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How Important Is the Information Effect of Monetary Policy?*

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Abstract

Is the "information effect" of monetary policy quantitatively important? We first use a simple model to show that under asymmetric information, monetary policy surprises are correlated with the unobserved state of the economy. This correlation implies that monetary policy surprises provide information about the state of the economy, and at the same time, explains why the estimation of the information effect may be biased. We then develop a New Keynesian DSGE model under asymmetric information and calibrate model parameters to match macroeconomic dynamics in the US and forecasting accuracy in the Greenbook. Under our calibration, both the central bank and the private sector initially have noisy information. Over time, the information effect of monetary policy mitigates information frictions by enhancing the two-way learning between the central bank and the private sector.

Keywords: monetary policy, information frictions, asymmetric information
JEL classification: E52, E58, D84

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1 Introduction

Monetary policy may have an information effect when information asymmetry exists between the central bank and the private sector. That is, the private sector believes the interest rate reveals the central bank's private information about the state of the economy and consequently revises its economic forecasts after an unexpected change in the interest rate. However, the empirical literature has yet to agree on whether the information effect of monetary policy is quantitatively important. On the one hand, Nakamura and Steinsson (2018) provide supportive evidence of the information effect, showing that professional forecasters positively revise their output growth forecasts after an unexpected interest-rate hike, contradicting the implications of a traditional New Keynesian model. On the other hand, Bauer and Swanson (2023) argue that the above result might be due to an omitted variable bias. They further show that after controlling for news about the state of the economy, the information effect of monetary policy is not significant.

In this paper, we first use a simple model to explain the reason for the different results between Nakamura and Steinsson (2018) and Bauer and Swanson (2023), namely, why an omitted variable bias may arise when estimating the information effect of monetary policy by measuring the relationship between the private sector's forecast revisions and monetary policy surprises. We show that with asymmetric information, monetary policy surprises are correlated with changes in the state of the economy. This correlation means monetary policy surprises provide useful information about the economy and, at the same time, may cause a bias when estimating the information effect using a reduced-form regression. To measure the information effect of monetary policy in the real world, we then build a New Keynesian DSGE model with asymmetric information. We calibrate information precision to match moments of macroeconomic dynamics and expectations in the US economy. Our calibration suggests that although the central bank's private information is initially noisy, the information effect is still quantitatively important because it enhances two-way learning between the central bank and the private sector.

Our simple model consists of a central bank and a continuum of professional forecasters. We assume that there is only one fundamental shock, which is not directly observable. Output is determined by both the fundamental shock and the interest rate set by the central bank. We assume that a public signal is available to all agents. In addition to the public signal, the central bank also observes a private signal. Each professional forecaster gets an individual-specific private signal, and the noise components of all individual signals cancel out in aggregation.

The central bank sets the interest rate following a targeting rule. The interest rate responds to the central bank's expected output, conditional on the central bank's imperfect information. We also assume that the interest rate contains a pure policy shock that captures any exogenous variations in the interest rate. Once the interest rate is set, professional forecasters perfectly observe it. Professional forecasters form expectations twice in a given period: once before the interest rate is set (pre-FOMC expectations) and once after (post-FOMC expectations). We define a *monetary policy surprise* as the difference between the actual and the pre-FOMC expected interest rate averaged across all forecasters. This definition corresponds to the monetary policy shocks constructed under the high-frequency identification method in the empirical literature.

Our simple model provides a micro-foundation for monetary policy surprises under asymmetric information. Monetary policy surprises comprise four components: the change in the fundamental shock, the noise in the central bank's private information, the noise in the public information, and the exogenous policy shock, However, if the central bank does not have private information, then monetary policy surprises will be the same as the exogenous policy shock, even if information is still imperfect. The reason is that without the central bank's private information, the endogenous response in the interest rate will be perfectly predictable, and therefore any surprise in the interest-rate comes from the exogenous policy shock.

The correlation between monetary policy surprises and fundamental shocks is positive. This is because in the absence of noise shocks, professional forecasters underestimate the fundamental shock due to imperfect information. As a result, professional forecasters, on average, expect a smaller interest rate response than the actual one after a positive fundamental shock.

The first implication is that due to the correlation between monetary policy surprises and fundamental shocks, monetary policy has an information effect. Our framework allows for a closed-form solution to the size of the information effect. We show that the information effect is stronger when the central bank has more precise private information or when professional forecasters have less precise private information. There is a non-linear relationship between the size of the information effect and the precision of the public information.

The second key message is that it is difficult to estimate the information effect from a reduced-form regression of the private sector's forecast revisions on monetary policy surprises. The first reason is that the estimated coefficient in this type of regression analysis might suffer from the omitted variable bias. We show that omitting the fundamental shock and the noise shock in the regression leads to an upward bias in the estimated coefficient of the information effect, which is consistent with the findings in Bauer and Swanson (2023). The second reason is that even after correcting for the omitted variable bias, the estimated reduced-form relationship between the private sector's expectations and monetary policy surprises still cannot yield a conclusion about the size of the information effect. This is because the estimated coefficient in this type of regression measures the combination of the information effect and the direct effect. Even if one gets a negative coefficient, i.e., a positive monetary policy surprise leads to a downward revision of output forecasts, it only suggests that the direct effect dominates the information effect, and the information effect could still be quantitatively important. In summary, our simple model suggests that a reduced-form regression cannot give a conclusive answer about the importance of the information effect of monetary policy.

To quantify the information effect in the real world, we develop a New Keynesian DSGE model under asymmetric information and calculate the model-implied information effect. We assume the demand shock is the only fundamental shock in the private sector. Since the demand shock directly affects the household's preference, we assume the household has perfect information about it. The central bank and all firms do not directly observe the demand shock.

The central element of our model is the information asymmetry. There is a public signal available to all agents. The central bank has two additional sources of information. First, the central bank has a private signal about the demand shock. Second, the central bank also learns from endogenous equilibrium variables of inflation and output with a time lag. On the firm side, we assume that individual firm's real marginal cost provides private information about the aggregate economy. The firm-specific real marginal cost is assumed to be a linear combination of the equilibrium real wage and an idiosyncratic wage bargaining shock. The idiosyncratic bargaining shock introduces heterogeneity in firms' expectations. Similar to the timing assumption in our simple model, the interest rate is set before all firms set prices, and firms use the interest rate as another public signal to learn about the demand shock.

We calibrate the model to match macroeconomic dynamics in the US economy and forecasting accuracy in the Greenbook. We first directly assign values to the parameters commonly used in the New Keynesian literature. We then internally calibrate the parameters that govern the degree of information frictions. We calibrate the process of the demand shock to match the auto-correlation and the standard deviation of realized inflation in the US. The standard deviation of the exogenous monetary policy shock is calibrated to match the standard deviation of the federal funds rate. The standard deviation of individual firms' real marginal costs is inferred from micro evidence on the size of price adjustments. We choose the standard deviation of the central bank's private signals and the public signals to match the inflation and output nowcast accuracy in the Greenbook.

Under our calibration, both firms and the central bank have imprecise information initially. According to empirical estimates, the average size of price changes is large in absolute value, which suggests that firms marginal costs have large idiosyncratic shocks. This implies that firms have noisy private information. The Greenbook shows that the central bank has sizable errors in its estimates of inflation and output in the current quarter, which suggests that both the public information and the central bank's private information are very noisy.

