals

$$p_t = \nu_0 \bar{\mathbb{E}}_t^f \left[m_t\right] + \nu_1 \bar{\mathbb{E}}_t^f \left[\mu_t\right] + \nu_p \bar{\mathbb{E}}_t^f \left[p_t\right] + l.p.t., \tag{4.7}$$

where $\nu_0 \equiv (1-\alpha)(1+\eta)$, $\nu_1 \equiv 1-\alpha$, $\nu_p \equiv (1-\alpha)\eta$, and $\bar{\mathbb{E}}_t^f [\cdot] \equiv \frac{1}{1-\mu}\int_\mu^1 \mathbb{E}_{it}^f [\cdot]\, di$ denotes the average expectation taken across flexible price firms. Notice that (4.7) differs from (3.1) only due to term $\nu_p \bar{\mathbb{E}}_t^f [p_t]$. Iterating on (4.7) can be used to show that

$$y_t - a_t = m_t - p_t = \phi_\xi \mathbb{E}_t^{cb}[\xi_t] - \sum_{j=0}^{\infty} \nu_p^j \left(\nu_0 \phi_\xi \bar{\mathbb{E}}_t^{f,j+1}\left[\mathbb{E}_t^{cb}\xi_t\right] + \nu_1 \bar{\mathbb{E}}_t^{f,j+1}[\xi_t]\right) + l.p.t., \tag{4.8}$$

where $\bar{\mathbb{E}}_t^{f,j+1}[\cdot]$ is defined by the recursion $\bar{\mathbb{E}}_t^{f,j+1}[\cdot] \equiv \bar{\mathbb{E}}_t^f\left[\bar{\mathbb{E}}_t^{f,j}[\cdot]\right]$.

Similar steps to those that lead to Proposition 3 now show that full disclosure $\tau_\omega^{\xi,\star} \to \infty$ and $\phi_\xi^\star = \frac{\nu_1}{1-\nu_p-\nu_0} = \frac{1-\alpha}{\alpha} > 0$ minimize the variance of the output gap (Appendix B.4).[22] The only difference to Proposition 3 is the presence of ν_p in the denominator of $\phi_\xi^\star$. As in Proposition 3, full disclosure maximizes the central bank's information about firms' responses to the mark-up

[21] Auclert *et al.* (2020) show that nominal frictions are also needed in a model of imperfect information to match impulse response functions of aggregate consumption and inflation to those in the data.

[22] An informative special case is once more that in which the central bank has full information $\tau_z^\xi \to \infty$. In this case, the output gap in (4.8) collapses to $y_t - a_t = \left(\phi_\xi - \frac{\nu_0\phi_\xi - \nu_1}{1-\nu_p}\right)\xi_t + l.p.t.$, because $\bar{\mathbb{E}}_t^{f,j+1}\left[\mathbb{E}_t^{cb}\xi_t\right] = \mathbb{E}_t^{cb}\xi_t = \xi_t = \mathbb{E}_t^f \xi_t$. This shows that $\phi_\xi^\star = \frac{\nu_1}{1-\nu_p-\nu_0} = \frac{1-\alpha}{\alpha}$ minimizes the variance of the output gap.

shock. This time in part also by increasing the commonality of firms' expectations about the central bank: the higher-order expectations $\bar{\mathbb{E}}_t^{f,j+1}\left[\mathbb{E}_t^{cb}\xi_t\right]$ collapse to $\mathbb{E}_t^{cb}\xi_t$ under full disclosure. Thus, disclosure once more enables monetary policy to best counter firms' responses. Clearly, because of the dispersion in firms' information, social welfare now also depends on the cross-sectional dispersion of prices, in addition to the volatility of the output gap (e.g. Hellwig, 2005). Section 7 shows how my results extend to the case in which the central bank's policy also optimally internalizes its effects on the cross-sectional dispersion of prices.

Learning from Prices: I have so far simplified the exposition by assuming that $\tau_p \to 0$, so that the central bank does not learn about firms' private sector information from the noisy observation of the price level. However, none of the main insights depend critically on this assumption. Appendix B.4 shows how my results readily extend to the case in which the central bank learns about firms' information x_t^ξ from the price level; that is to the case where τ_p is positive. The central bank still optimally uses monetary policy as in the full information case, $\phi_\xi^\star = \frac{\nu_1}{1-\nu_0}$; and conditional on this value of ϕ_ξ, full disclosure is once more optimal because it increases central bank information. Identical results hold if the central bank instead observes an *exogenous* signal of firms' information x_t^ξ. I postpone the discussion of how disclosure affects the informativeness of the price level when $\tau_p > 0$ to the next section.[23]

Other Monetary Policy Rules: I conclude this section with studying the consequences of alternative monetary policy rules. While the monetary policy rule in (2.8) makes the analysis particularly convenient, it is not central to the main results from this section. For example, suppose that the central bank in (2.8) also responds to the noise in its own disclosure, so that

$$m_t = m_{t-1} + \phi_0 + \phi_\xi \mathbb{E}_t^{cb}\left[\xi_t\right] + \phi_\omega \epsilon_{\omega t}^\xi. \tag{4.9}$$

Then, full disclosure $\tau_\omega^{\xi,\star} \to \infty$ and $\phi_\xi^\star = \frac{\nu_1}{1-\nu_0}$ remain the optimal policy (Appendix B.4). In fact, the only difference is that the optimal value of ϕ_ω is not defined in (4.9), as the variance of the term noise $\epsilon_{\omega t}^\xi$ tends to zero with full disclosure. The reason is intuitive. The more the central bank knows about firms' responses to the mark-up shock, the better it can offset them. Yet, full disclosure invariably maximizes the central bank's information about firms' responses. Full disclosure results in the lowest possible weight on firms' private sector information. Thus, even if the central bank's policy instrument could respond to the noise in the central bank's own disclosure, it would not gain from doing so. Appendix B.4 also shows

[23]Finally, notice that because my results hold for any amount of noise $\tau_p > 0$ the results also extend to the central bank limited attention case: that is, to the case in which we interpret the noise ϵ_{pt} in the central bank's signal of the price level (2.12) to be due to limited attention. The only requirement is that attention costs are increasing and convex. Appendix B.4 shows how the results also immediately extend to the case in which increased central bank attention decreases the noise in a direct signal of firms' private sector information.

that Proposition 3 extends to the case in which the central bank directly targets the variable that causes fluctuations in the output gap, the price level.

Finally, notice that, in this section, the welfare losses that have remained under the optimal policy are only due to the residual errors that exist in central bank beliefs about firms' expectations; those which arise because the central bank does not perfectly know firms' private sector information. The next section demonstrates how central bank disclosure also decreases this residual uncertainty by increasing the information content of the price level.

5 Disclosure and the Paradox of Transparency

I now shift the focus from increased responses to inefficient disturbances to another influential cost of disclosure. This cost stipulates that one of the consequences of central bank disclosure is that the central bank has to rely on less informative prices to steer monetary policy (e.g. Morris and Shin, 2005 and Amador and Weill, 2010).[24] In this section, I show how private sector and central bank uncertainty about each other's expectations combines with the conditional use of monetary policy to also qualify this second cost.

5.1 Equilibrium Prices

Since this cost does not depend on the precise nature of fluctuations, I focus on the special case in which only productivity shocks drive the economy ($\tau_\xi \to \infty$). This allows me to cleanly separate the effects of disclosure from those discussed in the previous section. I solve for the set of symmetric linear Bayesian equilibria when $\tau_\xi \to \infty$ using the method of undetermined coefficients. I then use this solution to show how disclosure modifies the informativeness of prices. Proposition 4 details the outcome of the first step, using Proposition 1.[25]

Proposition 4. *The set of symmetric linear equilibria with productivity shocks is non-empty, and is comprised of firm prices and associated central bank money supply equal to*

$$p_t = \nu_{-1} p_{t-1} + \nu_0 (m_{t-1} - a_{t-1}) + \mathtt{k}_0 x_t^\theta + \mathtt{k}_1 \omega_t^\theta + \mathtt{k}_2 \underline{p}_t \tag{5.1}$$

$$m_t = m_{t-1} + \mathtt{q}_0 z_t^\theta + \mathtt{q}_1 \underline{p}_t, \tag{5.2}$$

[24] See also Amato *et al.* (2002), Amato and Shin (2006), and the related work on the *learning externality* of additional public information in markets where agents learn from prices (see, for example, Vives, 1997; Amador and Weill, 2012; Vives, 2017; and the summary in Veldkamp, 2011.)

