Optimal Monetary Policy when Information is Market-Generated*†

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Abstract

The nature of the private sector's information changes the optimal conduct of monetary policy. When firms observe their individual demand and use it as a signal of real shocks, the optimal policy consists in maximizing the information content of that signal. When real shocks are deflationary (like labor supply shocks), the optimal policy is countercyclical and magnifies price movements, which contrasts with the exogenous information case, where optimal monetary policy is procyclical and stabilizes prices. When the central bank communicates its information to the public, this policy is still optimal if firms pay limited attention to central bank announcements.

Keywords: Optimal monetary policy, information frictions, endogenous information, expectations, central bank communication.

JEL codes: D83, E32, E52, F32.

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Central banks devote many resources to economic analysis, forecasting and communication. Yet, there is growing evidence that private agents pay little attention to publicly available data.[1] Moreover, firms' pricing decisions seem mostly related to sectoral conditions, rather than to aggregate conditions.[2] In this context, how can the central bank optimally use its information? Our answer is that the central bank can affect the local market conditions to which agents pay attention, in order to influence their decisions. Our main results are the following: (i) when firms learn from their market, the optimal monetary policy is the one that maximizes the information content of market variables; (ii) the optimal policy mimics a world where the central bank directly communicates its information to the public, without any need to rely on agents' attention to central bank announcements.

Using a one-period model with monopolistically competitive firms and imperfect information on aggregate shocks, we show that the nature of the information held by firms has crucial implications for monetary policy. In particular, the conduct of monetary policy changes if firms learn from their local market, instead of learning exclusively from exogenous noisy signals about fundamentals, as typically assumed. With exogenous information, nominal demand does not affect the signals firms observe, so it is not correctly anticipated by firms. Policy can then use surprise changes in nominal demand to manage economic activity. In this context, the central bank uses the "surprise channel" of monetary policy to produce real effects and maximize welfare.

When instead firms observe their individual demand and use it as an endogenous signal, the surprise channel vanishes. From their individual demand, firms extract a "demand signal", which is partially driven by aggregate nominal demand. Using this information, firms adjust their prices in a way that offsets nominal changes in aggregate demand, including those driven by monetary policy. As a result, the "surprise channel" disappears. Importantly, this result does not require firms to perfectly identify nominal aggregate demand. Indeed, local demand gives only partial information about aggregate demand. However, as the central bank does not have *direct control* over firms' errors, it loses its ability to manage output through surprise changes in nominal demand. Yet, the central bank can still influence agents' decisions by exploiting what we call the "signaling channel". The optimal strategy for the central bank is then to implement the "signaling policy", which consists in maximizing the information content of the demand signal.

This signaling policy can differ substantially from standard policy. Price stabilization

[1] See Carroll (2003) Mankiw *et al.* (2003), Coibion and Gorodnichenko (2012), Coibion *et al.* (2018).

[2] See, among others, Bils and Klenow (2004) and Boivin *et al.* (2009). Mackowiak and Wiederholt (2009) explain how these facts can arise from endogenous attention.

is typically optimal when information is exogenous.[3] Instead, in our setup with endogenous information, the demand signal is increasing in both nominal aggregate demand and aggregate price, where aggregate price reflects other firms' private information on real shocks. To maximize the information content of the demand signal, the signaling policy targets a positive correlation between nominal demand and prices, thus emphasizing the natural response of the demand signal to real shocks. Price stabilization is not optimal in this case.

To understand what the signaling policy looks like, consider a positive labor supply shock that decreases the marginal cost. If firms receive positive private signals on the shock, they reduce their individual prices. As many firms receive positive private signals, the aggregate price goes down, thus reducing the nominal demand of each individual good. A decline in the demand signal is therefore good news for a firm, as it signals that other firms in the market have observed a positive supply shock. As the central bank gets also a positive signal on the supply shock, the signaling policy consists in reducing money supply, which further reduces firms' nominal individual demand. This makes the demand signal a better signal of the supply shock and enables firms to set prices more accurately. The signaling policy is therefore counter-cyclical, while the standard policy with exogenous information would be procyclical to stabilize prices.

Moreover, we show that the signaling policy is a substitute for central bank communication. In fact, the signaling policy achieves optimality precisely by making the demand signal coincide with the signal firms would build if they had direct access to central bank's information. The signaling policy is thus a substitute for central bank's direct communication, and it is optimal whenever there are frictions in the transmission of central bank information to firms, for instance when firms pay limited attention to public disclosures.[4] When agents learn from their local demand, the limitations of central bank communication can be overcome through the signaling channel.

The degree of precision with which firms observe their demand signal is key to our results. We consider a general setting where firms observe the demand signal with noise.

[3]The optimality of price stabilization under exogenous information is a robust result. See for instance Ball *et al.* (2005), Adam (2007), Lorenzoni (2010), Paciello and Wiederholt (2014). They extend the sticky-price New-Keynesian literature, which has also established the benefits of price stability. This result is however relaxed when firms make production decisions along with pricing decisions (Angeletos and La'o, *forth.*), or when agents misuse information (Lorenzoni, 2010), or when the perfect-information allocation is suboptimal, as in the case of markup shocks (Ball *et al.,* 2005; Adam, 2007). Paciello and Wiederholt (2014) show that, even with markup shocks, price stabilization is optimal when attention is endogenous.

[4]See for instance Kohlhas (2017), who questions the use of central bank announcements when central bank communication is imperfect.

This formulation nests two cases: the exogenous information case, when the demand signal is infinitely noisy, and our baseline model, when the demand signal is perfectly observed. When the noise is small enough, optimal policy switches from being procyclical to being countercyclical. Furthermore, our results hinge on the fact that, in the absence of information frictions, the real shocks that we consider would drive efficient fluctuations of output. When instead we introduce "inefficient shocks" (i.e., markup shocks), the optimal policy consists in minimizing the informativeness of the demand signal. This result is in line with the literature on the social value of information.[5] In all remaining extensions, including alternative information structures, infinite horizon and a more realistic central bank target, our results carry through: the optimal policy consists in making the demand signal a better signal of real shocks.

Phelps (1969) and Lucas (1972) have been the first ones to underline the informational content of market variables. The way endogenous information affects economic outcomes has also been analyzed in more recent papers.[6] In this literature, optimal policy (as well as central bank communication) has been considered mostly in a context where firms observe market prices (e.g., Amador and Weill, 2010). We crucially shift our attention to the role of local demand, which is only partially driven by the aggregate price and responds to monetary policy. We contribute to this literature by showing that, if firms observe their local demand, the surprise channel of monetary policy loses its bite and a new channel appears, the market signaling channel.

The empirical literature supports our assumption that the central bank has some information that can be communicated through public statements and policy actions.[7] Baeryswil and Cornand (2010), Berkelmans (2011) and Tang (2015), have explored theoretically the consequences of the signaling channel of monetary policy instruments. Our signaling channel differs from theirs as we assume that agents' main source of information is their own local market. As for direct central bank communication, we do not rule it out and consider it jointly with our market signaling channel.