We show the information effect of monetary policy by comparing our calibrated model with a counter-factual economy where firms do not use the interest rate as a signal. With the information effect, the equilibrium under imperfect information quickly converges to the one under full information after a demand shock. In comparison, without the information effect, the deviation from the full information benchmark persists for a long time. This comparison shows that the information effect of monetary policy significantly reduces the degree of information frictions in the economy. This is because the interest rate facilitates a two-way learning mechanism between firms and the central bank. When firms learn from the interest rate, their pricing decisions are closer to the ones under full information. In turn, when the central bank learns from past inflation and output, the central bank gets more precise information, which makes the interest rate more informative about the underlying economy.

Related Literature

Our paper builds on the growing literature on the information effect of monetary policy. This concept was first proposed by Romer and Romer (2000), who show how private inflation forecasts respond to changes in the policy rate after FOMC announcements. Some recent studies (Campbell et al. (2012), Nakamura and Steinsson (2018), and Lunsford (2020)) provide further supportive evidence of how policy announcements lead to private-sector forecast revisions. Jarociński and Karadi (2020) use high-frequency co-movement between interest rates and stock prices to identify the information shock from FOMC statements. However, Bauer and Swanson (2023) argue that the empirical evidence of the Fed's information effect is not robust to sample and variable selections and that the estimated result may suffer from an omitted variable bias. The first contribution of our paper is to show why regression-based empirical estimation of the information effect may not yield a conclusive answer about the size of the information effect.

Motivated by the empirical relevance of the information effect of monetary policy, economists have started to model the information effect of the interest rate in a New Keynesian model, for example, Berkelmans (2011), Tang (2015), Melosi (2017), Andrade et al. (2019), and Jia (2023). With only a few exceptions in the existing literature, models about the information effect capture only one-sided information flow: the private sector learns the state of the economy from the central bank's interest-rate decisions. We contribute to this literature by modeling a two-sided information flow: firms learn from the central bank's interest-rate decisions, and the central bank learns from the firms' pricing decisions.

The paper most closely related to ours is Kohlhas (2022), who shows that when there is a two-way learning process, releasing the central bank's information is beneficial even for inefficient shocks, such as cost-push shocks. The difference between our paper and Kohlhas (2022) is that we focus on quantifying the size of the information effect in the US economy.

2 A Simple Model

In this section, we first set up a simple model where information is asymmetric between the private sector and the central bank (Section 2.1). Using this model, we provide a micro-foundation for monetary policy surprises and explain the implications of the information effect of monetary policy (Section 2.2).

2.1 Model Set-up

In our model, both the central bank and the private sector have imperfect information about the state of the economy. We first explain our assumptions on the state variable and the interest-rate rule. Then, we specify the sequence of events and how the central bank's and the private sector's expectations are formed.

2.1.1 Economic Fundamentals and the Policy Rule

There is only one exogenous state variable, x_t, which is not directly observable. For simplicity, we assume x_t is *i.i.d.* in each period, and follows

$$x_t \sim N\left(0, \nu_x^{-1}\right).$$

The economic outcome, y_t, is determined by the state of the economy, x_t, and the interest rate set by the central bank, i_t. Specifically,

$$y_t = x_t - \kappa i_t, \tag{1}$$

where $\kappa > 0$ captures the traditional effect of monetary policy on households' borrowing costs.

In the context of a New Keynesian model, one can regard x_t as a demand shock, for example, a natural-rate shock (r_t^n), and y_t as the output level. Under the assumption that shocks are *i.i.d.* in each period, $y_t = -\frac{1}{\sigma}(i_t - r_t^n)$.[1] Relating to Equation (1), $x_t = \frac{1}{\sigma} r_t^n$ and $\kappa = \frac{1}{\sigma}$.

This section assumes that the private sector's expectations are formed by a continuum of professional forecasters who do not make output decisions. Under this assumption, y_t is not affected by expectations in the private sector and is only affected by the direct effect of monetary policy. We will relax this assumption and allow equilibrium output and inflation to depend on the private sector's expectations in the next section.

The central bank sets the interest rate following a targeting rule conditional on its expectation, given by

$$i_t = \phi_y \mathbb{E}_t^{cb} y_t + e_t, \qquad e_t \sim N\left(0, \nu_e^{-1}\right) \tag{2}$$

where $\phi_y > 0$. The central bank chooses the value of ϕ_y and this value is perfectly known by the private sector. e_t is the traditionally modeled "monetary policy shock," which captures any exogenous variation in the interest rate that cannot be explained by the endogenous response to $\mathbb{E}_t^{cb} y_t$.

2.1.2 Sequence of Events

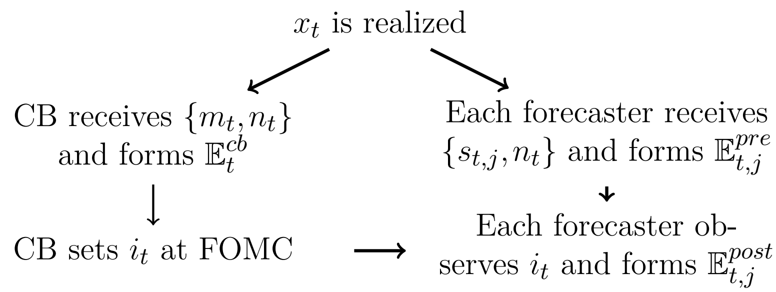
To capture the monetary policy *surprises*, we assume that in each period, the private sector forms expectations twice: once before and once after the policy announcement. This assumption allows us to model the monetary policy surprises in the same way as the empirical literature on high-frequency identification of monetary policy shocks. In this literature, monetary policy shocks are measured as the changes in market-based expectations in a short window around FOMC announcements (Nakamura and Steinsson (2018)).

Figure 1 illustrates the timing of events. Specifically, each period t can be divided into three stages. At stage 1, x_t is realized. At stage 2, a public signal, n_t, is received by both the central bank and private forecasters. In addition, the central bank receives a private signal, m_t, and each forecaster receives an individual-specific signal, $s_{t,j}$. Under their own information sets, the central bank and the professional forecasters form their expectations. At this point, the private sector's expectations are called pre-FOMC expectations. At the last stage, the central bank sets the interest rate at the FOMC meeting. The private sector observes the interest rate and updates expectations. At this stage, the private sector's expectations are called post-FOMC expectations.

Our assumption on the sequence of events is also very similar to Bauer and Swanson

[1] In addition, monetary policy is assumed to be discretionary and does not respond to lagged variables.

Figure 1: Sequence of Events



(2023). The stage at which the central bank and the private sector receive imperfect information corresponds to the stage of "economic news release" in Bauer and Swanson (2023). In addition, the "forecast revisions" in Bauer and Swanson (2023) are equivalent to the post-FOMC expectations in our model. This is because "forecast revisions" in Bauer and Swanson (2023) measures the changes in private-sector expectations from $t-1$ to t, the same as the expectations at t in our static model.

2.1.3 Information Sets and Expectations

We first specify the central bank's expectations and the interest rate rule and then the private sector's expectations before and after the FOMC announcements.

Central bank's expectations and policy decisions

Before making policy decisions, the central bank receives two signals: a public signal n_t and a private signal m_t. Both signals are assumed to be normally distributed around the true state, x_t. Specifically,

$$n_t = x_t + \varepsilon_t^n, \quad \varepsilon_t^n \sim N\left(0, \nu_n^{-1}\right),$$
$$m_t = x_t + \varepsilon_t^m, \quad \varepsilon_t^m \sim N\left(0, \nu_m^{-1}\right).$$

Conditional on $\{m_t,\ n_t\}$, the central bank's expectation on x_t is given by

$$\mathbb{E}_t^{cb} x_t \equiv \mathbb{E}_t[x_t | \mathcal{I}_t^{cb}] = \frac{\nu_m}{\nu_x + \nu_m + \nu_n} m_t + \frac{\nu_n}{\nu_x + \nu_m + \nu_n} n_t, \tag{3}$$

where $\mathcal{I}_t^{cb} = \{m_t,\ n_t\}$.