[25] Proposition 4 establishes the existence of a linear equilibrium. However, because of the potential for firms and the central bank to learn from each others actions, the economy can admit multiple linear equilibria (either one or three). This multiplicity introduces a well-known impediment to any welfare analysis. One has to decide on which equilibrium agents coordinate, and if so what the comparative statics are in each case. I circumvent this problem in Appendix C by focusing on the highest welfare equilibrium, in line with Harsanyi and Selten's (1988) *"Pay-off Dominance Argument"* (see also Amador and Weill, 2010). Appendix C shows how neither of my results depend crucially on the exact equilibrium selection device used. All hold in areas of the parameter space where the equilibrium is unique.

where $\underline{p}_t \equiv \theta_t + \epsilon^\theta_{xt} + \frac{1}{\mathtt{k}_0}\epsilon_{pt}$, $\{\mathtt{k}_j(\mathtt{k}_0, \mathtt{q}_0), \mathtt{q}_1(\mathtt{k}_0, \mathtt{q}_0)\} \in \mathbb{R}$ *for* $j = \{1, 2\}$, *and* $\mathtt{k}_0$ *and* $\mathtt{q}_0$ *solve*

$$\mathtt{k}_0 = \nu_0 \tau^\theta_x \frac{\mathtt{q}_0 \tau^\theta_z - \left(\tau^\theta_\omega + \tau^\theta_z\right)}{\left(\tau^\theta_\omega + \tau^\theta_z\right)\left(\tau_\theta + \tau^\theta_x\right) + \tau^\theta_\omega \tau^\theta_z}, \quad \mathtt{q}_0 = \phi_\theta \frac{\tau^\theta_z \left(\tau^\theta_x + \tau_p \mathtt{k}_0^2\right)}{\left(\tau^\theta_x + \tau_p \mathtt{k}_0^2\right)\left(\tau_\theta + \tau^\theta_z\right) + \tau^\theta_x \tau_p \mathtt{k}_0^2}, \tag{5.3}$$

where all solutions of $\mathtt{k}_0 \in (-\nu_0,\, 0)$ *and* $\mathtt{q}_0 \in (0,\, 1)$ *when* $\phi_\theta \in (0, 1)$.

The coefficients $\mathtt{k}_0$ and $\mathtt{q}_0$ are central to this section. Indeed, we can collect the various elements that make up the noisy signal of the price level $\bar{p}_t = p_t + \epsilon_{pt}$ and are also observed by the central bank on the left-hand side of (2.12) using (5.1), and then divide by $\mathtt{k}_0$ to arrive at

$$\frac{1}{\mathtt{k}_0}\left[\bar{p}_t - \nu_{-1}p_{t-1} - \nu_0\left(m_{t-1} - a_{t-1}\right) - \mathtt{k}_1 \omega^\theta_t - \mathtt{k}_2 \underline{p}_t\right] = x^\theta_t + \frac{1}{\mathtt{k}_0}\epsilon_{pt}.$$

This demonstrates that the observation of the noisy signal of the price level is equivalent to $x^\theta_t + \frac{1}{\mathtt{k}_0}\epsilon_{pt}$, or $\theta_t + \epsilon^\theta_{xt} + \frac{1}{\mathtt{k}_0}\epsilon_{pt}$. I equate this signal to $\underline{p}_t$ in Proposition 4. When the variance of the noise term $\frac{1}{\mathtt{k}_0}\epsilon_{pt}$, equal to $\mathtt{k}_0^{-2}\tau_p^{-1}$, is small, the price level conveys a precise signal of firms' private sector information to the central bank, and vice versa when $\mathtt{k}_0^{-2}\tau_p^{-1}$ is large.

The two coupled equations in (5.3) describe the fixed point problem, which connects the equilibrium weight that firms attach to their private sector information $\mathtt{k}_0$ in (5.1), to the weight that the central bank itself accords to its own private information $\mathtt{q}_0$, and to the variance of the noise in the price level $\mathtt{k}_0^{-2}\tau_p^{-1}$. The more weight firms attach to their private sector information (that is, the more negative $\mathtt{k}_0$ is), the more informative the price level, all else equal, becomes to the central bank (that is, the smaller $\mathtt{k}_0^{-2}\tau_p^{-1}$ becomes).

5.2 Disclosure and the Informativeness of Prices

We are now ready to characterize how disclosure τ^θ_ω affects the informativeness of the price level $\mathtt{k}_0^2\tau_p$. Indeed, it follows straightforwardly from Proposition 4 that disclosure can either *decrease* or *increase* the informativeness of the price level, depending on monetary policy ϕ_θ.

Proposition 5. *Increases in central bank disclosure* $\tau^\theta_\omega \in \mathbb{R}_+$ *either decrease or increase the informativeness of the price level* $\tau_p \mathtt{k}_0^2$, *and hence the central bank's own information about the productivity shock* θ_t. *This depends on whether* $\phi_\theta \lesseqgtr \hat{\phi}_\theta \equiv \frac{\tau_\theta + \tau^\theta_z + \alpha}{\tau_\theta + \tau^\theta_z + \tau^\theta_x} < 1$, *where* $\alpha = \frac{\tau^\theta_x \tau_p \mathtt{k}_0^2}{\tau^\theta_x + \tau_p \mathtt{k}_0^2}$.

Proposition 5 introduces the key statistic $\hat{\phi}_\theta \equiv \frac{\tau_\theta + \tau^\theta_z + \alpha}{\tau_\theta + \tau^\theta_z + \tau^\theta_x}$. If the responsiveness of monetary policy ϕ_θ is below this value, additional disclosure reduces the informativeness of prices, and thereby increases central bank uncertainty. The reason is an often studied learning externality (e.g. King, 1982; Vives, 1997; Morris and Shin, 2005; Amador and Weill, 2010, 2012).

When deciding on how much to respond to their private sector information, firms do not internalize the informativeness of the price level, and hence how much the central bank is able to learn from it. Because of this externality, when the central bank discloses additional information, firms optimally choose to rely less on their own private sector information when forming their expectations and more on the information from the central bank, which the central bank already knows. This decreases the informativeness of the price level.

Thus, when $\phi_\theta < \hat{\phi}_\theta$, a fundamental trade-off arises between, on the one hand, firms' uncertainty (and thus their ability to correctly set prices), and, on the other hand, the central bank's own information (and hence it's capacity to optimally set monetary policy).

However, Proposition 5 also shows that this paradox of transparency is overturned if the responsiveness of monetary policy ϕ_θ is instead set above the critical value $\hat{\phi}_\theta$.

We can discern the presence of the offsetting effect that, all else equal, increases the informativeness of the price level from (2.12) and Proposition 1. Combined, these show that

$$\bar{p}_t = \nu_0 \mathbb{E}_t^f \left[\phi_\theta \mathbb{E}_t^{cb} \theta_t - \theta_t \right] + l.p.t + \epsilon_{pt} = \nu_0 \left(\phi_\theta v_x - w_x \right) x_t^\theta + \text{ public signals,} \tag{5.4}$$

where w_x and v_x denote the weight on private sector information x_t^θ in firms' expectations about productivity $\mathbb{E}_t^f [\theta_t]$ and central bank expectations $\mathbb{E}_t^f \left[\mathbb{E}_t^{cb} \theta_t \right]$, respectively ($w_x > v_x > 0$).[26] "Public signals" here also capture last period terms (*l.p.t.*). It follows from (5.4) that the total weight $\mathtt{k}_0$ on private sector information x_t^θ in (5.3) can also be written as

$$\mathtt{k}_0 = \nu_0 \left(\phi_\theta v_x - w_x \right) < 0. \tag{5.5}$$

The learning externality is immediately visible from (5.4) and (5.5). On the one hand, the more precisely the central bank discloses its information, the less firms use their private sector information when forming their expectations about productivity. Disclosure decreases w_x, and thus makes $\mathtt{k}_0 = \phi_\theta v_x - w_x$ less negative (i.e. less informative) when ϕ_θ is small. However, on the other hand, the more precisely the central bank discloses its information, the less firms will also use their private sector information when forming their beliefs about central bank expectations; v_x also decreases with central bank disclosure. As a result, although both weights on private sector information decrease, $\mathtt{k}_0 = \phi_\theta v_x - w_x$ can become more negative when ϕ_θ is large. Disclosure in this case increases the informativeness of the price level.[27]

The intuition behind this second effects is as follows: The central bank observes a signal, the

[26]Because of the linear-normal information structure, we have that

$$\mathbb{E}_t^f [\theta_t] = w_x x_t^\theta + \text{weights} \times \text{public signals}, \quad \mathbb{E}_t^f \left[\mathbb{E}_t^{cb} \theta_t \right] = v_x x_t^\theta + \text{weights} \times \text{public signals},$$

where $w_x = \frac{\tau_\omega^\theta + \tau_z^\theta}{(\tau_\omega^\theta + \tau_z^\theta)(\tau_\theta + \tau_x^\theta) + \tau_\omega^\theta \tau_z^\theta}$ and $v_x = \frac{\tau_x^\theta \tau_z^\theta}{(\tau_\omega^\theta + \tau_z^\theta)(\tau_\theta + \tau_x^\theta) + \tau_\omega^\theta \tau_z^\theta} \frac{\tau_z^\theta \left(\tau_x^\theta + \tau_p \mathtt{k}_0^2 \right)}{\left(\tau_x^\theta + \tau_p \mathtt{k}_0^2 \right)(\tau_\theta + \tau_z^\theta) + \tau_x^\theta \tau_p \mathtt{k}_0^2}$.

[27]An extreme example arises when firms' private sector information is perfectly accurate $\tau_x^\theta \to \infty$. In this case, w_x is always equal to one in (5.5), while $v_x \in (0, 1)$ because of the noise in the central bank's information. As a result, disclosure in this case always increases the informativeness of the price level by decreasing v_x.

price level, that in part reflect firms' expectations about the central bank's own actions. This makes the central bank uncertain about whether any movement in firms' prices reflects private sector information about productivity or (potentially incorrect) private sector expectations about future central bank actions. *Central bank disclosure solves this identification problem.*

Indeed, firms' expectations about productivity and firms' expectations about future monetary policy offset each other. The former has a negative effect on firms' prices, while the latter has a positive effect. That is, why w_x and v_x enter with opposite signs in (5.4). By making the central bank's own information, and hence beliefs and plans, common knowledge, disclosure offers the central bank a clearer view of firms' private sector information about productivity; one that is uncorrupted by firms' (potentially incorrect) expectations of the central bank. It does so because disclosure not only increases firms' information about the central bank, but also importantly central bank information about firms' expectations. Indeed, when $\phi_\theta > \left(\hat{\phi}_\theta, 1\right)$ the decrease in v_x dominates the decrease in w_x. Central bank disclosure then decreases uncertainty for everyone, even the central bank itself.