Section 1 presents our baseline model. Section 2 describes the equilibrium. Section 3 studies optimal monetary policy. Section 4 introduces central bank communication. Section 5 presents extensions of the baseline setup and Section 6 concludes.

[5] See Angeletos and Pavan (2007) and Angeletos *et al.* (2016).

[6] See for instance Angeletos and Werning (2006), Amador and Weill (2010), Hellwig and Venkateswaran (2009), Chahrour and Gaballo (2018), Kohlhas (2017), Gaballo (2016; 2018) Benhima (*forth*).

[7] See for instance Romer and Romer (2000), Melosi (2016), Nakamura and Steinsson, (2018).

1 The model

We consider a one-period model with flexible prices. A representative household consumes a bundle of goods Y and supplies competitively a quantity N of homogeneous labor to a continuum of firms. Firms, which are owned by the household, are indexed by $i \in [0, 1]$. Each firm i produces a quantity Y_i of a differentiated good using a quantity N_i of labor, and sets prices monopolistically. The central bank conducts monetary policy with the goal of maximizing the household's utility. The economy is hit by a labor supply shock, which is not directly observed by firms nor by the central bank.

1.1 Household and firms

Household The utility function of the representative household depends on his consumption bundle, Y, on his labor, N, and on a labor supply shock, Z:

$$u(Y, N, Z) = \frac{Y^{1-\phi}}{1-\phi} - Z^{-1}\frac{N^{1+\eta}}{1+\eta}, \tag{1}$$

Y, the consumption bundle, is defined as $Y = \left(\int_0^1 C_i^{\frac{\varrho-1}{\varrho}} di\right)^{\frac{\varrho}{\varrho-1}}$, where C_i is the consumption of good i and $\varrho > 1$ is the elasticity of substitution between goods. $\phi > 0$ is the inverse of the elasticity of intertemporal substitution and $\eta > 0$ is the inverse of the Frisch elasticity of labor supply.

Z is a labor supply shifter, so we refer to it as the "supply shock". The supply shock, Z, moves the perfect-information level of output. $z = \log(Z)$ has a Gaussian distribution with mean zero and variance σ_z^2: $z \sim \mathcal{N}(0, \sigma_z^2)$. The household's budget constraint is

$$\int_0^1 P_i C_i di = \int_0^1 \Pi_i di + WN \tag{2}$$

where $\int_0^1 \Pi_i di$ is the sum of profits distributed by firms, P_i is the price of good i and W is the nominal wage.

The household shops the differentiated goods. He observes the prices and the quantities purchased. The individual good demand equation is then given by:

$$C_i = Y\left(\frac{P_i}{P}\right)^{-\varrho}, \tag{3}$$

where the consumer price index, P, is an average of the individual prices:

$$P = \left(\int_0^1 P_i^{1-\varrho} di \right)^{\frac{1}{1-\varrho}}. \tag{4}$$

Firms Firm i produces good i using the following linear technology:

$$Y_i = N_i, \tag{5}$$

Firm i is a price-setter. She chooses P_i monopolistically in order to maximize her expected profits, $\Pi_i = P_i Y_i - W N_i$, subject to the individual good demand equation, (3), the production technology, (5), and equilibrium in the goods market, $C_i = Y_i$, $i \in [0,1]$.

Denote by I_i the information set of firm i when she decides the price. We denote by $E_i(.) = E(.|I_i)$ the individual expectations and by $\bar{E}(.) = \int_0^1 E_i(.)di$ their cross-individual average.

We solve the firm's problem using a log-linear approximation and denote variables in logs by lower-case letters. In log terms, the optimal price set by the individual firm i is equal to the expected nominal marginal cost, which corresponds to the expected nominal wage, plus a constant markup: $p_i = E_i(w) + \log[1 + 1/(\varrho - 1)]$. The nominal wage is equal to the household's nominal marginal rate of substitution between consumption and labor. Neglecting constant terms, the optimal price is then (the details can be found in online appendix B.1):

$$p_i = \chi E_i(p) + (1-\chi)[E_i(q) - \delta E_i(z)], \tag{6}$$

where $\delta = 1/(\eta + \phi)$, $\chi = 1 - (\eta + \phi)$, q is nominal aggregate demand, defined as

$$q = y + p. \tag{7}$$

The price-setting equation (6) states that the optimal price of each good i is related positively to the nominal aggregate demand q and negatively to the labor supply shock z. We refer to these terms as the *nominal* determinant and the *real* determinant of prices. If $\chi > 0$ (i.e. $\eta + \phi < 1$), there are some strategic complementarities in price-setting.

Quantity equation The model is closed simply with a quantity equation. That is, we assume a cash-in-advance constraint that implies:

$$q = m + v, \tag{8}$$

where m is the log of money supply set by the central bank and $v \sim \mathcal{N}(0, \sigma_v^2)$ is a nominal shock (e.g. a velocity shock). This assumption captures the fact that there are exogenous shifts in nominal aggregate demand that monetary policy cannot control.

The demand y_i for the individual good i can be also written in log-linear form:

$$y_i = y - \varrho(p_i - p), \tag{9}$$

where we used the equilibrium relation $c_i = y_i$.

1.2 Information Structure

The household and the firms have different information sets. We assume, without loss of generality, that the household knows all the shocks.[8] Firms do not know z and participate only in the market for good i, so they have a more limited information set.

Exogenous signals Firm i does not observe z. Instead, she observes a private exogenous signal on z:

$$z_i = z + \varepsilon_i$$

where $\varepsilon_i \sim \mathcal{N}(0, \sigma_\varepsilon^2)$ and ε_i averages out in the aggregate: $\int_0^1 \varepsilon_i di = 0$.

Firms do not observe the nominal shock v either. This assumption is important as it will prevent firms from learning z from endogenous variables.

Importantly, we assume that firms cannot observe money supply, m nor nominal aggregate demand, q, nor any other aggregate variable. This assumption hinges on the empirical evidence that firms pay little attention to publicly available data, but also on the fact that aggregate information is typically not contemporaneously available to firms.

Market timing and demand signal We assume that the labor market opens after the goods market. In the beginning of the period, each firm i sets her price p_i and receives an order y_i from the household. At the end of the period, firms go on the competitive labor market and observe the nominal wage w. Therefore, when firm i sets her price p_i, she observes the demand for her good, but she does not know the nominal wage. As a result, the price is conditional on a limited information set. This assumption is crucial because observing the nominal wage would make the nominal marginal cost inference

[8] Even if the household does not directly observe all the shocks, he has all the relevant information. Indeed, the household perfectly observes the labor supply shock z, as well as the set of prices and quantities, because he participates in all markets.

problem trivial, as firms would observe it directly. Notoriously, marginal costs are difficult to measure.[9]

When setting her price, firm i observes her individual demand y_i. By combining her individual demand y_i and her price p_i, the firm can construct an endogenous signal $\tilde{y}$ that is independent of idiosyncratic shocks:

$$\tilde{y} = y_i + \varrho p_i = q + (\varrho - 1)p, \tag{10}$$

where we used Equation (9) and the quantity Equation (8). $\tilde{y}$ is an adjusted measure of the demand for goods that is invariant across goods. We refer to $\tilde{y}$ as the "demand signal". It depends positively on both nominal aggregate demand q and the aggregate price p.