To find the interest rate set by the central bank, combine Equations (2) and (1), and notice that $\mathbb{E}_t^{cb} i_t = i_t$. Next, substitute $\mathbb{E}_t^{cb} x_t$ with Equation (3). The interest rate is found as

$$i_t = \frac{\phi_y}{1+\kappa\phi_y}\left[\frac{\nu_m}{\nu_x+\nu_n+\nu_m}m_t + \frac{\nu_n}{\nu_x+\nu_n+\nu_m}n_t\right] + \frac{1}{1+\kappa\phi_y}e_t. \tag{4}$$

Pre-FOMC expectations in the private sector

In the private sector, professional forecasters are indexed by j, and $j \in (0,1)$. Before an FOMC meeting, each forecaster receives two signals: a public signal the same as the one received by the central bank, n_t, and a private individual-specific signal, which is denoted by $s_{t,j}$ and follows

$$s_{t,j} = x_t + \varepsilon^s_{t,j}, \quad \varepsilon^s_{t,j} \sim N\left(0, \nu_s^{-1}\right)$$

Forecaster j's pre-FOMC expectation about the state of the economy is formed as

$$\mathbb{E}^{pre}_{t,j}x_t \equiv \mathbb{E}_t[x_t|\mathcal{I}^{pre}_{t,j}] = \frac{\nu_s}{\nu_x+\nu_n+\nu_s}s_{t,j} + \frac{\nu_n}{\nu_x+\nu_n+\nu_s}n_t. \tag{5}$$

where $\mathcal{I}^{pre}_{t,j} = \{s_{t,j},\ n_t\}$.

In addition to forming expectations about x_t, the professional forecasters also form expectations about the interest rate. Individual forecasters understand that the interest rate is set conditional on the central bank's imperfect information according to Equation (4). In addition, since individual forecasters do not observe the central bank's private signal, m_t, they use their own signals to form expectations about m_t. Specifically, forecaster j's pre-FOMC expected i_t is given by

$$\begin{aligned}\mathbb{E}^{pre}_{t,j}i_t &= \frac{\phi_y}{1+\kappa\phi_y}\left[\frac{\nu_m}{\nu_x+\nu_n+\nu_m}\mathbb{E}^{pre}_{t,j}m_t + \frac{\nu_n}{\nu_x+\nu_n+\nu_m}n_t\right] \\ &= \frac{\phi_y}{1+\kappa\phi_y}\left[\frac{\nu_m}{\nu_x+\nu_n+\nu_m}\left(\frac{\nu_s}{\nu_x+\nu_n+\nu_s}s_{t,j} + \frac{\nu_n}{\nu_x+\nu_n+\nu_s}n_t\right) + \frac{\nu_n}{\nu_x+\nu_n+\nu_m}n_t\right] \end{aligned} \tag{6}$$

where the first line makes use of $\mathbb{E}^{pre}_{t,j}e_t = 0$ and the second line makes use of $\mathbb{E}^{pre}_{t,j}m_t = \mathbb{E}^{pre}_{t,j}x_t$.

Post-FOMC expectations in the private sector

After an FOMC meeting, the interest rate becomes a public signal. Professional forecasters use this public signal to update their beliefs about the state of the economy. To see how the interest rate serves as another signal of x_t, re-arrange Equation (4) and get

$$\hat{i}_t = \frac{i_t - \frac{\phi_y}{1+\kappa\phi_y}\frac{\nu_n}{\nu_x+\nu_n+\nu_m}n_t}{\frac{\phi_y}{1+\kappa\phi_y}\frac{\nu_m}{\nu_x+\nu_n+\nu_m}} = x_t + \varepsilon^m_t + \frac{1}{\phi_y\frac{\nu_m}{\nu_x+\nu_n+\nu_m}}e_t \tag{7}$$

Equation (7) shows that $\hat{i}_t$ is an unbiased signal of x_t, with the precision of the signal given by

$$\nu_i^{-1} = \nu_m^{-1} + \left(\frac{\nu_x + \nu_n + \nu_m}{\phi_y \nu_m}\right)^2 \nu_e^{-1}. \tag{8}$$

Lemma 1 *$\hat{i}_t$ is an unbiased signal of x_t, and its precision, ν_i,*

- *increases with the precision of the central bank's private information (ν_m),*
- *decreases with the precision of the public information (ν_n),*
- *increases with the interest-rate rule coefficient (ϕ_y), and*
- *decreases with the standard deviation of the policy shock (σ_e).*

Forecaster j's post-FOMC expectation about the state of the economy is given by

$$\mathbb{E}_{t,j}^{post} x_t \equiv \mathbb{E}_t[x_t | \mathcal{I}_{t,j}^{post}] = \frac{\nu_s}{V} s_{t,j} + \frac{\nu_n}{V} n_t + \frac{\nu_i}{V} \hat{i}_t, \tag{9}$$

where $\mathcal{I}_{t,j}^{post} = \left\{ s_{t,j},\ n_t,\ \hat{i}_t \right\}$ and $V = \nu_x + \nu_n + \nu_s + \nu_i$.

2.2 Model Implications

In this section, we provide a micro-foundation for monetary policy surprises under asymmetric information and a closed-form solution to the information effect of monetary policy.

2.2.1 A Micro-Foundation for Monetary Policy Surprises

The monetary policy surprise, mps_t, or the unexpected change in the interest rate, is defined as the difference between the actual and the average of the pre-FOMC expected interest rate. To calculate mps_t, we first take the difference between i_t (Equation (4)) and each individual forecaster's pre-FOMC expected i_t (Equation (6)), which is given by

$$mps_{t,j} = \frac{\phi_y}{1+\kappa\phi_y} \frac{\nu_m}{\nu_x + \nu_n + \nu_m} \left(m_t - \frac{\nu_s}{\nu_x + \nu_n + \nu_s} s_{t,j} - \frac{\nu_n}{\nu_x + \nu_n + \nu_s} n_t \right) + \frac{1}{1+\kappa\phi_y} e_t. \tag{10}$$

Then, we integrate over all forecasters and substitute signals with their relationships with the state of the economy, x_t. It yields that

$$mps_t = \frac{\phi_y}{1+\kappa\phi_y} \frac{\nu_m}{\nu_x + \nu_n + \nu_m} \left(\frac{\nu_x}{\nu_x + \nu_n + \nu_s} x_t + \varepsilon_t^m - \frac{\nu_n}{\nu_x + \nu_n + \nu_s} \varepsilon_t^n \right) + \frac{1}{1+\kappa\phi_y} e_t, \tag{11}$$

Equation (11) illustrates how monetary policy surprises arise from asymmetric information between the central bank and the private sector. We explain the contribution of each component in the following proposition.

Proposition 1 *There is a positive monetary policy surprise after*

- *a positive shock to the state of the economy ($x_t > 0$),*
- *a positive noise shock in the central bank's private information ($\varepsilon_t^m > 0$),*
- *a negative noise shock in the public information ($\varepsilon_t^n < 0$), or*
- *a positive exogenous policy shock ($e_t > 0$).*

To get the intuition for Proposition 1, compare i_t in Equation (4) and $\mathbb{E}_{t,j}^{pre}\, i_t$ in the first line of Equation (6). The difference is $mps_{t,j}$, and two factors drive it. The first factor is the conventionally modeled monetary policy shock (e_t). The second factor is the difference between m_t and $\mathbb{E}_{t,j}^{pre}\, m_t$. An important assumption in our model is that $m_t \neq \mathbb{E}_{t,j}^{pre}\, m_t$, i.e., the central bank has some private information that professional forecasters do not know. This assumption is novel in our model, leading to three results.