Finally, notice the two basic features of our model that lead to this benefit of disclosure: First, that the central bank both learns new information from firms (through the observation of the price level) but also provides new information to them (through its public disclosures). And second, that the central bank uses its own information to set nominal demand. The latter makes forward-looking firms' prices depend positively on expected central bank information about productivity, and hence offsets the effect of expected productivity itself. Combined, these features create the identification problem for the central bank that disclosure resolves. This also illustrates how similar results to Proposition 5 could extend to other circumstances in which agents learn from market outcomes.

5.3 Optimal Use of Information

An important question Proposition 5 raises is whether disclosure optimally increases or decreases the informativeness of prices. To accommodate for the endogenous informativeness of the price level, I solve for the optimal use of central bank information with a mix of the primal and dual approach (Appendix C).

Proposition 6. *When productivity shocks drive the economy, the unique optimal policy is full disclosure $\tau_\omega^{\theta,\star} \to \infty$ combined with monetary policy that undoes the nominal friction $\phi_\theta^\star = 1$. Increases in central bank disclosure globally increase the informativeness of the price level.*

Proposition 6 provides the second of our two main results. It shows that monetary policy should once more be set to its full-information value; and that conditional on this value, full disclosure maximizes the informativeness of the price level. At the optimal monetary policy, full disclosure decreases both firm and central bank uncertainty by the largest possible amount.

Central bank disclosure has several benefits that here combine to make full disclosure optimal. To see these, consider the output gap that arises from Proposition 1 when only productivity shocks drive the economy,

$$
\begin{aligned}
y_t - a_t &= \phi_\theta \mathbb{E}_t^{cb}\left[\theta_t\right] - \nu_0 \mathbb{E}_t^{f}\left[\phi_\theta \mathbb{E}_t^{cb}\theta_t - \theta_t\right] - \theta_t + l.p.t. \qquad (5.6)\\
&= \nu_0\left(\mathbb{E}_t^{f}\theta_t - \theta_t\right) + \nu_0\left(\phi_\theta \mathbb{E}_t^{cb}\theta_t - \mathbb{E}_t^{f}\left[\mathbb{E}_t^{cb}\theta_t\right]\right) + (1-\nu_0)\left(\phi_\theta \mathbb{E}_t^{cb}\theta_t - \theta_t\right) + l.p.t, \quad (5.7)
\end{aligned}
$$

where I have added and subtracted $\nu_0 \phi_\theta \mathbb{E}_t^{cb}\theta$ from (5.6). Public disclosure of central bank information has three distinct effects on this expression, the first two of which are identical to those discussed in Section 4. Central bank disclosure *(i)* increases firms' responses to fundamental shocks ($\mathbb{E}_t^{f}\theta_t$ is closer to θ_t, on average); and (*ii*) increases the commonality of expectations ($\mathbb{E}_t^{f}\theta_t$ and $\mathbb{E}_t^{f}\mathbb{E}_t^{cb}\theta_t$ are both closer to $\mathbb{E}_t^{cb}\theta_t$, on average). Both effects improve welfare in (5.7), either by allowing firms' prices to better reflect unobserved productivity or by increasing monetary policy's ability to replicate the flex-price outcome.

The third effect (*iii*) is, however, new to the setup with productivity shocks. It arises from how disclosure, by increasing the commonality of beliefs, also increases the informativeness of the price level ($\phi_\theta^\star = 1 > \hat{\phi}_\theta$). This, in turn, makes the central bank's own expectation of the productivity shock more accurate ($\mathbb{E}_t^{cb}\theta_t$ is closer to θ_t, on average). Similar to (*ii*), this third effect increases the ability of monetary policy to replicate the first best outcome. The more the central bank knows about productivity, the lower the optimal welfare losses are.[28]

Combined, these benefits of disclosure make full disclosure optimal. Indeed, even when $\phi_\theta < \hat{\phi}_\theta$, the benefit from allowing firms to set their prices more in line with productivity, in addition to the partially improved conduct of monetary policy, dominates the decrease in the informativeness of the price level. One consequence of this dominance of full disclosure is that monetary should optimally be set to its full-information value ($\phi_\theta^\star = \phi_\theta^{\star,full}$). Full disclosure once more separates monetary policy from any informational consequences.[29] As a result, we can once more apply the insights from Svensson and Woodford (2004), which show that monetary policy should in such cases be set to its full-information value.

Finally, that the optimal full-information value of monetary policy always falls within the

[28]The reason that this third effect did not arise in Section 4 is that only firms' expectations of the mark-up shock, in addition to the central bank's expectations and firms' expectations of the central bank's expectations, mattered in equilibrium for the output gap (see 4.3). The realization of the shock itself did not matter. By contrast, the realization of the productivity shock here directly matters for (5.7).

[29]Notice, for example, that the weight on private information $\mathtt{k}_0$ in Proposition 4 becomes completely independent of monetary policy ϕ_θ when $\tau_\omega^\theta \to \infty$. In particular, $\mathtt{k}_0 \to -\nu_0 \frac{\tau_x^\theta}{\tau_x^\theta + \tau_z^\theta + \tau_\theta}$ when $\tau_\omega^\theta \to \infty$.

range where $\phi_\theta^{\star,full} = 1 > \hat{\phi}_\theta$ is clearly a particular feature of our model. But as Section 7 shows, this result (and the related benefit of disclosure) provides an appropriate departure point for natural extensions of our framework.

5.4 Discussion and Extensions

Nominal Frictions: Although less central than in Section 4, the price adjustment cost $\psi > 0$ plays an important role for the results in this section. Clearly, that disclosure can increase the informativeness of prices does not depend on the presence of the nominal friction ψ. Indeed, the key statistic $\hat{\phi}_\theta$ in Proposition 5 is independent of ψ. That said, the presence of the nominal friction is important for the welfare benefits that disclosure entails.

Consider the output gap $y_t - a_t = m_t - p_t - a_t$. If $\psi \to 0$, and hence $\nu_0 \to 1$, the output gap becomes $y_t - a_t = m_t - \mathbb{E}_t^f[m_t] + \mathbb{E}_t^f[a_t] - a_t$ (Proposition 1). This shows that, beyond the provision of information, the central bank can do no better than to set $\phi_\theta = 0$, so as to ensure that firms do not make expectational errors about monetary policy ($m_t - \mathbb{E}_t^f m_t = 0$). Only in the presence of nominal frictions $\psi > 0$ can optimal monetary policy help the economy adjust to productivity shocks. Thus, only when $\psi > 0$ does the central bank's knowledge about the fundamentals of the economy matter under the optimal policy.

Dispersed Information: I have once more simplified the above exposition by assuming all firms observe the same private sector signal x_t^θ. However, as in Section 4, my main results extend to the case in which firms observe individual-specific information $x_{it}^\theta = \theta_t + \epsilon_{ixt}^\theta$, where $\epsilon_{ixt}^\theta \sim \mathcal{N}\left(0, 1/\tau_x^\theta\right)$ and $\mathbb{E}\left[\epsilon_{ixt}^\theta \epsilon_{jxs}^\theta\right] = 0$ for all $j \neq i$ and $s \neq t$. The dispersed information setup considered at the end of Section 4 provides a tractable example (Appendix C.4). The two key differences that nevertheless exist between the dispersed and common information case are: First, the price level in the dispersed information case provides a noisy signal of the *average* private sector signal ($\int_0^1 x_{it}^\theta = \theta_t$) instead of $x_t^\theta = \theta + \epsilon_{xt}^\theta$. But since Proposition 5 and 6 hold for $\tau_x^\theta \to \infty$, this distinction does not affect my results.[30] Second, as in Section 4, the presence of dispersed private sector information causes social welfare to also depend on the cross-sectional dispersion of prices. This changes the optimal monetary policy. However, as Section 7 shows, Proposition 6 (and the related benefit of disclosure; $\phi_\theta^\star > \hat{\phi}_\theta$) provides an appropriate departure point for quantitative extensions of our framework.

Other Monetary Policy Rules: I close this section by noting that, as in Section 4, the above results do not depend on the specificities of the monetary policy rule in (2.8). Appendix C.4 provides an example of this in the case in which the central bank directly targets the variables

[30] Consider (5.7) in the case in which firms' private sector information is perfectly accurate $\tau_x^\theta \to \infty$. Then, the first component is clearly always equal to zero. The variance of the second and third component are, by contrast, once more minimized by full disclosure $\tau_\omega^\theta \to \infty$ and $\phi_\theta = 1$. See also footnote 28.

that cause changes to the output gap in (5.6), the price level and labor productivity.

6 A Quantitative Model

The analysis that I have covered has shown how the two-sided informational flow between firms and the central bank can alter the desirability of central bank disclosure. To keep my analysis analytically tractable, I have however focused on a model that abstracts from several potentially important features. In this section, I solve an extended version of the above model, which resembles that of Lorenzoni (2009), to provide a more accurate assessment of the social benefits of central bank disclosure. Unlike the baseline model, the extended economy features an imperfectly informed household and a signaling role for monetary policy. It also allows for dispersed information among firms. The next section then uses the extended model to take a first pass at two basic quantitative questions. First, do the benefits of disclosure that arise from an increase in common knowledge outweigh the aforementioned costs for calibrated parameter values? And second, if so, are the welfare benefits substantial?