To understand, consider the limit case where $\varrho \to 1$, where $\tilde{y} \to y_i + p_i = q$.[10] In this limit case, $\tilde{y}$ converges to the total spending on good i. Households consume a smaller quantity of more expensive goods, but they still spend equal amounts across goods. Thus, spending on individual goods is proportional to total spending q. The nominal demand for good i, observed by firm i, is therefore a good indicator of total nominal demand q.

On the contrary, when $\varrho \to +\infty$, goods become perfect substitutes and the endogenous signal becomes driven exclusively by the price level. Firms then observe the signal $p_i = p$.[11] Under perfect substitutability between goods, the goods market becomes perfectly competitive, and prices must equalize. The price that households are willing to pay for the individual good i therefore reveals the competitors' price, which is p.

When ϱ is at an intermediate level, the demand signal is a combination of the state of aggregate nominal demand, q, and of the aggregate price, p, with a larger weight on prices when ϱ is large. Intuitively, for a given individual price, p_i, a higher demand y_i can be driven either by higher aggregate demand q or by a higher competitors' price p. The role of prices becomes larger as the elasticity of substitution increases.

Finally, in order to make our analysis more general, we allow for the possibility that y_i is observed with an individual noise x_i, with $x_i \sim N(0, \sigma_x^2)$. Firms thus observe a noisy endogenous signal $\tilde{y}_i = \tilde{y} + x_i$. Note that the exogenous information assumption is nested for $\sigma_x = +\infty$. In our baseline model we focus on the limit case with $\sigma_x = 0$, where the endogenous signal $\tilde{y}$ is perfectly observed.

[9] The difficulties associated with the measurement of the marginal cost have been emphasized by Bils (1987), Rotemberg and Woodford (1999), Bils and Kahn (2000).

[10] The markup $\varrho/(\varrho - 1)$ goes to infinity when ϱ goes to 1, but is still well-defined for $\varrho > 1$.

[11] This can be seen by writing the endogenous signal as $\tilde{y}/(\varrho - 1) = (y_i + p_i)/(\varrho - 1) + p_i = q/(\varrho - 1) + p$. With $\varrho \to +\infty$, the endogenous signal $\tilde{y}/(\varrho - 1)$ converges to $p_i = p$.

Information of the Central Bank The monetary authority observes neither the real shock, z, nor the nominal shock, v. Similarly to firms, it receives a noisy signal z^{cb}:

$$z^{cb} = z + \xi$$

where $\xi \sim \mathcal{N}(0, \sigma_\xi^2)$ is the central bank noise. We abstract for the moment from central bank's direct communication of its signal z^{cb}, by assuming that firms do not observe z^{cb}.

1.3 Monetary Policy

The goal of the central bank is to choose money supply, m in order to maximize the welfare of the representative agent. In online appendix B.2, we show that this is akin to minimizing a loss function L whose arguments are the volatility of the price gap and the dispersion of individual prices:

$$L = V(p - p^*) + \Phi V(p_i - p) \tag{11}$$

where $\Phi = \varrho/(1-\chi)$ and p^* is the optimal price level that would hold under perfect information:

$$p^* = q - \delta z$$

p^* depends on the nominal aggregate demand, q, and on the perfect information output $y^* = \delta z$. Under perfect information, firms would decrease their price in response to a positive supply shock. On the contrary, they would increase their price in response to an increase in nominal aggregate demand.[12]

Money supply is assumed to react linearly to the central bank signal: $m = \beta z^{cb}$. The nominal aggregate demand defined in Equation (8) therefore boils down to:

$$q = \beta(z + \xi) + v = \beta z + \nu, \tag{12}$$

where $\nu = \beta\xi + v$ is the total nominal disturbance, which depends on the central bank noise ξ and on the nominal shock v. We assume that the central bank commits to β before the realization of the shocks.

[12] The price gap is tightly linked to the output gap $y - y^*$, as $y - y^* = -(p - p^*)$. Therefore, $V(y - y^*) = V(p - p^*)$. The loss function thus represents the standard central bank's dual goal of stabilizing the output gap and limiting price dispersion. It is however useful in our context to focus on the price gap.

2 Equilibrium in the baseline model

In this section, we study the equilibrium for a given policy parameter β in the baseline model, when the endogenous signal $\tilde{y}$ is perfectly observed by firms ($\sigma_x = 0$). We focus especially on how monetary policy influences equilibrium outcomes.

An equilibrium is a set of quantities $\{y_i\}_{i\in[0,1]}$, and prices $\{p_i\}_{i\in[0,1]}$ such that price-setting follows (6), aggregate demand follows (7), monetary policy follows (12), $p = \int_0^1 p_i di$ and $y = \int_0^1 y_i di$, and the information set I_i of price setter i includes z_i and y_i for all $i \in [0,1]$.

2.1 A Simple model

Before analyzing the full model, we present a simple version of it. We show how the introduction of endogenous information leads us from a situation in which monetary policy uses the traditional "surprise channel", to a new one in which the central bank exploits the "signaling channel" that we emphasize in this paper.

In this simple model, we assume that the demand signal observed by firms is equal to q. This corresponds to a limit case of our model where ϱ goes to 1 and where the demand signal $\tilde{y}$, described in Equation (10), converges to nominal demand q.[13] We also assume that the central bank is perfectly informed ($\xi = 0$), so that $z^{cb} = z$, and that there is no nominal shock ($v = 0$). This means that there is no nominal demand disturbance ($\nu = 0$) and that nominal demand depends only on the response of the monetary instrument to z: $q = \beta z$. Finally, we assume that there are no strategic complementarities ($\chi = 0$). For the intuition, we focus on the individual price gap $p_i - p^* = p_i - p + p - p^*$, as helping firms set their individual price at the optimal level p^* contributes both to closing the price gap $p - p^*$ and to limiting individual price deviations from the mean $p_i - p$.

Individual price gap Under the simplifying assumption that there are no strategic complementarities ($\chi = 0$), the equilibrium individual price gap satisfies:

$$p_i - p^* = [E_i(q) - q] - \delta[E_i(z) - z]. \tag{13}$$

This gap is simply a function of the errors made by firms on q and z.

[13] At this stage we cannot rule out a discontinuity in the model. However, in online appendix B.7, we show that the solution of the simple model does correspond to the limit of the full model when $\varrho \to 1$.