First, mps_t positively changes with ε_t^m, as the central bank positively changes i_t after a positive noise shock in its private information. Second, mps_t positively changes with x_t. This is because professional forecasters understand that m_t is an unbiased signal of x_t and expect that the noise component is zero. Therefore, for each individual forecaster, $\mathbb{E}_{t,j}^{pre} m_t = \mathbb{E}_{t,j}^{pre} x_t$. In addition, professional forecasters underestimate the realization of x_t on average due to imperfect information and, therefore, underestimate the change in i_t in response to x_t.

The third result may be counter-intuitive at first: mps_t negatively changes with ε_t^n. This is because private forecasters use the public signal for two reasons. First, they correctly understand that the interest rate responds to the public signal as Equation (4) describes. Second, the private sector also uses the public signal to form expectations of the central bank's private signal. Specifically, each forecaster expects that $\mathbb{E}_{t,j}^{pre} m_t = \mathbb{E}_{t,j}^{pre} x_t$, and forms $\mathbb{E}_{t,j}^{pre} x_t$ by combining the individual-specific signal and the public signal (Equation (5)). Consequently, the public signal is over-weighted in the private sector's expectation of the interest rate. Notice that the key assumption for the private sector outweighs the public signal: some of the central bank's information is private. If every piece of the central bank's information is known to the private sector, then $\mathbb{E}_{t,j}^{pre}\, m_t = m_t$. In this case, a monetary policy surprise is only the result of an exogenous policy shock.

Is the assumption that the central bank has some private information plausible? We argue that although it might be the case that the private sector has the same access to economic data as the central bank does, it could still be argued that the private sector and the central bank use different sets of indicators to evaluate the state of the economy and to form expectations on the interest rate. In this case, the information sets of the central bank and the private sector do not overlap, so we argue that the central bank has some private information. We show further evidence of the information asymmetry in Section 3.2 using data from the Greenbook and the Survey of Professional Forecasters.

Proposition 1 shows that mps_t is positively correlated with x_t. In the following proposition, we characterize how the effect of x_t on mps_t depends on the degree of information frictions and the parameters of the interest-rate rule.

Proposition 2 *A positive innovation in the unobserved state variable (x_t) results in a positive monetary policy surprise. In addition, for a given change in x_t, the size of mps_t*

- *increases with the precision of the central bank's private information (ν_m),*
- *decreases with the precision of the forecasters' private information (ν_s),*
- *decreases with the precision of the public information (ν_n),*
- *increases with the policy rule coefficient (ϕ_y), and*
- *does not change with the standard deviation of the policy error (σ_e).*

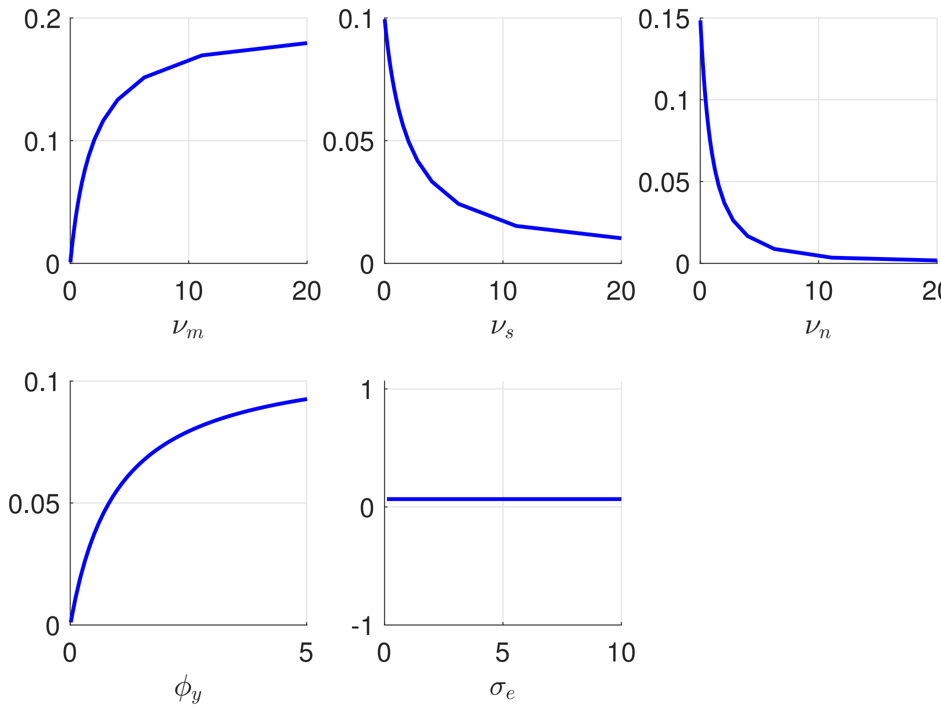
We demonstrate Proposition 2 in Figure 2. The intuition for Proposition 2 is the following. First, when the central bank has precise private information, it makes i_t very responsive to m_t. (See Equation (4).) This leads to a larger mps_t after a change in x_t, conditional on the private sector's expected interest rate. Second, conditional on the central bank's information, when the private sector has less information, the expected interest rate changes by a smaller amount, leading to a large mps_t. Third, although the public signal changes both the central bank's and the private sector's expectations, it is over-weighted by private forecasters. Therefore, when the public signal is less precise, it makes the expected interest rate less responsive to x_t compared to the response of the actual interest rate, which is equivalent to a larger mps_t.

In addition, the policy coefficient, ϕ_y, directly affects the correlation between mps_t and x_t. Intuitively, conditional on the differences in expectations between the central bank and the private sector about the state of the economy, a larger ϕ_y means a larger change in i_t, and thus a greater mps_t. Lastly, the standard deviation of the policy error, σ_e, does not affect the correlation between mps_t and x_t, as e_t is exogenous to x_t.

2.2.2 Economic News Predicts Monetary Policy Surprises

Bauer and Swanson (2023) argue that there might be an omitted variable bias if one regresses the private sector's forecast revisions only on monetary policy surprises. The reason is that

Figure 2: mps_t after a Positive Innovation in x_t



All figures plot the coefficient with mps_t in Equation (11). Benchmark parameters are set as: $\sigma_x = 1$, $\sigma_m = 1$, $\sigma_n = 1$, $\sigma_e = 0.1$, $\kappa = 1$, and $\phi_y = 1.5$.

the monetary policy surprise is not exogenous and is correlated with other variables that also explain forecast revisions in the private sector. To provide evidence of this endogeneity problem, Bauer and Swanson (2023) show that monetary policy surprises are predictable by economic news, which is defined as the difference between the realized and the expected economic indicators. Specifically, Bauer and Swanson (2023) estimate the predictability of mps_t by the following regression

$$mps_t = \boldsymbol{\alpha} + \boldsymbol{\beta'} \boldsymbol{news_t} + \boldsymbol{\varepsilon_t}, \tag{12}$$

where $\boldsymbol{news_t}$ denotes a vector of macroeconomic news, such as the surprise components in unemployment, and financial news, such as changes in the S&P 500 index. Their estimation shows that news about higher output or inflation predicts a positive policy surprise.