6.1 Extensions to Baseline Economy

The representative household's preferences once more equal

$$\mathcal{U} = \mathbb{E}_0^h \sum_{t=0}^{\infty} \beta^t \left[\log\left(C_t\right) - \frac{1}{1+\eta} L_t^{1+\eta} \right], \tag{6.1}$$

where, unlike in Section 2, the household now also has imperfect information about the fundamentals of the economy and bases its expectations $\mathbb{E}_t^h\left[\cdot\right] = \mathbb{E}\left[\cdot \mid \Omega_t^h\right]$ upon the information set Ω_t^h (described below). I dispense with the cash-in-advance constraint (2.4) and instead assume that money is held in bank deposits, earning an interest rate of i_t. This brings the economy in line with the cash-less limit economies that are the standard in the literature (following Woodford, 2002b). The household's budget constraint therefore in place of (2.3) becomes

$$\int_0^1 P_{it} C_{it} di + \left(1 + i_t\right) M_t^d \leq \int_0^1 \Pi_{it} di + W_t L_t + M_{t-1}^d + T_t^h. \tag{6.2}$$

The central bank, which controls the interest rate on bank deposits, follows a simple *Taylor Rule*, in which it targets deviations of output from its full information flex-price levels,

$$i_t = \exp\left(\mathbb{E}_t^{cb}\left[y_t - a_t\right]\right)^{\phi} \exp\left(\epsilon_{mt}\right), \tag{6.3}$$

where $\epsilon_{mt} \sim \mathcal{N}\left(0, \tau_m^{-1}\right)$ denotes a monetary policy shock.[31] As with (2.8), the central bank

[31] The introduction of the monetary policy shock ϵ_{mt} in (6.3) here serves a technical purpose, similar to that

can affect real outcomes with (6.3) by influencing nominal demand in the economy.

Finally, I keep the production side of the economy unchanged with the exception of the stochastic processes for labor productivity and firms' mark-ups. I assume that both of these follow stationary *AR(1)s* in logarithms,

$$A_t = A_{t-1}^{\rho_a} \exp(\theta_t), \quad \mathcal{M}_t = \mathcal{M}_{t-1}^{\rho_\mu} \exp(\xi_t), \tag{6.4}$$

where $\rho_a \in (0, 1)$ and $\rho_\mu \in (0, 1)$.

6.2 Linearized Equilibrium Conditions

I once more study a log-linear approximation to the rational expectation equilibria. Following well-known steps, Appendix D shows that the equilibrium conditions of the model reduce to three key log-linear equations. First, an *Euler equation,* which determines the optimal intertemporal allocation of consumption and output,

$$y_t = \mathbb{E}_t^h [y_{t+1}] - \left(i_t - \mathbb{E}_t^h [\pi_{t+1}]\right), \tag{6.5}$$

where π_t denotes the inflation rate for the consumption index. Second, a *New-Keynesian Phillips Curve*, which relates firms' expectations of mark-ups and marginal cost, proportional to the output gap, to expected future and current inflation,

$$\pi_t = \beta \bar{\mathbb{E}}_t^f [\pi_{t+1}] + \lambda \bar{\mathbb{E}}_t^f [y_t - a_t] + \bar{\mathbb{E}}_t^f [\mu_t], \tag{6.6}$$

where $\lambda \equiv \frac{1+\eta}{\psi}\rho$ and $\bar{\mathbb{E}}_t^f [\cdot] \equiv \int_0^1 \mathbb{E}\left[\cdot \mid \Omega_{it}^f\right] di$ denotes firms' average expectation based upon Ω_{it}^f (defined below). And lastly third, a log-linear central bank Taylor Rule,

$$i_t = \phi \mathbb{E}_t^{cb} [y_t - a_t] + \epsilon_{mt}. \tag{6.7}$$

Combined, (6.3)-(6.6) closely resemble the equilibrium conditions of the dispersed information New Keynesian model in Lorenzoni (2009), extended to the case in which the private sector and the central bank have non-nested information sets.

6.3 Information Structure

The information structure mirrors that from Section 2. The substantive differences are that (i) firms now also observe and learn about central bank expectations from the current value of

of ϵ_{pt} in Section 2. It prevents the private sector from perfectly inferring the central bank's private information directly from observations of the central bank interest rate.

the central bank interest rate, and that (ii) firms now observe individual-specific information,

$$\Omega_{it}^{f} = \{x_{it-j},\, \omega_{t-j},\, \bar{\pi}_{t-j},\, i_{t-j}\}_{j=0}^{\infty}\,, \tag{6.8}$$

where $x_{it}' \equiv \begin{bmatrix} x_{it}^{a} & x_{it}^{\mu} \end{bmatrix}$ is comprised of

$$x_{it}^{a} = a_t + \epsilon_{xt}^{a} + \epsilon_{ixt}^{a} :\ \epsilon_{ixt}^{a} \sim \mathcal{N}\left(0, 1/\bar{\tau}_{x}^{a}\right), \quad x_{it}^{\mu} = \mu_t + \epsilon_{xt}^{\mu} + \epsilon_{ixt}^{\mu} :\ \epsilon_{ixt}^{\mu} \sim \mathcal{N}\left(0, 1/\bar{\tau}_{x}^{\mu}\right), \tag{6.9}$$

and $\omega_t' \equiv \begin{bmatrix} \omega_t^{a} & \omega_t^{\mu} \end{bmatrix}$ equals

$$\omega_t^{a} = z_t^{a} + \epsilon_{\omega t}^{a} :\ \epsilon_{\omega t}^{a} \sim \mathcal{N}\left(0, 1/\tau_{\omega}^{a}\right), \quad \omega_t^{\mu} = z_t^{\mu} + \epsilon_{\omega t}^{\mu} :\ \epsilon_{\omega t}^{\mu} \sim \mathcal{N}\left(0, 1/\tau_{\omega}^{\mu}\right), \tag{6.10}$$

$$z_t^{a} = a_t + \epsilon_{zt}^{a} :\ \epsilon_{zt}^{a} \sim \mathcal{N}\left(0, 1/\tau_{z}^{a}\right), \qquad z_t^{\mu} = \mu_t + \epsilon_{zt}^{\mu} :\ \epsilon_{zt}^{\mu} \sim \mathcal{N}\left(0, 1/\tau_{z}^{\mu}\right). \tag{6.11}$$

In the terminology of Myatt and Wallace (2011), firms' private information in (6.9) is subject to both sender and receiver noise (see also Hellwig *et al.*, 2012; Colombo *et al.*, 2014; and Vives and Yang, 2017). Notice that I also dispense with the somewhat artificial assumption of one-period perfect state verification used in (2.13) and instead assume that firms do not observe previous period's realization of the fundamentals. As a result, I also employ the more standard assumption that firms' private signals x_{it} and the central bank's signals $z_t \equiv \begin{bmatrix} z_t^{a} & z_t^{\mu} \end{bmatrix}$ pertain to the level of the driving forces a_t and μ_t, instead of the shocks to these.

Finally, I assume that Ω_t^{h} is set such that $\bar{\mathbb{E}}_t^{f}[\cdot] = \mathbb{E}_t^{h}[\cdot]$. The aggregate equations for output and inflation in (6.5) and (6.6), respectively, that result from this assumption are identical to those in Lorenzoni (2009), where households and firms inhabit an "island-structure". It is also equivalent to the assumption used in Svensson and Woodford (2003).

Turning to the central bank, its information set is virtually unaltered. Indeed, besides that the central bank now uses the (stationary) inflation rate to infer firms' private information instead of the (non-stationary) price level and the absence of one-period perfect state verification, it is identical to before,

$$\Omega_t^{cb} = \{z_{t-j},\, \omega_{t-j},\, \bar{\pi}_{t-j},\, i_{t-j}\}_{j=0}^{\infty}\,. \tag{6.12}$$

where $\bar{\pi}_t = \pi_t + \epsilon_{pt}$ with $\epsilon_{pt} \sim \mathcal{N}\left(0,\, \tau_p^{-1}\right)$.

6.4 Solution and Calibration

Unlike the framework presented in Section 2, the equilibrium solution for output and inflation can no longer be derived analytically. The central bank learns about common disturbances from an endogenous market outcome, inflation. The combination of endogenous public information with the absence of perfect state verification has since Townsend (1983) been known to imply that standard state space representations of the equilibrium have infinite-dimensional state vectors. I therefore solve the model numerically instead.

In this subsection, I first describe how to adapt the solution method proposed in Nimark (2017) to the current setting with a non-atomistic agent, the central bank. I keep details to a minimum and focus on the important role that higher-order expectations, influenced by central bank disclosure, play in the equilibrium solution. I then calibrate the model separately for the mark-up shock and the productivity shock case to match data on forecast accuracy from the "*Survey of Professional Forecasters*" (for the private sector) and the "*Greenbook*" (for the central bank).[32] I calibrate for each persistent shock separately to avoid confounding the two distinct benefits of disclosure discussed in Section 4 and 5.