Exogenous Signal Only Let's first assume that firms do not observe the demand signal and that they can only use their private signal z_i, so that $E_i(.) = E(.|z_i)$. In this case, firms make errors on q,

$$E_i(q|z_i) - q = E(q|z_i) - q = \beta[E(z|z_i) - z], \tag{14}$$

that the central bank can exploit by using the policy parameter β. Equation (13) then becomes

$$p_i - p^* = (\beta - \delta)[E(z|z_i) - z] \tag{15}$$

By setting $\beta = \delta$, the central bank reaches the first best. Namely, the optimal way to exploit the surprise in q is to move aggregate demand in line with optimal supply ($q = \delta z$). By doing so, the central bank nails the optimal price down to zero and makes the informational problem of firms irrelevant. Stabilizing prices is then the optimal policy.

Since, under exogenous information, monetary policy manages output by using surprises in nominal demand, we say that it acts through the "surprise channel".

Endogenous signal and cursed firms Now, we assume that firms perfectly observe the demand signal, which is equal to q in this simple model. Nevertheless, we assume that firms are *cursed* in the sense of Eyster and Rabin (2005). They do not extract any information from q regarding the state of the real shock z, i.e., they neglect the reasons why nominal demand changes. In this case, firms make no errors on q:

$$E_i(q) - q = E(q|z_i, q) - q = 0, \tag{16}$$

but still make errors on z: $E_i(z) - z = E(z|z_i) - z \neq 0$. As a result, the price gap is now independent of the monetary policy parameter β but still depends on firms' errors on z:

$$p_i - p^* = -\delta[E(z|z_i) - z] \tag{17}$$

Firms adjust the nominal component of their price perfectly by changing their prices proportionally to changes in aggregate demand, but they do not use the endogenous signal to infer the real component. In the presence of the endogenous signal, monetary policy becomes completely neutral as it loses its ability to surprise agents.

Endogenous Signal and Rational Firms We now suppose that firms are not cursed, i.e., they know the central bank's reaction function and they are aware that the demand signal $q = \beta z$ gives information regarding the state of the real shock z. As a result, when agents observe variations in q, they understand that they are due to the real shock, as long as $\beta \neq 0$: $E_i(z) = E(z|z_i, q) = E(z|z_i, \beta z) = z$. As firms know both the real and the nominal components of the marginal cost, we have $p_i = p^*$.

Here, the surprise channel is still absent, but the action of the central bank helps firms learn the real shock, for any $\beta \neq 0$. The surprise channel is then replaced by a market signaling channel, which we call for short the "signaling channel". If, before, the central bank was directly steering the economy towards its first best, now the central bank uses monetary policy to transmit its knowledge to the public and maximize the informational content of market variables, leading firms to behave optimally.

Until now we have considered a demand signal that perfectly reflects monetary policy, which naturally makes the signaling channel overrule the traditional surprise channel. In what follows, we examine in a more complex setting the conditions under which the signaling channel prevails and how the central bank can best exploit it.

2.2 The full baseline model

We now go back to the general case with central bank noise ($\sigma_\xi > 0$), nominal shocks ($\sigma_v > 0$) and $\varrho > 1$. We thus have that $q = \beta z^{cb} + v = \beta z + \nu$, with $\nu = \beta \xi + v$. In this more general case, the endogenous signal has to be determined in equilibrium. We also allow for strategic complementarities ($\chi \geq 0$). The individual price gap now depends on price expectations as well:

$$p_i - p^* = \chi[E_i(p) - p^*] + (1 - \chi)\{[E_i(q) - q] - \delta[E_i(z) - z]\} \tag{18}$$

Endogenous signal and signal extraction Following the literature, we restrict ourselves to analyze linear equilibria. We guess that, by normalizing the demand signal $\tilde{y}$, firms extract an endogenous signal of the form:

$$\tilde{z} = z + \kappa^{-1}\nu,$$

where κ is the elasticity of the demand signal to z relative to ν. Similarly to what happens in Lucas' economy, firms cannot precisely understand whether changes in their individual demand are due to the nominal disturbance, represented by ν, or to the real shock, represented by z.

Agents use their exogenous signal z_i and the endogenous one $\tilde{z}$ when expressing their expectations:

$$E_i[z|z_i, \tilde{z}] \quad = \quad \gamma z_i + \tilde{\gamma}\tilde{z}, \tag{19}$$

where $\gamma = \sigma_\varepsilon^{-2}/[\sigma_\varepsilon^{-2} + \sigma_z^{-2} + P]$ and $\tilde{\gamma} = P/[\sigma_\varepsilon^{-2} + \sigma_z^{-2} + P]$ are Bayesian weights, with P the precision of the endogenous signal $\tilde{z}$.

Equilibrium endogenous signal and equilibrium price gaps We show that our guess is verified and we characterize the solution for κ. We do this by guessing and verifying that individual prices are linear functions of the signals z_i and $\tilde{z}$, before deriving the equilibrium demand signal $\tilde{y}$, then normalizing it. The following Lemma (all proofs are in online appendix B) characterizes the solution:

Lemma 1 *For a given policy parameter β, κ is characterized in equilibrium by*

$$\kappa = \beta - \lambda. \tag{20}$$

where λ is given by

$$\lambda = \frac{(\varrho - 1)(1 - \chi)\gamma\delta}{1 + [\varrho(1 - \chi) - 1]\gamma} \tag{21}$$

A solution for κ always exists and, when $\beta < 0$, it is unique.

The demand signal $\tilde{y}$ depends positively on both nominal demand and prices. The total response of the signal to the real shock, κ, can thus be decomposed into two terms: β, the policy-induced response of nominal demand to z, and $-\lambda$, the "natural" response of prices to z. The "natural" response of the signal to z is negative because it is optimal for firms to decrease their price if they expect a positive supply shock.

Using the definition of the endogenous signal with Equations (12) and (20), we can show that $\tilde{z}$ depends on q and z:

$$\tilde{z} = \kappa^{-1}(q - \lambda z). \tag{22}$$

Importantly, the fact that the demand signal depends on nominal demand and on the real shock implies that the surprise channel disappears. Given that agents directly observe $\tilde{z}$, we find that:[14]

$$E_i(q) - q = \lambda[E_i(z) - z]. \tag{23}$$

[14]From Equation (22) it follows that $E_i(q) - q = \lambda[E_i(z) - z] + \kappa[E_i(\tilde{z}) - \tilde{z}]$. Additionally, we use $E_i(\tilde{z}) = \tilde{z}$ to get Equation (23) .

Agents do not perfectly observe nominal demand q, but now their errors depend on the parameter λ, which is not under the control of the central bank. Namely, there is a surprise, but the central bank cannot use it to manage output. In contrast, in the simple model with exogenous information, agents did not have any endogenous signal and their errors on q depended on the policy instrument β (see Equation (14)). In that context, the central bank could intervene and exploit the surprise channel to reach the first best.