Our model allows for an analytic solution to the predictability of monetary policy surprises from economic news. To make our results comparable to those of Bauer and Swanson (2023), we define $news_t$ in our model as the difference between the actual and the pre-FOMC expected state of the economy, i.e., $news_t = x_t - \int \mathbb{E}^{pre}_{t,j} x_t$, where $\mathbb{E}^{pre}_{t,j} x_t$ is given by Equation

(5). It yields that

$$news_t = \frac{\nu_x}{\nu_x + \nu_n + \nu_s} x_t - \frac{\nu_n}{\nu_x + \nu_n + \nu_s} \varepsilon_t^n. \tag{13}$$

Re-arrange Equation (11) to express mps_t as a function of $news_t$:

$$mps_t = \frac{\phi_y}{1 + \kappa\phi_y} \frac{\nu_m}{\nu_x + \nu_n + \nu_m} news_t + \frac{\phi_y}{1 + \kappa\phi_y} \frac{\nu_m}{\nu_x + \nu_n + \nu_m} \varepsilon_t^m + + \frac{1}{1 + \kappa\phi_y} e_t \tag{14}$$

where $news_t$ is given by Equation (13). Comparing Equation (14) with Equation (12) immediately yields that

$$\boldsymbol{\alpha} = 0, \quad \boldsymbol{\beta} = \frac{\phi_y}{1 + \kappa\phi_y} \frac{\nu_m}{\nu_x + \nu_n + \nu_m},$$
$$\boldsymbol{\varepsilon_t} = \frac{\phi_y}{1 + \kappa\phi_y} \frac{\nu_m}{\nu_x + \nu_n + \nu_m} \varepsilon_t^m + + \frac{1}{1 + \kappa\phi_y} e_t.$$

The first thing to notice is that $\beta > 0$. It means that mps_t is predictable from economic news, and the sign reflects the targeting rule of monetary policy, i.e., the interest rate increases after a positive shock to the state of the economy. This is consistent with the empirical results in Bauer and Swanson (2023).

More importantly, the size of β depends on the degree of information friction. Specifically, β increases with ν_m and decreases with ν_n. The intuition is that $news_t$ measures the fraction of x_t that is underestimated by the private sector (less the overestimated fraction of x_t due to the noise in the public signal), which leads to a difference between the actual and the expected i_t. A larger mps_t can result from either a larger change in the actual i_t or a smaller change in the expected i_t. The former requires the central bank to have more precise information, and the latter requires the private sector to have more precise information.

Monetary policy surprises are predictable from economic news in both our model and in Bauer and Swanson (2023), but for different reasons. In Bauer and Swanson (2023), the underlying assumption is that the private sector has perfect information about the state of the economy but imperfect information about the policy rule (i.e., the value of ϕ_y in our model). In contrast, we assume that the private sector has perfect information about the policy rule and imperfect information about the state of the economy, which gives rise to both the correlation between monetary policy surprises and the state of the economy and the predictability of monetary policy from economic news. If there is public information available that perfectly reveals the state of the economy ($\nu_n = \infty$), monetary policy surprises will be driven entirely by the exogenous policy shock, will not be correlated with the state of the economy, and will not be predictable from economic news. Also, notice that mps_t is still correlated with x_t and is predictable from economic news if perfect information is available only to the central bank ($\nu_m = \infty$). In this case, the private sector still underestimates the changes in i_t in response to x_t, and the correlation between mps_t and x_t and the predictability of mps_t from $news_t$ still holds.

2.2.3 The Information Effect of Monetary Policy

Because monetary policy surprises are correlated with the state of the economy, professional forecasters find it useful to extract information about the state of the economy from monetary policy surprises. In this section, we show that our model gives a closed-form solution to the information effect of monetary policy and analyze how the size of the information effect depends on the degree of information frictions.

To make our model-implied information effect comparable to the ones measured in the empirical literature, we express the post-FOMC expectations in Equation (9) as a function of mps_t, which yields

$$\mathbb{E}_{t,j}^{post} x_t = \frac{1+\kappa\phi_y}{\phi_y}\frac{\nu_i}{V}\frac{\nu_x+\nu_n+\nu_m}{\nu_m} mps_{t,j} + \underbrace{\frac{\nu_s}{\nu_x+\nu_n+\nu_s} s_{t,j} + \frac{\nu_n}{\nu_x+\nu_n+\nu_s} n_t}_{\mathbb{E}_{t,j}^{pre} x_t} \tag{15}$$

Post-FOMC expectations of y_t can be immediately derived by subtracting κi_t from $\mathbb{E}_{t,j}^{post} x_t$. Integrating over all forecasters, one can find that the average post-FOMC expectations of economic output is given by

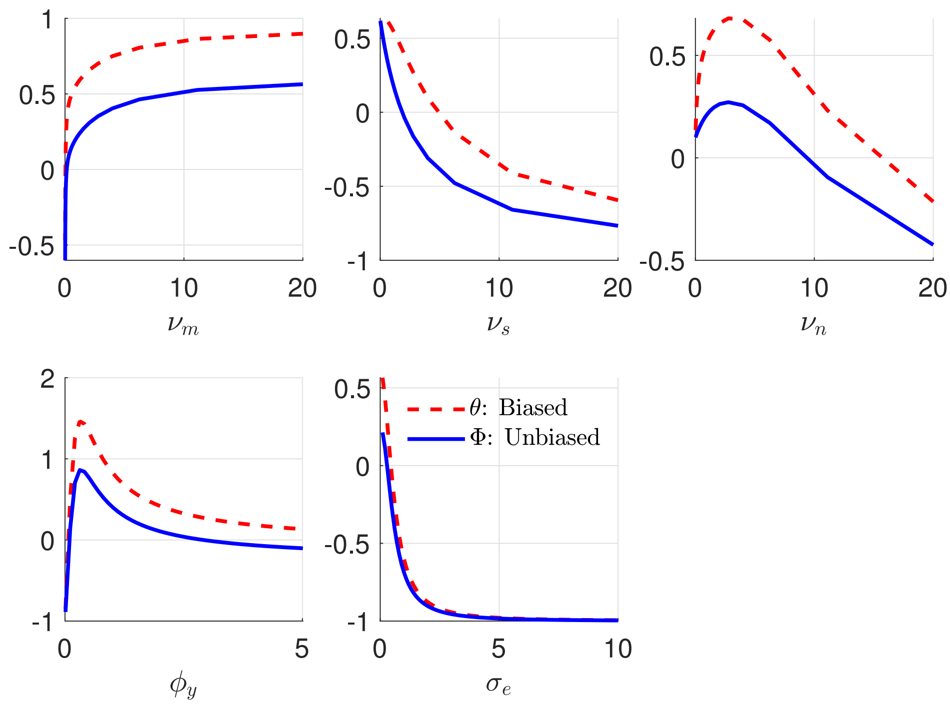
$$\begin{aligned}\overline{\mathbb{E}}_t^{post} y_t = & \underbrace{\left[\frac{1+\kappa\phi_y}{\phi_y}\frac{\nu_i}{V}\frac{\nu_x+\nu_n+\nu_m}{\nu_m} - \kappa\right]}_{\Phi} mps_t + \underbrace{\frac{\nu_s}{\nu_x+\nu_n+\nu_s}\left(1-\kappa\frac{\phi_y}{1+\kappa\phi_y}\frac{\nu_m}{\nu_x+\nu_n+\nu_m}\right)}_{\Psi_1} x_t \\ & + \underbrace{\left[\frac{\nu_n}{\nu_x+\nu_n+\nu_s}\left(1-\kappa\frac{\phi_y}{1+\kappa\phi_y}\frac{\nu_m}{\nu_x+\nu_n+\nu_m}\right) - \kappa\frac{\phi_y}{1+\kappa\phi_y}\frac{\nu_n}{\nu_x+\nu_n+\nu_m}\right]}_{\Psi_2} n_t \end{aligned} \tag{16}$$

The coefficient on mps_t, Φ, in Equation (16) corresponds to the effect of monetary policy surprises on the private sector's forecast revisions. Our model shows that Φ is the combined effect of the information effect and the direct effect of monetary policy. The first term, $\frac{1+\kappa\phi_y}{\phi_y}\frac{\nu_i}{V}\frac{\nu_x+\nu_n+\nu_m}{\nu_m}$, is the information effect, and the second term, $-\kappa$, is the direct effect. The information effect is positive, and its size depends on the precision of signals and the coefficients of the interest-rate rule.