Dynamic Models with Two-sided Information: Nimark (2017) shows that when all disturbances are stationary, an approximate solution can be found to linear rational expectations equilibria in models with endogenous information. This can be done by direct truncation of the state vector comprised of higher-order expectations, to achieve a finite-dimensional representation. I extend this solution method to deal with the additional complication of a non-atomistic agent (the central bank) in Appendix D. When the model is solved, the approximate law of motion for the endogenous triplet $q_t = \begin{bmatrix} \pi_t & y_t & i_t \end{bmatrix}'$ admits the form

$$q_t = \alpha_0 X_t^{(0:\bar{k})} + \alpha_1 u_t, \tag{6.13}$$

where $u_t = \begin{bmatrix} \epsilon_t & \epsilon_{xt}^j & \epsilon_{zt}^j & \epsilon_{\omega t}^j & \epsilon_{pt} & \epsilon_{mt} \end{bmatrix}'$ with $j = \{a, \mu\}$ and $\epsilon_t = \{\theta_t, \xi_t\}$, depending on which of the two persistent shocks drive the economy. $X_t^{(0:\bar{k})}$ here denotes the expectational state vector comprised of the entire hierarchy of private sector and central bank higher-order expectations about the persistent fundamental $X_t^{(0)} = \{a_t, \mu_t\}$ up to the $\bar{k}$th order,

$$X_t^{(0:\bar{k})} = \begin{bmatrix} X_t^{(0)} & X_t^{(1)\prime} & \ldots & X_t^{(\bar{k})\prime} \end{bmatrix}', \quad X_t^{(k)} = \begin{bmatrix} \bar{\mathbb{E}}_t^f X_t^{(k-1)} \\ \mathbb{E}_t^{cb} X_t^{(k-1)} \end{bmatrix}, \quad k \in \left[1,\, 2,\, \ldots,\, \bar{k}\right]. \tag{6.14}$$

The true equilibrium law of motion has $\bar{k} \to \infty$. I truncate this expectational state vector at $\bar{k} = 50$. All impulse response functions are stable from around $\bar{k} = 15$.

Similar to Nimark (2017), Appendix D shows that common knowledge about individual

[32] The Greenbook contains forecasts computed by the Staff of the Federal Reserve. These forecasts are published a few days before the FOMC meeting and collected with a five year lag in "*the Greenbook data set*" (Reifschneider *et al.*, 1997). The data for private sector forecasts comes from the *Survey of Professional Forecasters* conducted by the Federal Reserve Bank of Philadelphia. The sample stretches from 1968Q1 to 1993Q4. In February 1994, the Federal Reserve Market Committee began a long process of increased disclosure, altering the informational assumption used to calibrate the model (Dincer and Eichengreen, 2009).

rationality, combined with the Kalman Filter, ensures that $X_t^{(0:\bar{k})}$ follows a *VAR(1)*,[33]

$$X_t^{(0:\bar{k})} = MX_{t-1}^{(0:\bar{k})} + Nu_t. \tag{6.15}$$

Because the private sector and the central bank learn from the observation of each other's actions, the matrices M and N depend on the coefficients in α_0 and α_1, and *vice versa.* I solve for the fixed point $\{M, N\} \mapsto \{\alpha_0, \alpha_1\} \mapsto \{M, N\}$ by repeated iteration.

Calibration: The parameter β is set to 0.99, such that the time period can be interpreted as one quarter. The inverse Frisch elasticity of labor supply η is set to one, and the value of the elasticity of substitution ρ to six, which implies a mark-up of 20%. The price adjustment parameter ψ is set such that the slope of the New Keynesian Phillip's Curve is $\lambda = 0.25$, and the standard deviation of the idiosyncratic monetary policy shock to two. The parameter on the interest rule is set such that the model with productivity shocks is consistent with a Taylor Rule coefficient on inflation of one-and-a–half. This implies $\phi = 1.81$. These values are all in the range of those used in existing studies within the New Keynesian framework.

Next, I determine the parameters that control the mark-up and productivity shock, in addition to the noise in the private information about these. The persistence parameters are set to $\rho_\mu = 0.70$ and $\rho_a = 0.80$, respectively, consistent with existing studies. For each persistent shock, the parameters which control the average precision of private information (τ_x^a or τ_x^μ) are set under complete central bank opacity ($\tau_\omega^j \to 0, j = \{a, \mu\}$) to match pre-February 1994 data on the one-quarter ahead root-mean-square error of GNP/GDP forecasts from the *Survey of Professional Forecasters* for the private sector and the *Greenbook* for the central bank. In February 1994, the Federal Reserve Open Market Committee commenced a long process of increased transparency. I therefore do not employ data after this quarter as it would conflict with the complete opacity assumption otherwise used in the calibration. To start, I set the dispersion in firms' private information $(\bar{\tau}_x^a)^{-1}$ and $(\bar{\tau}_x^\mu)^{-1}$ equal to zero, to make my results comparable to those in Section 4 and 5. I then explore the robustness of my results to realistic amounts of dispersion in firms' information.

Finally, to set τ_p, I follow Lorenzoni (2009) and interpret ϵ_{pt} as measurement error in early releases of inflation data and match the signal-to-noise ratio in these. Specifically, I interpret $\bar{\pi}_t$ as the first release and π_t as the last. I then choose τ_p to match the ratio between the standard deviation of the measurement error and the standard deviation of the innovation to inflation. The latter is measured by running a simple univariate regression of final release

[33] I here adjust the standard Kalman Filter for the fact that the central bank can back-out part of the noise component in private sector signals. Specifically, the central bank can from the observation of its own private information z_t and its own action i_t back-out the value of the monetary policy shock ϵ_{mt} from (6.7). This is the shock that otherwise prevents the private sector from perfectly inferring z_t from the observation of i_t.

Table I: Baseline Shock and Information Parameters

Productivity Shock				Mark-up Shock			
ρ_a	0.80	σ_θ	0.60	ρ_μ	0.70	σ_ξ	0.16
σ_x^a	0.65	σ_z^a	0.40	σ_x^μ	0.20	σ_z^μ	0.10
σ_p	0.28	σ_ω^a	$\to\infty$	σ_p	1.30	σ_ω^μ	$\to\infty$

(i) The mapping between standard deviation σ and precision τ is $\tau = 1/\sigma^2$

inflation on two lags. Lorenzoni (2009) employs this approach an obtains a ratio of 1.97 for PCE inflation. Matching this value, I obtain the parameters listed in Table I. The noise in inflation is for both the mark-up and productivity shock case substantial, consistent with the evidence presented in, for example, Runkle (1998).

A feature that immediately stands out from Table I is that the central bank has superior private information. To match the data on forecast accuracy, central bank private information has to be around 38 to 50 percent more precise than that of the private sector.[34] This is consistent with the empirical results in Romer and Romer (2000), which document a substantial information advantage for the US Federal Reserve relative to the mean forecast from the Survey of Professional Forecasters.[35]

7 Quantitative Benefits of Learning by Sharing

In this section, I present estimates of the welfare benefits of central bank disclosure using the calibrated model. I demonstrate how disclosure increases the commonality of expectations, and thereby central bank information, to such an extent that it can be beneficial, irrespective of the source of macroeconomic fluctuations. To make my results comparable to those in Section 4 and 5, I start with quantitative results under the baseline calibration in which all firms observe the same information. I then end the section with a breakdown of the sensitivity of the quantitative results to the presence of dispersed private sector information, as well as to the importance of higher-order expectations and central bank signaling.

7.1 A First Best Benchmark

I once more take my welfare criterion to be the *ex ante* utility of the representative household. Similar to Sections 3 to 5, the central bank can in the extended model replicate the first best

[34]This follows, for example, from a comparison of $\sigma_x^a = 0.65$ and $\sigma_z^a = 0.40$ for the productivity shock case.

[35]In principle, because of the two-sided learning between the private sector and the central bank, the calibrated model could exhibit multiple stationary equilibria for the calibrated parameters (see Section 5). In practice, however, I seeded the algorithm with 1,000 randomly drawn initial values for M and N. In all cases, the recursion $\{M,\, N\} \mapsto \{\alpha_0,\, \alpha_1\} \mapsto \{M,\, N\}$ converged to the same fixed point.

outcome in several limit cases. For example, when both the central bank and the private sector have full information about all shocks, the central bank can achieve the full information flex-price outcome by letting $\phi \to \infty$ (Appendix D). This ability to replicate the first best extends to the case where the private sector has imperfect information but the central bank has full information, both about all shocks as well as about the private sector's beliefs about them. The central bank can in this case still replicate the first best by letting $\phi \to \infty$.[36] Thus, as in Section 4 and 5, welfare losses are only necessarily a feature under the optimal monetary policy when the central bank itself has imperfect information.

7.2 Mark-up Shock Case

I start with the case in which the economy is driven by mark-up shocks. Figure 1 illustrates the changes to *private sector uncertainty* about the first four orders of the expectational state vector $X_t^{(0:\bar{k})}$ as we increase the precision of central bank disclosure.[37] The remaining orders follow a similar pattern and are omitted for clarity. By introspection, the private sector cannot be uncertain about its own expectations under the baseline calibration. The figure therefore only depicts elements that pertain to private sector uncertainty about central bank expectations, in addition to the mark-up shock. Figure 2 illustrates the associated changes to *central bank uncertainty* about the vector of higher-order expectations $X_t^{(1:\bar{k})}$.