At the core of this result is the endogenous nature of the demand signal, which puts a constraint on the surprise about q. To understand, abstract for a moment from the role of the demand signal as a signal of z (as in the cursed firms' assumption), and suppose that the demand signal increases. To firms, this increase can come either from an increase in q, or from an increase in prices, i.e., a decline in z, as can be seen from Equation (22). For *given beliefs about* z, firms *fully* attribute the increase in the demand signal to q, and adjust their prices accordingly. So, for given beliefs about z, prices move one-for-one with q. Of course, if beliefs about z are incorrect, then the assessment of q is also incorrect, as implied by Equation (23). In any case, this error is never directly controlled by the central bank.

As a consequence, the average price gap and the individual price deviation from the mean do not directly depend on the policy parameter β, thus leaving no room for the surprise channel of monetary policy. Indeed, as shown in online appendix B.4, Equations (18) and (22) yield:

$$\begin{aligned} p - p^* &= (\lambda - \delta) \quad (1 + \gamma\tilde{\chi}) \quad \left[\bar{E}(z) - z\right] \\ p_i - p &= (\lambda - \delta) \quad [1 - (1 - \gamma)\tilde{\chi}] \quad \left[E_i(z) - \bar{E}(z)\right] \end{aligned} \tag{24}$$

where $\tilde{\chi} = \chi/(1 - \chi\gamma)$, $E_i(z)$ follows Equation (19), and $\bar{E}(z) = \int_0^1 E_i(z)di$.

In other words, even though there are surprises on nominal aggregate demand, there is no surprise channel. However, as we show in the next section, monetary policy can still improve the quality of agents' information and get closer to the optimal allocation by exploiting the signaling channel.

3 Optimal monetary policy

The goal of the central bank is to set β in order to minimize the loss function (11). We first analyze optimal monetary policy in the baseline model with no noise in the endogenous signal ($\sigma_x = 0$) and then we study how our results are affected by the precision of the endogenous demand signal by allowing some noise ($\sigma_x > 0$).

3.1 Baseline model

Since $\nu = \beta\xi + v$, the precision of the endogenous signal $\tilde{z}$ is $\kappa(\beta)^2(\sigma_v^2 + \beta^2\sigma_\xi^2)^{-1}$, where $\kappa(\beta)$ is defined by Equation (20). We denote this precision as $P(\beta)$. We define the signaling policy as the policy that maximizes the information on z contained in $\tilde{z}$:

Definition 1 (The signaling policy) *The signaling policy is the policy that maximizes the precision of the endogenous signal $P(\beta)$.*

The following Lemma characterizes the optimal policy as the signaling policy:

Lemma 2 *The optimal policy that minimizes L under the constraint* (24)*, with $\kappa = \kappa(\beta)$ as defined by Equation* (20)*, is the signaling policy.*

Lemma 2 shows that information is the only concern of monetary policy. More specifically, only information on the *real* shock matters. Indeed, the endogenous signal, as defined in Equation (22), depends on q and z, which implies that the errors on z and q are related, as shown in Equation (23). Improving information on the real component of the endogenous signal then also helps firms assess better the nominal component. This generates a form of "divine coincidence", since the policy-maker does not need to choose between improving information on one or the other component. As a result, the signaling policy that maximizes the precision with which agents observe the real shock is also the optimal one.

The optimal β can be characterized using Lemma 2. As β increases in absolute value, the sensitivity of the signal to the real shock z ($\kappa(\beta)$) rises as well, thus increasing its precision. However, the same increase in β also inflates the noise of the signal ν. The signaling policy trades off these two effects, as shown in the following Proposition:

Proposition 1 *The optimal monetary instrument β^* is the unique solution to*

$$\beta^* = -\frac{\sigma_v^2}{\lambda(\beta^*)\sigma_\xi^2}, \tag{25}$$

with $\lambda(\beta) = \kappa(\beta) - \beta$.

The value of β^* is negative. This derives from the fact that $\kappa = \beta - \lambda$. For $\tilde{z}$ to be a good signal, κ needs to be large in absolute value. As compared to setting a positive β, setting a negative β generates a larger κ in absolute value, while adding the same amount of noise. As a result, a negative β is preferable.

Namely, the central bank uses a counter-cyclical monetary policy to emphasize the natural effect of the real shock on the demand signal. Given that an increase in z would naturally decrease the demand signal through lower prices, the monetary authority emphasizes that movement by reducing nominal demand, which further lowers the demand signal. In doing so, the monetary authority targets a positive correlation between money supply and the price level. This implies that the signaling policy emphasizes the response of prices to real shocks, contrary to a standard policy.

Comparative statics on Equation (25) show that the absolute value of β^* is decreasing in the variance of the central bank noise σ_ξ^2. A reactive policy is more costly in terms of noise if the information of the central bank is less precise. At the same time, the absolute value of β^* is increasing in the variance of the nominal shock, σ_v^2, as the benefits of an active policy are greater when the endogenous signal is made more noisy by nominal shocks. In the limit case where there are no nominal shocks ($\sigma_v = 0$), β^* goes to zero, as the endogenous signal naturally fully reveals z. Finally, the absolute value of β^* is decreasing in the term λ, the "natural" elasticity of the demand signal to z. Indeed, a strong policy response is less necessary when the non-policy part of the endogenous signal is relatively more informative. This is the case when private information is more precise (γ is larger, i.e. σ_ϵ is lower) and when strategic complementarities are milder (χ is lower).