Proposition 3 *The information effect of mps_t is positive, and its size*

- *increases with the precision of the central bank's private information (ν_m),*

Figure 3: The Information Effect of Monetary Policy



Notes: The solid blue line plots the value of Φ in Equation (16), and the dashed red line plots the value of θ in Equation (17). Benchmark parameters are set as: $\sigma_x = 1$, $\sigma_m = 1$, $\sigma_n = 1$, $\sigma_s = 1$, $\sigma_e = 0.1$, $\kappa = 1$, and $\phi_y = 1.5$.

- *decreases with the precision of the forecasters' private information (ν_s),*
- *has a non-linear relationship with the precision of the public information (ν_n) and the policy rule coefficient (ϕ_y), and*
- *decreases with the standard deviation of the policy error, σ_e.*

The solid blue line in Figure 3 illustrates how Φ changes with different parameters. First, when the central bank has more precise private information or professional forecasters have less precise private information, the central bank has an information advantage over the private sector; in this case, the information effect is stronger.

Second, the precision of the public information has a non-linear effect on the size of Φ. This is because when ν_n increases, two competing forces jointly determine the size of the information effect. First, under a larger ν_n, mps_t is smaller after a given change in x_t (Proposition 2), or equivalently, the private sector expects a larger change in x_t for a given mps_t. However, a larger ν_n also makes $\hat{i}_t$ a less precise signal of x_t (Lemma 1), for which the private sector updates expected x_t by a smaller amount.

The effect of ϕ_y also has a non-linear effect on the size of Φ for a similar reason. The two competing forces associated with a larger ϕ_y are: first, a larger ϕ_y implies that a given mps_t implies a smaller change in x_t, and second, a larger ϕ_y makes $\hat{i}_t$ a more precise signal of x_t. Lastly, a smaller σ_e increases the degree of the information effect of monetary policy, because a smaller σ_e makes $\hat{i}_t$ a more precise signal of x_t.

Equation (16) also implies that if one measures Φ by regressing $\overline{\mathbb{E}}_t^{post} y_t$ only on mps_t, the estimated Φ would suffer from the omitted variable bias. Regressing $\mathbb{E}_t^{post} y_t$ on mps_t only omits two variables, x_t and ϵ_t^n. Both x_t and ϵ_t are correlated with mps_t and determine $\mathbb{E}_t^{post} y_t$.

To calculate the size of the omitted variable bias in our model, we rewrite Equation (16) to express the regression equation in Nakamura and Steinsson (2018). Specifically, we single out mps_t as the only independent variable and leave other variables as error terms in explaining post-FOMC expectations, i.e.,

$$\overline{\mathbb{E}}_t^{post} y_t = \boldsymbol{\phi} + \boldsymbol{\theta} mps_t + \boldsymbol{\eta_t}. \tag{17}$$

$\boldsymbol{\theta}$ in Equation (17) is estimated by the correlation between $\overline{\mathbb{E}}_t^{post} y_t$ and mps_t. Some additional algebra shows that

$$\begin{aligned} \theta &= \frac{cov(mps_t, \overline{\mathbb{E}}_t^{post} y_t)}{var(mps_t)} \\ &= \frac{(\Phi A + \Psi_1 + \Psi_2)A/\nu_x + \Phi B^2/\nu_m + (\Phi C + \Psi_2)C\nu_n + \Phi D^2/\nu_e}{A^2/\nu_x + B^2/\nu_m + C^2/\nu_n + D^2/\nu_e}. \end{aligned} \tag{18}$$

where A, B, C, and D are coefficients when mps_t in Equation (11) is re-written in terms of $mps_t = Ax_t + B\varepsilon_t^m + C\varepsilon_t^n + De_t$.

In Figure 3, we plot $\boldsymbol{\theta}$ by the dashed red lines and compare it with the actual size of the information effect (Φ). All five panels suggest that the omitted variable bias leads to an overestimation of the size of the information effect.

Bauer and Swanson (2023) suggest that controlling for economic news is a way to correct for the omitted variable bias. However, can the bias be eliminated entirely? Our model suggests no. To see this, substitute x_t in $\mathbb{E}_t^{post} y_t$ with $news_t$ using Equation (13), and rewrite $\mathbb{E}_t^{post} y_t$ as

$$\mathbb{E}_t^{post} y_t = \Phi mps_t + (\Psi_1 + \Psi_2)\frac{1}{P} news_t - \left((\Psi_1 + \Psi_2)\frac{Q}{P} + \Psi\right)\epsilon_t^n \tag{19}$$

where P and Q are coefficients when $news_t$ in Equation (13) is written in terms of $news_t =$

$Px_t + Q\epsilon_t^n$.

Equation (19) suggests that adding $news_t$ to the regression can be regarded as controlling for the state of the economy, but still leaves out the noise component of the public information in the error term. Since the noise shock is correlated with mps_t and affects $\mathbb{E}_t^{post} y_t$, the estimation of the coefficient on mps_t will still be biased.

In summary, there are three key takeaways from the simple model. First, asymmetric information between the central bank and private agents generates an information effect on monetary policy. Second, the size of the information effect of monetary policy cannot be easily measured by the private sector's forecast revisions after monetary policy surprises. Third, the size of the information effect crucially depends on the precision of both the public and the private information.

3 A New Keynesian DSGE Model

Our simple model suggests that the key to quantifying the information effect of monetary policy is to assess information precision in the real world. To capture imperfect information in the real world, we build a New Keynesian DSGE model where the central bank and the private sector have asymmetric information about the underlying economy. Our New Keynesian model has two additional features that are not in our simple model. First, it features different effects of information frictions on inflation and output. Second, the private sector's expectations matter in aggregate equilibrium variables. We first set up the model and explain the information structure (Section 3.1). We then calibrate the model parameters to match moments of macroeconomic dynamics and expectations in the US economy (Section 3.2).

3.1 Model Set-up

The economy consists of a representative household, a continuum of intermediate firms, and a central bank. We assume that a demand shock is the only type of fundamental shock in the private sector.

3.1.1 Optimization Problems

The representative household chooses consumption C_t and labor supply N_t to maximize its lifetime utility

$$\mathbb{E}_0^{HH} \sum_{t=0}^{\infty} \beta^t \exp(d_t) \left[\log(C_t) - \frac{N_t^{1+\psi}}{1+\psi} \right],$$

where $\beta \in (0,1)$ is the deterministic discount factor and $1/\psi > 0$ is the Frisch elasticity of labor supply. $\mathbb{E}_t^{HH}(\cdot) \equiv \mathbb{E}(\cdot|\mathcal{I}_t^{HH})$ is an expectation operator conditional on the household's information set, $\mathcal{I}_t^{HH}$, which will be specified below. C_t denotes final goods consumption, which consists of intermediate goods according to the Dixit–Stiglitz aggregator $C_t = \left(\int_{[0,1]} C_{t,j}^{(\nu-1)/\nu} dj\right)^{\frac{\nu}{\nu-1}}$, where ν is the elasticity of substitution between different intermediate goods $C_{t,j}$.