The results in Figure 1 and 2 mirror those from Section 4. First, disclosure decreases private sector uncertainty about the mark-up shock, visible from the X_0-line in Figure 1. This, all else equal, leads to larger private sector responses. Second, disclosure also decreases central bank uncertainty about private sector expectations and *vice versa*, which is evident from the rest of the lines in Figures 1 and 2. As in Section 4, this in turn allows the central bank to better counter private sector responses to the mark-up shock, as it knows more about them. Which of these two effects dominates depends on the forcefulness by which monetary

[36] One may think that firms will always learn the central bank's private information when $\phi \to \infty$ from the observation of the interest rate. This is, however, not the case because central bank expectations of the size of the output gap also decrease as we increase ϕ. Define the central bank's forecast error of the output gap as $\varsigma^{cb}_{y_t-a_t} = (y_t - a_t) - \mathbb{E}^{cb}_t [y_t - a_t]$. Then,

$$\begin{aligned} y_t &= \mathbb{E}^h_t [y_{t+1}] + \mathbb{E}^h_t [\pi_{t+1}] - i_t = \mathbb{E}^h_t [y_{t+1}] + \mathbb{E}^h_t [\pi_{t+1}] - \phi \mathbb{E}^{cb}_t [y_t - a_t] \\ &= \mathbb{E}^h_t [y_{t+1}] + \mathbb{E}^h_t [\pi_{t+1}] - \phi (y_t - a_t) - \phi \varsigma^{cb}_{y_t-a_t}, \end{aligned}$$

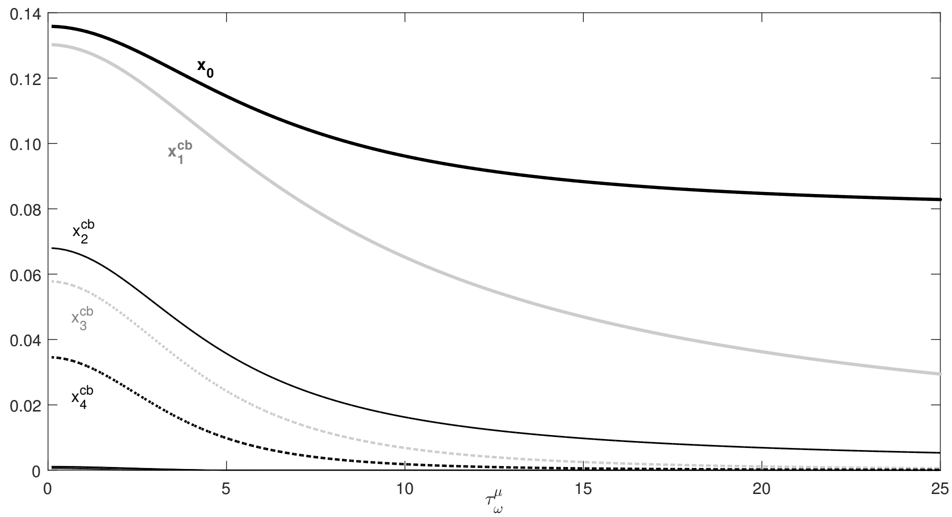
and hence $\lim_{\phi\to\infty} y_t = a_t + \lim_{\phi\to\infty} \varsigma^{cb}_{y_t-a_t}$. But then it follows from

$$i_t = \phi \mathbb{E}^{cb}_t [y_t - a_t] = \phi (y_t - a_t) - \phi \varsigma^{cb}_{y_t-a_t}$$

that $\lim_{\phi\to\infty} i_t = \lim_{\phi\to\infty} \phi\varsigma^{cb}_{y_t-a_t} - \lim_{\phi\to\infty} \phi\varsigma^{cb}_{y_t-a_t} = 0$. In the limit where $\phi \to \infty$, the interest rate becomes completely uninformative.

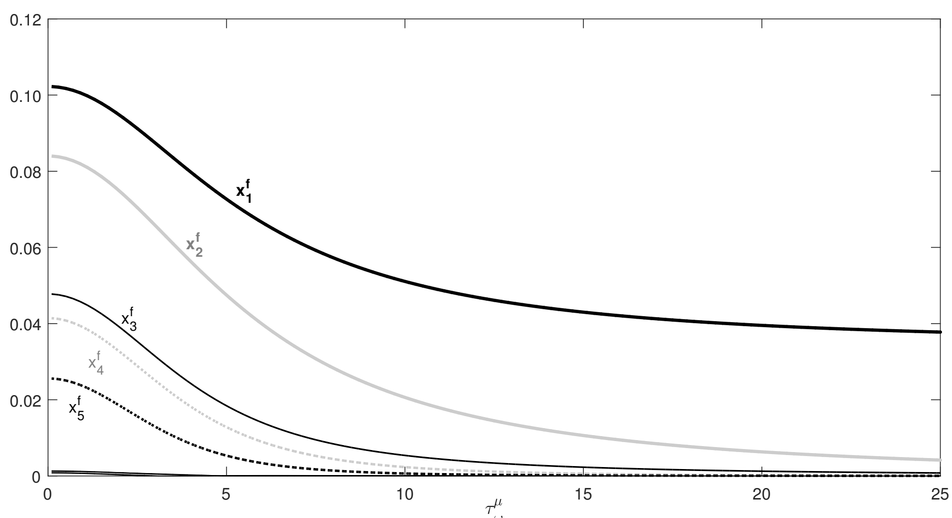
[37] The first four orders of expectations in $X_t^{(0:\bar{k})}$ are μ_t, $\mathbb{E}^f_t\mu_t$, $\mathbb{E}^{cb}_t\mu_t$, $\mathbb{E}^f_t\mathbb{E}^{cb}_t\mu_t$, $\mathbb{E}^{cb}_t\mathbb{E}^f_t\mu_t$, $\mathbb{E}^f_t\mathbb{E}^{cb}_t\mathbb{E}^f_t\mu_t$, $\mathbb{E}^{cb}_t\mathbb{E}^f_t\mathbb{E}^{cb}_t\mu_t$, $\mathbb{E}^f_t\mathbb{E}^{cb}_t\mathbb{E}^f_t\mathbb{E}^{cb}_t\mu_t$, and lastly $\mathbb{E}^{cb}_t\mathbb{E}^f_t\mathbb{E}^{cb}_t\mathbb{E}^f_t\mu_t$.

Figure 1: Private Sector Uncertainty about $X_t^{(0:\bar{k})}$ with Mark-up Shocks



The figure illustrates the root mean-squared error of *private sector* estimates of the first four orders of expectations in $X_t^{(0:\bar{k})}$. The panel is plotted for the calibrated values in Table I. Subscripts indicate order of expectation in $X_t^{(0:\bar{k})}$. For example, the line for X_1^{cb} represents the root mean-squared error of the private sector's estimate of the central bank's expectation of the mark-up shock (and similarly for the second-order expectation in X_2^{cb}).

Figure 2: Central Bank Uncertainty about $X_t^{(1:\bar{k})}$ with Mark-up Shocks



The figure illustrates the root mean-squared error of *central bank* estimates of the first four orders of expectations in $X_t^{(1:\bar{k})}$. The panel is plotted for the calibrated values in Table I. Subscripts indicate the orders of expectation in $X_t^{(0:\bar{k})}$. For example, the line for X_1^f represents the root mean-squared error of the central bank's estimate of the private sector's expectation of the mark-up shock (and similarly for the second-order expectation in X_2^f).

policy attempts to offset private sector responses (Corollary 1).

Table II shows that for the calibrated value of monetary policy the latter effect already dominates the former. Public disclosure of central bank information about the mark-up shock *decreases* welfare losses measured in life-time consumption by around 58 percent.[38] Table II illustrates the breakdown of this welfare benefit that I obtain when I let the central bank disclose its information but fix private sector and central bank higher-order uncertainty to that from the (complete opacity) baseline. All else equal, the increase in private sector responses to the mark-up shock increases welfare losses by around 56 percentage points. But this increase is more than offset by a substantial fall in central bank and private sector higher-order uncertainty about each other's expectations. Indeed, for the calibrated parameters, the fall in higher-order uncertainty is around twice as important in welfare terms as the direct increase in private sector responses to the mark-up shock.

Consistent with Proposition 3, this benefit of central bank disclosure carries over from the baseline value of monetary policy to its optimal combination with communication policy, which I find to be $\phi \to \infty$ and $\tau^{\mu}_{\omega} \to \infty$.[39] Once more the optimal monetary policy equals that under full information. At the optimal value of monetary policy, central bank disclosure decreases welfare losses by around 27 percentage points, due to decreases in central bank uncertainty about private sector expectations and *vice versa*. This, in turn, contributes to an overall welfare benefit of moving from the calibrated complete opacity policy to the optimal policy that is as large as to almost eliminate all welfare losses. This is clearly a forceful implication of the extended model paired with the calibrated parameters and is in part driven by the central bank's quite precise private information about mark-up shocks (Table I). Admittedly, a large share of the benefits from moving to the combined optimal policy derive solely from the optimal use of monetary policy. But the conclusion remains that disclosure contributes a healthy share to the total (around one-quarter of the total welfare gains).

7.3 Productivity Shock Case

I now turn to the productivity shock case. The left-hand panel in Figure 3 illustrates the two competing effects of central bank disclosure on the central bank's own information about productivity discussed in Section 5. On the one hand, disclosure decreases the private sector's weight on its own private information in its expectation about productivity, decreasing the information content of inflation. This, all else equal, *increases* central bank uncertainty. However, on the other hand, disclosure also decreases the central bank's uncertainty about

[38] With full disclosure, I in practice mean $\tau^{\mu}_{\omega} = 1e + 5$. I then cross-check all results with $\tau^{\mu}_{\omega} = 1e + 7$.