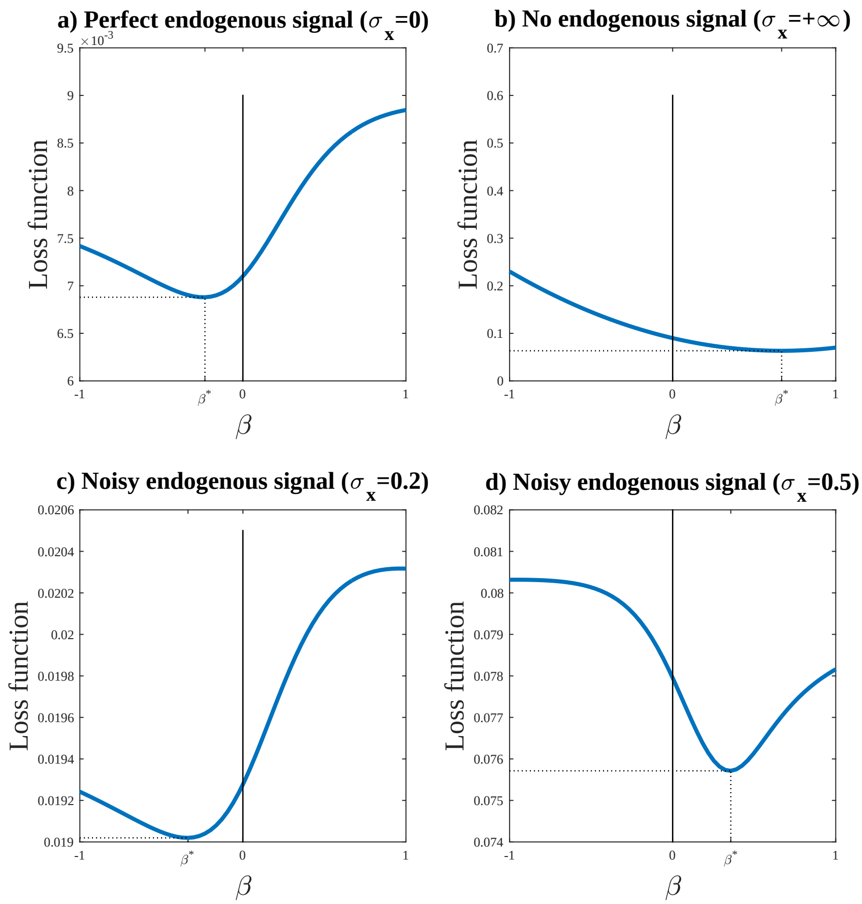
Competition and optimal policy Consider more specifically the role of ϱ, which measures the degree of competition between goods. When ϱ increases, λ increases as well and β^* is smaller in absolute value. As ϱ increases, the average price p gets a larger weight in the endogenous signal. As p aggregates the private information of firms on z, $\tilde{y}$ becomes a better signal of z. The private information of firms is better revealed, and the role of policy diminishes. Introducing noise through central bank intervention in fact would be more costly, as it blurs the demand signal, which is now a better "natural" signal of z.

This analysis shows that the negative effects of imperfect competition go beyond the standard deadweight loss. Imperfect competition also limits the amount of information revelation through demand signals, by making those signals more sensitive to nominal demand than to prices. The necessity for the central bank to intervene using the signaling policy is therefore stronger whenever competition is weaker.

3.2 The Role of the Endogenous Signal's Precision

In the baseline model, we assumed that the observed individual demand could be perfectly backed out to an endogenous signal that depends only on aggregate shocks. However, it is reasonable to assume that either cognitive limits, or some individual demand shocks could blur the endogenous signal, so that firms observe $\tilde{y}_i = \tilde{y} + x_i$ with $\sigma_x > 0$. The endogenous signal extracted from this observation is therefore perturbed both by the demand shock ν and by the idiosyncratic noise x_i: $\tilde{z}_i = z + \kappa^{-1}\nu + \tau^{-1}x_i$, where κ and τ are endogenous.

Figure 1: Effect of CB noise on Optimal Policy



Note: We set $\varrho = 7$, $\phi + \eta = 0.5$, which yields $\delta = 2$ and $\chi = 0.5$. We set $\sigma_z = \sigma_v = \sigma_\epsilon = 0.1$ and $\sigma_\xi = 0.2$.

The results here are simulated. We take $\phi + \eta = .5$, which yields $\delta = 2$ and $\chi = 0.5$. We set $\sigma_z = \sigma_v = \sigma_\epsilon = 0.1$, $\sigma_\xi = 0.2$, and $\varrho = 7$. Figure 1 represents the loss function expressed as a function of β, for different precisions of the endogenous signal. Panel a) represents the baseline case where the endogenous signal is perfectly observed ($\sigma_x = 0$) and where optimal policy corresponds to the signaling policy, with a negative β^* and a countercyclical optimal policy. Panel b) represents the polar opposite case where firms can only use their exogenous signal z_i ($\sigma_x = +\infty$) and where the traditional surprise channel is active. The loss function of the central bank is minimized for a positive policy parameter β. Here the policy-maker faces a trade-off: by setting β as close as possible to δ, he shuts down firms' incentives to respond to their expectation on z, but he introduces an extra noise due to the error in his signal. As a result, $0 < \beta^* < \delta$. Optimal policy is procyclical so that prices need to respond less to the supply shock.

Panels c) and d) represent intermediate cases. With low noise in the endogenous signal, β^* is negative, as in our baseline. With high noise, β^* is positive, as in the case with no endogenous signal.[15] Indeed, as market signals are less precise, the central bank renounces its signaling channel in order to make use of the more traditional surprise channel. The dominant channel and hence the sign of β^* therefore depends on the precision of the demand signal.[16]

4 Central Bank Communication

Here we examine whether explicit communication by the central bank, which we have ruled out so far, affects our main results. We consider first the case where the central bank can perfectly transfer its signal to the public, then the more realistic one where the central bank communicates its signal to the public with noise. This last scenario applies if the understanding of the public is affected by interpretation errors or inattention.

We show that the signaling policy is a substitute for perfect communication. In fact, we find that when implementing the signaling policy, monetary policy *de facto* mimics the information structure that we observe under perfect communication. An important implication is that the signaling policy is still optimal if communication is noisy.

[15] Online appendix C.1 confirms these insights for a broader range of parameters.

[16] Paciello and Wiederholt (2014) show, in a model with endogenous attention, that price stabilization and lower attention maximize welfare. Price stabilization reduces the need for firms to focus their attention on macroeconomic fundamentals, which enables the central bank to optimally use the surprise channel. This calls into question the optimality of the signaling channel that we emphasize. Note however that minimizing attention is optimal because, in their framework, the central bank is perfectly informed about the economic fundamentals. In our framework, the central bank is not perfectly informed, so it is not necessarily optimal to reduce firms' attention and delegate demand management to the central bank. This can be seen from Figure 1 where the loss function is higher when the endogenous signal is observed with higher noise. See online appendix C.2 for a further discussion on this point.

4.1 Perfect Central Bank Communication

Suppose that the central bank can perfectly communicate its own signal about the real shock, $z^{cb} = z + \xi$, to the public. As a result, firms receive now two exogenous signals, z^{cb} and z_i. Additionally, they can still use the demand signal $\tilde{y}$ as a source of information.

Using z^{cb}, they can perfectly infer the monetary policy component $m = \beta z^{cb}$ of nominal demand q, but they still do not observe the nominal shock v. We thus guess that they can extract an endogenous signal of the form $\bar{z} = z - \lambda_c^{-1} v$, that is built using the demand signal $\tilde{y}$ and the central bank signal z^{cb}.

We show in online appendix B.8 that the equilibrium λ_c is similar to λ in the baseline case with no communication, and is independent of β. The endogenous signal $\bar{z}$ therefore reveals z partly through the "natural" reaction of prices. But, consistently with our guess, policy is irrelevant for the precision of the endogenous signal. Unlike our baseline model, the central bank cannot affect firms' information through monetary policy, because its signal is already in firms' information set.