The household's preference is subject to a stochastic demand shock, which is assumed to follow

$$d_t = \rho d_{t-1} + \varepsilon_t^{\beta}, \qquad \varepsilon_t^{\beta} \sim N(0, \sigma_{\beta}^2)$$

A continuum of monopolistic competitive firms is indexed by $j \in [0,1]$ and produces intermediate goods under both a Calvo-type price rigidity (Calvo (1983)) and information frictions. Production technology is homogeneous, and each firm's production function is linear, given by $Y_{t,j} = N_{t,j}$.

When firm j gets the opportunity to reset the price, it chooses $P_t^*(j)$ to maximize its expectation of the sum of all discounted profits, while $P_t^*(j)$ remains effective. The profit-optimization problem is given by

$$max_{P_t^*(j)} \Sigma_{k=0}^{\infty} \theta^k \, \mathbb{E}_t^j \left\{ Q_{t,t+k} \left[P_t^*(j) Y_{t+k}(j) - MC_{t+k}(j) N_t(j) \right] \right\}, \tag{20}$$

where θ is the Calvo parameter, the probability that the current price does not change from this period to the next. The individual firm's expectations operator $\mathbb{E}_{t,j}^{Firm}$ is conditional on its information set, $I_{t,j}^{Firm}$. $Q_{t,t+k}$ is the stochastic discount factor given by: $Q_{t,t+k} = \beta^k \frac{U'(C_{t+k})}{U'(C_t)} \frac{P_t}{P_{t+k}}$. $MC_{t+k}(j)$ denotes the firm-specific marginal cost.

Let $mc_{t,j}$ denote the log approximated real marginal cost of firm j. We assume $mc_{t,j}$ is a linear combination of the real equilibrium wage and a firm-specific wage bargaining shock $\eta_{t,j}$. The bargaining shock introduces heterogeneity among firms. The household's intra-temporal labor supply decision derives the real equilibrium wage, given by $w_t = c_t + \psi n_t$. Market clearing conditions in the goods and labor markets yield $c_t = y_t = n_t$. Therefore, the real marginal cost of firm j is given by

$$mc_{t,j} = (1+\psi) y_t + \eta_{t,j}, \quad \eta_{t,j} \sim N(0, \sigma_{\eta}^2).$$

3.1.2 Monetary Policy

Monetary policy follows a Taylor-type targeting rule. Since the central bank is also subject to incomplete information, the interest rate responds to the central bank's expected, not actual, inflation and output, given by

$$i_t = \phi_\pi \mathbb{E}_t^{CB} \pi_t + \phi_y \mathbb{E}_t^{CB} y_t + e_t, \tag{21}$$

where $e_t \sim N(0, \sigma_e^2)$ stands for the exogenous monetary policy shock. $\mathbb{E}_t^{CB}$ denotes the central bank's expectations operator. The policy coefficients satisfy $\phi_\pi > 1, \phi_y > 0$.

3.1.3 Signals

Since the demand shock directly affects households' preference, we assume that households know d_t perfectly. Firms and the central bank reply on imperfect signals to infer the realization of the demand shock. We assume that there is an unbiased public signal that is available to all agents. Denote the public signal as

$$n_t = \varepsilon_t^\beta + \varepsilon_t^n, \quad \varepsilon_t^n \sim N(0, \sigma_n^2). \tag{22}$$

Besides n_t, the central bank also receives a private signal m_t, which follows

$$m_t = \varepsilon_t^\beta + \varepsilon_t^m, \quad \varepsilon_t^m \sim N(0, \sigma_m^2). \tag{23}$$

In addition to exogenous signals n_t and m_t, endogenous variables can also be regarded as signals. We assume that the central bank keeps track of the history of realized output and inflation, so inflation and output enter the central bank's information set with a time lag of one period. Firms use the interest rate as a signal. In addition to this public signal, firms also use their firm-specific marginal costs as private signals. Firm-specific marginal costs contain information about the demand shock, d_t, because the equilibrium wage changes with output, which is directly affected by d_t.

We summarize the information sets of each economic agent as follows.

$$I_t^{HH} = \{d_{t-k}, n_{t-k} | k \geq 0\}; \tag{24}$$

$$I_t^{CB} = \{\pi_{t-1-k}, y_{t-1-k}, n_{t-k}, m_{t-k}, e_{t-k} | k \geq 0\}; \tag{25}$$

$$I_{t,j}^{Firm} = \{i_{t-k}, n_{t-k}, mc_{t-k,j} | k \geq 0\}. \tag{26}$$

3.1.4 Equilibrium

Using the lowercase variables to denote the log deviations from their non-stochastic steady states, the inter-temporal Euler equation of the representative household and the market clearing conditions yield the following IS curve:

$$y_t = \mathbb{E}_t^{HH} y_{t+1} - \left(i_t - \mathbb{E}_t^{HH}\pi_{t+1}\right) + \left(d_t - \mathbb{E}_t^{HH} d_{t+1}\right). \tag{27}$$

where π_t is the inflation rate, given by $\pi_t = p_t - p_{t-1}$.

On the firm side, the first-order condition for optimal pricing is given by

$$p_{t,j}^* = (1-\beta\theta)\mathbb{E}_{t,j}^{Firm} \sum_{k=0}^{\infty} (\beta\theta)^k (p_{t+k} + mc_{t+k,j}). \tag{28}$$

Aggregate price level p_t is the weighted average between firms that cannot re-optimize and firms that re-optimize their prices, i.e., $p_t = \theta p_{t-1} + (1-\theta)\int p_{t,j}^* dj$. It is well known in the literature that under full information, aggregating the heterogeneous firms' optimal prices (28) leads to the following forward-looking Phillips curve

$$\pi_t = \beta \mathbb{E}_t \pi_{t+1} + \frac{(1-\beta\theta)(1-\theta)}{\theta}(1+\psi) y_t, \tag{29}$$

where $\mathbb{E}_t$ is the expectation formed under full information. However, the assumption that firms use their firm-specific marginal costs as private signals makes price aggregation a non-trivial task. The equilibrium conditions contain three types of non-nested conditional expectations $\mathbb{E}_t^{HH}$, $\mathbb{E}_{t,j}^{Firm}$, and $\mathbb{E}_t^{CB}$, which results in a breakdown of the law of iterated expectations and leads to the infinite regress problem of "forecasting the forecasts of others" (see Townsend (1983)).

To address the issue, we first follow Han, Ma, and Mao (2023) and reformulate the individual firm's optimal pricing problem by introducing an auxiliary variable, $z_{t,j}$. Define $z_{t,j} = (1-\theta)(p_{t,j}^* - p_{t-1})$ so that the price aggregation implies $\pi_t = \int_{[0,1]} z_{t,j} dj$. Rewriting equation (28) recursively in terms of $z_{t,j}$ leads to

$$z_{t,j} = (1-\beta\theta)(1-\theta) mc_{t,j} + (1-\theta)\mathbb{E}_{t,j}^{Firm}\pi_t + \beta\theta \mathbb{E}_{t,j}^{Firm} z_{t+1,j}, \tag{30}$$

Aggregating $z_{t,j}$ yields the dispersed-information Phillips curve

$$\pi_t = (1-\beta\theta)(1-\theta)(1+\varphi) y_t + (1-\theta)\int \mathbb{E}_{t,j}^{Firm}\pi_t + \beta\theta \int \mathbb{E}_{t,j}^{Firm} z_{t+1,j}, \tag{31}$$

In Equation (31), realized inflation depends both on the fundamental shock and on expectations. The fundamental shock, d_t, affects inflation because we assume each firm perfectly observes its own real marginal cost, which is affected by the demand shock through the change in equilibrium wage. Comparing Equations (29) and (31) shows the different impact of expectations. Under imperfect information, firms' expectations have a contemporaneous effect. When firms expect higher inflation, they increase their own prices on top of the actual changes in their marginal costs, which leads to higher actual inflation.