[39] In practice, I allow for values of ϕ and τ^{μ}_{ω} up to to $1e + 5$ and cross-check with values equal to $1e + 7$. To be precise, whenever I write, for instance, $\phi \to \infty$ in the below I mean $\phi = 1e + 5$. All welfare results are constant to the sixth decimal place in Table II and III for values above $1e + 4$.

Table II: Welfare Effects of Disclosure with Mark-up Shocks

	Parameters		$\%\Delta W_C$
Calibrated benchmark	$\phi = 1.81$	$\tau_\omega^\mu \to 0$	...
	Breakdown of Benefits from Disclosure		
A. Benchmark with full disclosure	$\phi = 1.81$	$\tau_\omega^\mu \to \infty$	-58.54
B. Benchmark with constant h.o. unc.†	$\phi = 1.81$	$\tau_\omega^\mu \to \infty$	$+56.10$
A-B. Benefit from decrease in h.o. unc.			-114.63
	Breakdown of Benefits from Optimal Policy		
A. Optimal policy	$\phi \to \infty$	$\tau_\omega^\mu \to \infty$	-96.46
B. Benefit from optimal mon. policy	$\phi \to \infty$	$\tau_\omega^\mu \to 0$	-69.82
A-B. Benefit from central bank disclosure			-26.64

(i) W_C denotes the life-time consumption equivalent of W.

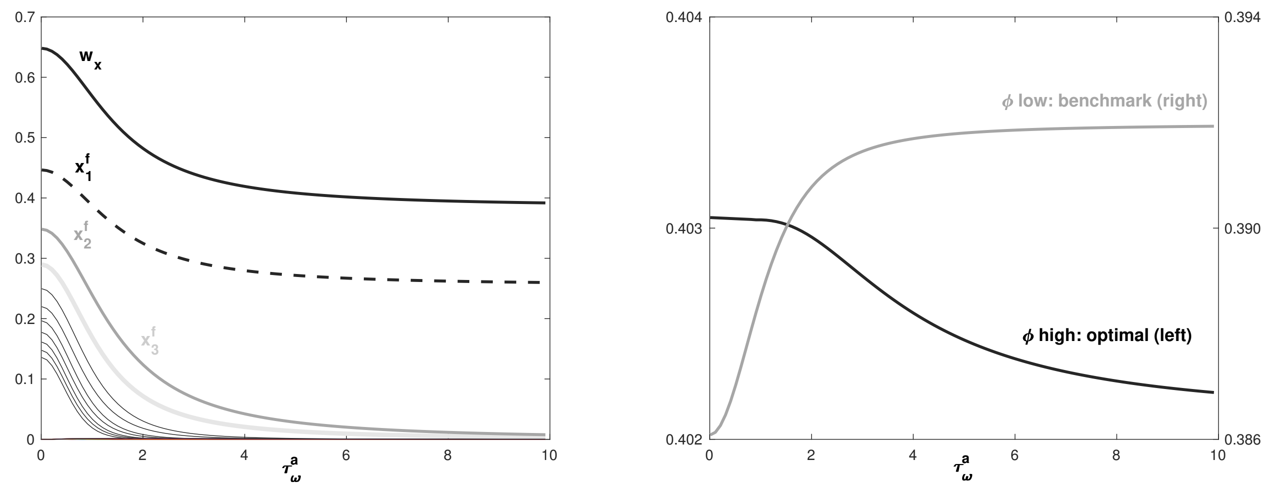
(ii) $\%\Delta W_C$ denotes the %change in W_C relative to the calibrated benchmark.

(†) Private sector and central bank higher-order uncertainty fixed at benchmark values.

private sector expectations of its own beliefs, and so on. This, in turn, allows the central bank to better back out changes in private sector information about productivity from changes to inflation, *decreasing* central bank uncertainty.

Similar to the results in Section 5, the right-hand panel in Figure 3 shows that for “small values” of monetary policy ϕ, here consistent with the baseline value, the former effect dominates the latter. Disclosure on balance increases central bank uncertainty about productivity by crowding out private sector information from inflation. However, consistent with Proposition 5 and 6, for larger values of monetary policy, disclosure instead decreases central bank uncertainty. Figure 3 illustrates this for $\phi \to \infty$, which I once more find to be optimal. At the optimal monetary policy, disclosure decreases central bank uncertainty about productivity by alleviating the identification problem that arises when the central bank attempts to infer private sector information from inflation outcomes. We can see the welfare benefits from this learning by sharing effect in Table III, where I breakdown the effect of disclosure on the private sector and the central bank by fixing central bank higher-order uncertainty to its (complete opacity) baseline value. Moving from the calibrated benchmark to the optimal policy decreases welfare losses by around 33 percent. A large share of this decrease is due to more informed private sector choices (c. 13 percentage points). But a more substantial share is, in fact, driven by the decrease in central bank uncertainty and the associated improvement

Figure 3: Central Bank Uncertainty about $X_t^{(0:\bar{k})}$ with Productivity Shocks



The left panel shows (i) the *private sector's* weight on private sector information w_x in its expectation of productivity $a_t = X_t^{(0)}$; and (ii) the root mean-squared error of *central bank* estimates of $X_t^{(1:\bar{k})}$. Both are plotted as a function of the precision of central bank disclosure τ_ω^a when $\phi = 1.81$. The right panel depicts the root mean-squared error of *central bank* estimates of productivity $a_t = X_t^{(0)}$ as a function of central bank disclosure τ_ω^a. The panel is plotted for $\phi = 1.81$ (left-hand scale) and $\phi \to \infty$ (right-hand scale).

Table III: Welfare Effects of Disclosure with Productivity Shocks

	Parameters		$\%\Delta W_C$
Calibrated benchmark	$\phi = 1.81$	$\tau_\omega^a \to 0$	...
Breakdown of Benefits from Disclosure			
A. Benchmark with disclosure	$\phi = 1.81$	$\tau_\omega^a \to \infty$	-2.95
B. Private sector benefit of disclosure†	$\phi = 1.81$	$\tau_\omega^a \to \infty$	-14.31
A-B. Central bank cost of disclosure			$+11.36$
Breakdown of Benefits from Optimal Policy			
A. Optimal policy	$\phi \to \infty$	$\tau_\omega^a \to \infty$	-32.72
B. Benefit from optimal mon. policy	$\phi \to \infty$	$\tau_\omega^a \to 0$	$+8.61$
C. Private sector benefit of disclosure†	$\phi \to \infty$	$\tau_\omega^a \to \infty$	-12.84
A-B-C. Central bank benefit of disclosure			-28.49

(i) W_C denotes the life-time consumption equivalent of W.

(ii) $\%\Delta W_C$ denotes the %change in W_C relative to the calibrated benchmark.

(†) Central bank higher-order uncertainty fixed at calibrated benchmark value.

in monetary policy (c. 28 percentage points).[40]

Finally, importantly, disclosure also increases the informativeness of inflation for other values of monetary policy ϕ that we could have considered for our baseline. One example is that calibrated to match the post-Great Moderation estimates in Clarida *et al.* (2000).

7.4 Alternative Specifications

I conclude this section by exploring the sensitivity of the quantitative results. Specifically, I re-compute the welfare benefits of disclosure in the three cases: (i) when the parameters that control the dispersion in firms' private information are set to match the pre-February 1994 dispersion in one-quarter ahead GNP/GDP forecasts from the Survey of Professional Forecasters, consistent with our baseline calibration ($\bar{\sigma}_x^\mu = (\bar{\tau}_x^\mu)^{-0.5} = 0.11$ and $\bar{\sigma}_x^a = (\bar{\tau}_x^a)^{-0.5} = 0.20$);[41] ($ii$) when the signaling role of monetary policy is absent ($i_t \notin \Omega_t^f$); and (iii) when households have full information. Table IV summarizes the results, while Appendices E.1 to E.5 document in detail how in all three cases the main insights from Table II and III continue to hold. I also here show that my conclusions extend to the case where (iv) firms and the central bank compute only two higher-order expectations ($\bar{k} = 3$; c.f. Nagel, 1995) and (v) when the discount factor decreases from $\beta = 0.99$ to $\beta = 0.75$, decreasing the extent to which firms' prices depend upon expectations of future firm and central bank actions.

Dispersed Information: As discussed in e.g. Hellwig (2005), Angeletos and Pavan (2007), and Angeletos *et al.* (2016), dispersed information among firms can have important consequences for the benefits of central bank disclosure. Because of strategic complementarities, dispersed private sector information may namely cause public signals to receive either too little or too much weight. This depends in part on how monetary policy is set. Thus, the welfare effects of additional central bank disclosure may differ with dispersed information from those reported in Tables II and III. However, as Table IV and Appendix E.1 illustrate, the main insights from my analysis extend to the case in which firms observe dispersed information.

For both the mark-up and productivity shock case, I re-compute the optimal monetary and disclosure policy, taking into account the welfare consequences of the price dispersion that now exists. I find that the optimal policy remains unaltered in both cases: The optimal

[40] Interestingly, moving to the optimal monetary policy ($\phi \to \infty$) without at the same time disclosing the private information that monetary policy is based on ($\tau_\omega^a \to 0$) is socially costly. It increases welfare losses by around nine percentage points relative to the benchmark case. This provides a stark example of the interdependence of monetary and communication policy discussed in this paper.