Even if they observe its policy component, firms still do not fully observe nominal aggregate demand q, so they rely on the demand signal as a nominal source of information, as before. As a result, the equilibrium price gap and the individual price deviation from the mean still depend only on errors about z (see proof in online appendix B.9):

$$
\begin{aligned}
p_{-}p^* &= (\lambda_c - \delta) \quad (1 + \gamma_c \tilde{\chi}_c) \quad \left[\bar{E}(z) - z\right] \\
p_i - p &= (\lambda_c - \delta) \quad [1 - (1 - \gamma_c)\tilde{\chi}_c] \quad \left[E_i(z) - \bar{E}(z)\right]
\end{aligned}
\tag{26}
$$

where $\tilde{\chi}_c = \chi/(1 - \chi\gamma_c)$. The only potential difference between the case with communication and the baseline case then lies in the structure of information about z.

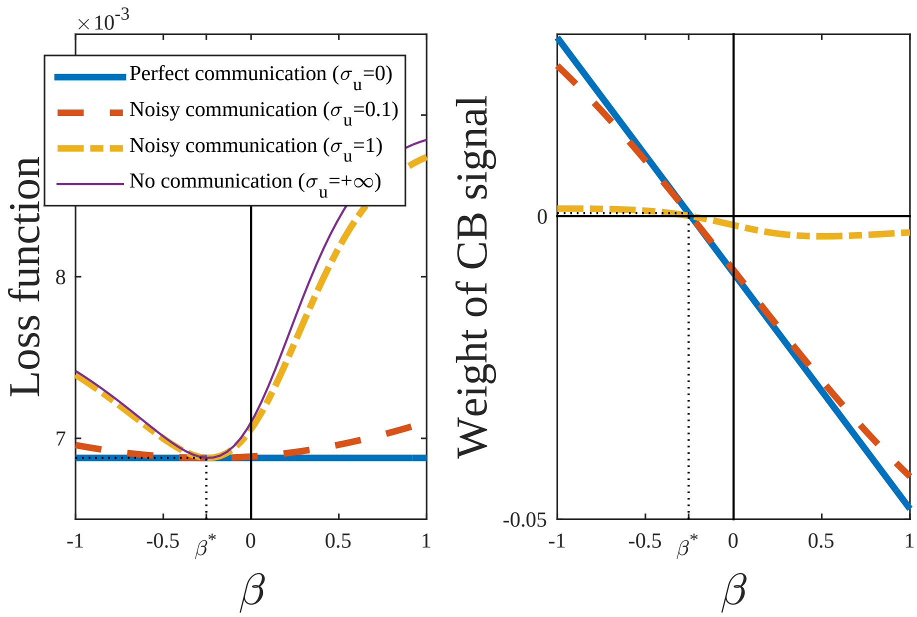
Equilibrium precision of information In the baseline model, β directly affects $\tilde{z}$'s precision, $P(\beta)$. Instead, in the case with perfect communication, z^{cb} and $\bar{z}$ can be combined into a new signal $z^* = E(z|z^{cb}, \bar{z})$, whose precision is given by $P_c = \lambda_c^2 \sigma_v^{-2} + \sigma_\xi^{-2}$, which is independent of policy.

We can prove that, in general, the precision with communication is strictly larger than without communication. Nevertheless, the two precisions are identical when the central bank implements the optimal policy, i.e., when $\beta = \beta^*$:

Proposition 2 *For all $\beta \neq \beta^*$, we have $P(\beta) < P_c$. For $\beta = \beta^*$, we have $P(\beta) = P_c$.*

The intuition is as follows. When firms share the same information as the central bank, they combine the central bank signal z^{cb} with their endogenous signal to optimally extract information about z. To do this, they trade off the informational content of the z^{cb} with the noise it introduces in their expectations. On the contrary, when there is no communication, firms use only their endogenous signal. So, in general, it is easier for firms to infer the real shock with communication. The only exception is when the central bank implements the signaling policy. In that case, the monetary authority itself trades off the informational value of monetary policy with the additional noise it introduces. As a result, the optimal endogenous signal in the no communication case coincides with the signal that optimally combines the central bank signal and the endogenous signal in the communication case (i.e. $\tilde{z}(\beta^*) = z^*$). The signaling policy is therefore a substitute for communication. Note that since firms behave as if they had the same set of signals, the equilibrium prices and quantities are exactly the same in the two cases.

Figure 2: Optimal policy with central bank communication



Note: We set $\varrho = 7$, $\phi + \eta = 0.5$, which yields $\delta = 2$ and $\chi = 0.5$. We set $\sigma_z = \sigma_v = \sigma_\epsilon = 0.1$ and $\sigma_\xi = 0.2$. The weight of CB signal corresponds to α^{cb} when the optimal pricing equation is written as a function of signals: $p_i = \alpha z_i + \tilde{\alpha}\tilde{z} + \alpha^{cb} z^{cb}$.

The left panel of Figure 2 shows that indeed, the loss function in the no communication case becomes exactly equal to the loss function in the perfect communication case for $\beta = \beta^*$. The right panel of the figure shows that the weight firms put on z^{cb} when setting their price is equal to zero when the signaling policy is implemented. The signaling policy in fact makes the central bank signal redundant (see online appendix B.11 for a proof).

4.2 Noisy Central bank Communication

With perfect communication, the central bank can maximize welfare by simply communicating its signal, so the signaling policy is irrelevant. However, when central bank communication is noisy, the signaling policy improves firms' information. Even in the presence of communication, it is optimal to make market information as revealing as possible through monetary policy, as long as communication is noisy.

We assume now that the central bank signal z^{cb} is imperfectly processed by the agents, so that they receive the communication signal $\bar{z}_i = z + \xi + u_i$, with $u_i \sim \mathcal{N}(0, \sigma_u^2)$.

Figure 2 represents simulation results. In the presence of noisy communication, β^* is independent of communication noise σ_u and is equal to the value that holds in the absence of communication. Moreover, the figure shows that the loss functions are all identical for $\beta = \beta^*$. This is intuitive. By using the signaling policy, the central bank can replicate the perfect communication outcome, which dominates imperfect communication. The signaling policy makes the endogenous signal the best summary of the central bank's information and of firms' private information, thus overcoming the potential limits of direct communication.

Consistently, the weight firms put on the central bank signal when setting their price is zero in the presence of noisy communication, when $\beta = \beta^*$. As before, the signaling policy makes the central bank's signal redundant. When monetary policy is optimal, firms are not willing to use the central bank signal under perfect communication, and all the more so when the signal is noisy.

5 Extensions

We consider extensions to our model. We first assume that the central bank uses a noisy measure of prices and we study the implications of a more traditional price-targeting policy. We then take a first pass at extending our framework to a dynamic setting. This indicates how our model could be extended to more standard settings. Next, we consider alternative information assumptions and alternative shocks. In what follows we summarize the main results, while the details are in online appendix A.

5.1 Price target

We have assumed so far that the central bank actions were not conditional on any endogenous information. We suppose now that instead of observing a noisy signal of the real shock, the central bank observes the price level with noise, which is a more realistic assumption. The monetary policy noise is represented by ξ_p, so that the central bank observes $p - \xi_p$, with $\xi_p \sim \mathcal{N}(0, \sigma_{\xi_p})$. The central bank follows a Taylor rule of the form $m = -\beta_p(p - \xi_p)$. A positive β_p would correspond to a standard price-stabilization policy. The rest of the model is identical to our baseline.

We find that the signaling policy is still optimal. As in our baseline model, the central bank targets a positive correlation between money supply and prices, which amounts to setting a negative β. It is optimal for the central bank to make money supply respond positively to prices because that improves the demand signal's ability to reveal z. Indeed, following an increase in z, prices decline as in our baseline, decreasing the demand signal. The central bank measures a decrease in prices, and reacts by decreasing money supply, which reinforces the decline in the demand signal.

5.2 Dynamic extension

Here we examine how our simple static framework can be extended to a dynamic one. We keep the same structure as in our baseline model, and consider now that time is infinite and discrete. We focus on a cashless economy, as defined by Woodford (2003), where monetary policy is defined in terms of nominal interest rate, and money is not introduced explicitly. The central bank sets the nominal policy rate i_t^{cb}, and the effective interest rate faced by the household is then $i_t = i_t^{cb} - v_t$, where v_t is an interest rate shock that is not under the control of the central bank, as in our baseline. The monetary policy rule is now defined as $i_t^{cb} = -\beta z^{cb}$. As in standard New Keynesian models, the nominal interest rate can be used to control the nominal demand q via the Euler equation. A positive β leads to stimulating nominal demand following a positive signal. The rest of the model is identical to the baseline. In particular, firms still receive an endogenous signal that depends on nominal spending and prices: $\tilde{y} = q + (\varrho - 1)p$.

Under the assumption of i.i.d. shocks, the optimal policy is still the signaling policy. However, now the sign of β^* can be positive. This comes from the fact that the effect of aggregate prices on the endogenous signal is now ambiguous. On the one hand, higher prices increase the demand for the individual good, for a given level of nominal demand. This effect was present in the static model and is governed by the elasticity of substitution ϱ. However, now higher prices decrease nominal demand through a higher real interest rate, which decreases the demand for the individual good. This effect was absent in the static model and is governed by the elasticity of intertemporal substitution. When the former effect dominates, β^* is negative, as in the baseline. When the latter effect dominates, β^*

is positive. Indeed, in that case, a positive supply shock, by decreasing prices, will have a positive effect on the endogenous signal. An increase in the endogenous signal is therefore good news about z for firms. When the central bank itself gets good news about z, it can reinforce the information content of the endogenous signal by decreasing the nominal interest rate. This further stimulates nominal demand, which will reinforce the positive effect of z on the endogenous signal. Although we cannot exclude this case completely, it is likely only for particularly low values of ϱ, and particularly large values of elasticity of intertemporal substitution. Our main predictions are therefore most likely to carry through in this simple dynamic framework. But in general, this extension shows that richer models could change the nature of the signaling policy by changing the structure of the endogenous signal.

5.3 Alternative information structures

In our baseline model, we have assumed that the central bank and firms received exogenous information only on the real shock z. Here, we relax this assumption.

Marginal cost signal Firms' information problem is to infer their marginal cost. In our simple framework, this marginal cost corresponds to the wage, which is observed only at the end of period. If the wage were known at the price-setting stage, then the signal extraction problem of firms would become trivial, as it would be optimal to simply set $p_i = w$. As argued earlier, in our view, it is reasonable to assume that firms do not observe their marginal cost. However, it is also reasonable to assume that firms have some information on their marginal cost. We introduce this idea by assuming that firms observe a signal on the wage. We then examine numerically how this assumption affects the equilibrium outcome and optimal policy. It appears that as the wage becomes more accurately observed, β^* gets closer to zero. This has the same effect as a greater accuracy of the private signal on z (a lower σ_ϵ). A greater accuracy of private information in general makes the endogenous signal a better signal of the real shock, which renders central bank intervention less necessary.

Online appendix A.4 further shows that, when both the demand signal and the marginal cost signal are noisy, the dominant channel depends mostly on the quality of information on demand, and only marginally on the quality of information on the marginal cost. For a given quality of information on demand, better information on the marginal cost enables firms to set prices more accurately and renders all types of monetary policy intervention less desirable, but does not affect significantly the relative strength of the two channels.

Signal on the nominal shock We assume that both the central bank and firms receive noisy signals on υ. We show that, while the central bank effectively emphasizes the price response to real shocks, it stabilizes prices in response to nominal shocks. As the nominal shock is inflationary, the central bank reduces money supply following a positive signal on the nominal shock, in order to limit its impact on the endogenous signal. This stabilizes the response of prices to the nominal shock, which is standard. The goal of the central bank is still to make the endogenous signal the best possible signal of the real shock, which is possible by minimizing the impact of nominal shocks on the endogenous signal. This is an implication of the divine coincidence through which better information on the real shock implies better information on nominal demand.

5.4 "Inefficient" shocks

In our baseline model, we have considered "efficient" shocks, i.e., shocks that move the social optimum in the same direction as the private optimum. We can also consider "inefficient" shocks, i.e., shocks that move the private optimum but not the social optimum, hence introducing inefficient fluctuations. To this end, we introduce a shock ρ to the elasticity of substitution between goods ϱ, which is akin to a mark-up shock. As in the baseline, both firms and the central bank have imperfect information on ρ. In that case, the central bank does not want to improve the information of firms. On the contrary, the optimal policy minimizes the precision of the endogenous signal. Since a mark-up shock is inflationary, monetary policy is restrictive following a mark-up shock, so that the endogenous signal does not reveal that shock to the agents. This lowers the responsiveness of output to the inefficient mark-up shocks.[17]

6 Conclusion

Optimal monetary policy is deeply affected by the assumptions on the information structure of the economy. In traditional settings with exogenous information, the central bank uses the "surprise channel" to produce real effects. When instead signals come from local markets, the central bank uses the "signaling channel", thus influencing the endogenous signals observed by agents. This constitutes what we call the "signaling policy". When the economy is hit by supply shocks, the signaling policy must be counter-cyclical, whereas

[17] Our results are consistent with Angeletos and Pavan (2007) and Angeletos *et al.* (2016). They find that when the business cycle is driven by distortionary forces, welfare decreases with information.

exogenous information would have led to a pro-cyclical policy.

Our results call for further research. First, the signaling policy prevails whenever local demand is observed with sufficient accuracy. Whether this is actually verified in the data is still an open question. Second, in a more general model, the structure of the endogenous signals, and hence the precise nature of the signaling policy (pro- or counter-cyclical), would depend on the structure of the model and on parameter values, as our dynamic extension shows. Third, adding asymmetric information on the household side could also change the nature of the signaling policy. Finally, endogenous inattention could introduce a trade-off between a signaling policy that requires high attention on behalf of firms, thus with high attention costs, and a price-stabilizing policy that requires less attention, thus with low attention costs.

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