[41] I measure the dispersion in individual forecasts by their average cross-sectional standard deviation. This provides me with a target equal to 0.33 percentage points. Because individual-specific error terms add additional noise to the private sector's information in (6.10), I also recalibrate the values of τ_x^μ and τ_x^a to once more match the observed one-quarter ahead root-mean squared error of the average pre-February 1994 GNP/GDP forecast from the Survey of Professional Forecasters ($\sigma_x^\mu = (\tau_x^\mu)^{-0.5} = 0.50$ and $\sigma_x^a = (\tau_x^a)^{-0.5} = 0.60$).

monetary policy remains $\phi^\star \to \infty$, while full disclosure is still optimal in both the mark-up and the productivity shock case ($\tau_\omega^{\mu,\star} \to \infty$ and $\tau_\omega^{a,\star} \to \infty$).

Table IV and Appendix E.1 show the breakdown of the quantitative results when only mark-up shocks drive the economy. Consistent with the results in Table II, full disclosure improves welfare, both at the calibrated pre-February 1994 benchmark and at the optimal value of monetary policy. The benefit from the central bank being able to better predict (and hence offset) private sector responses to the mark-up shock once more dominates the increase in private sector responses. Furthermore, relative to the results in Table II, central bank disclosure is somewhat more beneficial under the optimal monetary policy (welfare losses decrease by -50 percent vs. -26 percent previously), while somewhat less so at the calibrated benchmark (-26 percent now vs -115 percent before). This illustrates how the introduction of dispersion information modifies our quantitative results, while upholding our conclusions.

Turning to the productivity shock case, Table IV and Appendix E.1 show that the results with dispersed information are remarkably similar to those in Table III. For example, going from complete opacity to full disclosure now decreases welfare losses by around 32 percent at the optimal monetary policy (Appendix E.1). Around 30 percentage points of this decrease is due to the increase in central bank information about productivity (compared to 28 percentage points in Table III). The benefit from the central bank being able to better back out information from inflation once more dominates the learning externality. This, in turn, makes disclosure more beneficial, and the overall effects similar to those in Table III.

Finally, an interesting exercise is to re-calibrate the noise in private information about productivity to target double the amount of dispersion in forecasts to that observed in the SPF data. This shows how the above benefit of central bank disclosure extends to circumstances in which full disclosure is no longer optimal. In fact, in this case, maintaining modest amount of private sector uncertainty about central bank expectations is preferable ($\tau_\omega^{a,\star} = 1.98$).[42] The optimal monetary policy, by contrast, remains the same. However, although full disclosure is no longer optimal, moving from the complete opacity baseline to the combined optimal policy still reduces welfare losses in part because of the increase in central bank knowledge about productivity. (A similar exercise for the mark-up shock case shows that for double the amount of the dispersion in forecasts full disclosure is still optimal).

Central Bank Signaling: Under opacity or partial disclosure, movements in the interest rate provide firms with a noisy signal of the central bank's private information. By contrast, full disclosure separates the interest rate from its signaling effect. A concern could therefore be that the lion-share of the quantitative benefits of disclosure reported in Table II and III arise

[42] Recall that the standard deviation of the productivity process a_t is one. Hence, $\tau_\omega^{a,\star} = 1.98$ equates to a noise-to-signal ratio of only around one half.

from the separation of monetary policy from its informational consequences rather than from a decrease in higher-order uncertainty. Table IV and Appendix E.2 shows that this is not the case. In fact, the resulting separation of monetary policy contributes at most one percentage point to the quantitative benefits of disclosure. This is because the interest rate, both in the benchmark calibration and at the optimal value of monetary policy, provides a rather dim indicator of the central bank's private information.[43] This is consistent with the substantial effect of central bank disclosure on financial markets, and on private sector uncertainty about future interest rates, documented in for example Blinder *et al.* (2008).

Household Information and Higher-Order Expectations: Changes to the prevalence of higher-order uncertainty have important implications for our results. Suppose, for example, that the representative household has full information about the state of economy instead of imperfect information. This includes full information about firm and central bank (higher-order) expectations. This brings the economy explored in this section closer to that from Section 2. In this case, the benefits of disclosure decrease somewhat relative to those reported in Table II and III, both in the mark-up and in the productivity shock case (Table IV). The Euler equation (6.5) no longer "adds" higher-order expectations to the equilibrium dynamics of the model, as for example $\mathbb{E}_t^h \mathbb{E}_t^{cb}[a_t] = \mathbb{E}_t^{cb}[a_t]$. As a result, firm and central bank uncertainty about each other's actions become less important for output, and thus welfare. This, in turn, makes the benefits of disclosure highlighted above somewhat smaller. However, despite the decreased importance of higher-order uncertainty, the quantitative benefits of disclosure still, on balance, resemble those in Table II and III (Table IV and Appendix E.3).

The other main differences between the household full and imperfect information case pertain to the model with productivity shocks (Appendix E.3). First, since output becomes more responsive, due to the increase in household information, monetary policy increases in relative importance (relative to disclosure policy). Second, disclosure becomes detrimental for welfare at the calibrated benchmark, even when keeping central bank uncertainty constant. This provides a stark example of the interdependence between monetary and disclosure policy discussed in this paper. As in, for example, Angeletos and Pavan (2009), if the policy instrument is set suboptimally, additional public information about an efficient disturbance can become socially costly. Lastly, because of the increase in household information, welfare losses are now also overall of a smaller magnitude.

Limited Higher-Order Expectations: Finally, our conclusions also extend to case in which we directly decrease the amount of higher-order expectations that households, firms, and the central bank compute, or decrease the discount factor. In these cases, both the benefits and costs of disclosure decrease (Appendix E.4 and E.5). Yet, because of the relative symmetry

[43]See also the derivations in footnote 37.

Table IV: Welfare Effects of Disclosure: Alternative Specifications

	A. Mark-up Shock Case					
	Baseline	*Dispersed*	*Household*	*Limited k*	*Discount Rate*	*Signaling*
$\phi = 1.81$	-58.54	-62.33	-13.44	-41.06	-62.95	-58.94
$\phi^{\star} \to \infty$	-26.64	-50.38	-12.25	-38.15	-32.39	-26.75
	B. Productivity Shock Case					
	Baseline	*Dispersed*	*Household*	*Limited k*	*Discount Rate*	*Signaling*
$\phi = 1.81$	$+11.36$	$+7.78$	$+0.22$	-18.72	$+8.23$	$+11.46$
$\phi^{\star} \to \infty$	-28.49	-29.61	-9.95	-2.98	-25.21	-29.23

(i) The first row in Panel A and B shows the %change in life-time consumption due to full disclosure. The second row, by contrast, shows the %change in life-time consumption due to changes in central bank uncertainty that are caused by full disclosure (evaluated at the optimal monetary policy).
(ii) The productivity shock case nets out firm benefits of disclosure (see Table III).
(iii) Dispersed information ($\sigma_x^{\mu} = 0.50$, $\sigma_{x,f}^{\mu} = 0.11$; $\sigma_x^a = 0.60$, $\sigma_{x,f}^a = 0.20$); discount rate ($\beta = 0.75$); limited higher-order expectations ($k = 3$); no signaling ($i_t \notin \Omega_t^f$); and household full information.

of the decrease in costs and benefits, the quantitative effects of disclosure remain similar to those in Table II and III (Table IV).[44]

Summary of Quantitative Results: Combined, the quantitative results illustrate the importance of higher-order uncertainty for an accurate picture of the social value of central bank disclosure. Specifically, the quantitative results have shown that for realistic parameter values disclosure provides the central bank with more information, both indirectly about private sector expectations and by directly simplifying the central bank's own inference problem when it learns from market outcomes. And although the extended model merely provides a first pass at a full quantitative assessment, the results suggest that the welfare benefits that arise from an improved conduct of monetary policy could be substantial. Indeed, they could make disclosure beneficial even in cases when other prominent forces push towards opacity.

8 Concluding Remarks

In this paper, I have explored the consequences of policymakers' need to learn additional information for the social value of policymaker disclosures. At the heart of my results has been that communication decreases higher-order uncertainty. A central bank's disclosure not only provides more information to the private sector, but also increases common knowledge between the private sector and the central bank. This has important consequences for what

[44] One noteworthy difference is that (when we restrict the amount of higher-order expectations computed) central bank disclosure decreases central bank uncertainty in the productivity shock case even under the pre-Feburary 1994 baseline value of monetary policy.

the central bank knows about private sector expectations, what it can learn from private sector actions, and hence for the set of potential outcomes that monetary policy can attain. In this sense, the benefits of disclosure that I have stressed in this paper arise from its capacity to increase the efficacy of central banks' traditional policy instrument, monetary policy.

My results also speak to the current debate about the efficacy of central bank forward guidance. Recent work by Wiederholt (2017) and Angeletos and Lian (2018) has shown how incomplete common knowledge among agents dampens general equilibrium multipliers of expected monetary policy. Yet, as argued by Weale (2013) and others, rather than change average future interest rate expectations *per se*, forward guidance often simply creates less dispersed expectations; expectations which are also more closely aligned with the central banks' own. My results suggest that forward guidance by decreasing higher-order uncertainty between the private sector and the central bank increases the potential efficacy of subsequent monetary policy choices. I further conjecture such decreases in higher-order uncertainty could more generally have important consequences for how public disclosures interact with the preponderance of macroeconomic puzzles that rest on powerful effects of policy.[45]

[45] See, for example, the "Forward Guidance Puzzle" (McKay *et al.*, 2016; Werning, 2015; Angeletos and Lian, 2018), or "The Paradox of Toil" with decreases in labor taxes (Eggertsson, 2010; Mulligan, 2010).

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