Due to dispersed information, solving the equilibrium in the time domain requires including a large number of higher-order expectations to form a suitable state space (see Kasa (2000), Huo and Takayama (2018), Rondina and Walker (2021), and Jurado (2023)). We solve this problem using the analytic policy function iteration (APFI) method and its accompanying "z-Tran" toolbox developed in Han, Tan, and Wu (2022). APFI is built on policy function iteration in the frequency domain, which requires only one state variable (i.e., the frequency z in the spectral density) and thus does not suffer the above curse of dimensionality.

Technically, given a candidate model solution, Han, Tan, and Wu (2022) show how to apply the inverse discrete-time Fourier transform to calculate the conditional expectations in the frequency domain when applying the Wiener-Hopf formula. APFI then utilizes the equilibrium conditions to construct an updated solution candidate given the existing candidate and its implied conditional expectations. APFI stops when the relative distance between the updated and existing solution candidates is smaller than a pre-specified criterion.

3.2 Calibration

The model is calibrated to the US economy at a quarterly frequency. We first assign values to the parameters commonly used in the New Keynesian literature. The discount factor, β, is equal to 0.99. The inverse Frisch elasticity of labor supply, $1/\psi$, is set to 0.5. We set the Calvo parameter $\theta = 2/3$, consistent with an average price duration of three quarters. Coefficients in the monetary policy response function are set as $\phi_\pi = 1.5$ and $\phi_y = 0.5$.

We focus on calibrating the remaining parameters, whose values determine the degree of information friction in the economy. These parameters include the demand shock process $\{\rho, \sigma_\beta\}$, the standard deviation of the monetary policy shock, σ_e, and the standard deviations of the signals, $\{\sigma_n, \sigma_m, \sigma_\eta\}$. We calibrate these parameters internally to match the moments of the realized macro data series and the nowcast accuracy from the Greenbook data set.

Our internally calibrated parameters are listed in Table 1 with their corresponding targets. Although every targeted moment is determined simultaneously, in what follows, we discuss each of the moments in relation to the parameters for which the moments yield the most identification power.

The first four parameters have a direct impact on realized aggregate equilibrium variables. First, we set the persistence parameter ρ to match the first auto-correlation of quarterly

Table 1: Internally Calibrated Parameters

Parameter	Value	Description
ρ	0.85	AR(1) of demand shock d_t
σ_β	1.88	Std. Dev. of demand shock ε_t^β
σ_e	0.24	Std. Dev. of monetary policy shock e_t
σ_n	5.64	Std. Dev. of public signal shock ε_t^n
σ_m	4.70	Std. Dev. of CB's private signal shock ν_t^β
σ_η	29.1	Std. Dev. of firm j's cost-push shock $\eta_{t,j}$

inflation. Second, we choose the standard deviation of the demand shock, σ_β, to match the standard deviation of quarterly inflation. Since the monetary policy shock e_t enters the monetary policy rule (Equation (2)) directly, we pick σ_e to match the standard deviation of the nominal interest rate. We calibrate the standard deviation of an individual firm's cost-push shock $\eta_{t,j}$ (i.e., σ_η) to match firms' pricing behaviors. Specifically, the targeted moment is the average of the absolute size of a price change conditional on a price change, which is found to be 9.7 percent by Klenow and Kryvtsov (2008). The standard deviations of the public signal and the central bank's private signal jointly determine how far away the central bank's expectations are from the ones under full information. We calibrate them jointly to match the standard deviations of nowcast errors of output growth $gy_t = y_t - y_{t-1}$ and inflation in the Greenbook data set.

Under our calibration, the standard deviation of the monetary policy shock is small, consistent with the fact that the Federal Reserve has good control when setting the policy rate. Both the central bank's private signal and the public signal are both noisy, as suggested by their large value relative to σ_β. This explains the sizable nowcast errors of the central bank. The standard deviation of the central bank's nowcast error is 0.23, which is over one-third of the standard deviation of realized inflation (0.59). If the public or private information is precise, the central bank would know the realized equilibrium well and thus have small nowcast errors. Firms' information is also noisy, as both the public and private information from their firm-specific marginal costs have large standard deviations.

We present the model-implied moments under our calibration in Table 1. The left column of Table 2 shows that the model-implied moments almost perfectly match their data counterparts under our calibration. The right column of Table 2 computes some non-targeted moments. Although we perfectly match the process of inflation dynamics, we cannot explain the positive auto-correlation of output growth, meaning that we do not have a hump-shaped output response. We will explain in Section 4 that the absence of a hump-shape output response is due to our assumption that households have perfect information. Our calibration

Table 2: Data and Model-Simulated Moments

Targeted Moment	Data	Model	Untargeted Moment	Data	Model
$\sigma(\pi_t)$	0.59	0.60	$\sigma(gy_t)$	0.79	0.79
$corr(\pi_t, \pi_{t-1})$	0.89	0.89	$corr(gy_t, gy_{t-1})$	0.31	-0.46
$\sigma(i_t)$	0.95	0.94	$corr(i_t, i_{t-1})$	0.97	0.83
$\sigma(\pi_t - \mathbb{E}_t^{CB}\pi_t)$	0.23	0.23	$\sigma(\pi_t - \mathbb{E}_{t-1}\pi_t)$	0.28	0.36
$\sigma(gy_t - \mathbb{E}_t^{CB}gy_t)$	0.53	0.57	$\sigma(gy_t - \mathbb{E}_{t-1}^{CB}gy_t)$	0.68	0.77
avg. $\lvert\Delta p_j\rvert$	9.7%	9.7%	$\sigma(\pi_t - \mathbb{E}_t^{SPF}\pi_t)$	0.24	0.24
			$\sigma(\pi_t - \mathbb{E}_{t-1}^{SPF}\pi_t)$	0.31	0.37

also under-predicts the auto-correlation in the interest-rate process, which may suggest that the interest-rate process in the real world has some inertial response that the persistence in inflation or output cannot explain.

In both the data (SPF and Greenbook) and our model, the standard deviations of inflation nowcast errors are very similar between the central bank and professional forecasters. Our model predicts a higher standard deviation of the central bank's forecast errors than the data. This may indicate that the central bank has some advanced information about the future economy. Our model predicts very well the nowcast errors of professional forecasters. The standard deviation of inflation nowcasts is only slightly higher than that in the Greenbook, which is consistent with our calibration of a noisy public signal and a noisy central bank private signal.

4 The Information Effect of Monetary Policy

To illustrate the information effect of monetary policy, we compare three cases. The first case is under perfect information. The second case is under imperfect information, and the interest rate enters into all firms' information sets, i.e., monetary policy has an information effect. The third case is under imperfect information, but we assume that firms do not use the interest rate as a signal. In other words, firms only use their marginal costs to infer information about the aggregate economy.

4.1 The Effect of Information Frictions

Figure 4 plots the impulse responses, with the red, blue, and green lines representing the three cases correspondingly. The difference between case 1 and case 2 arises for two reasons. The first reason is the imperfect information, which explains the difference between case 1 and case 3. The second reason is that conditional on having only imperfect information, firms use an additional signal, the interest rate, which accounts for the difference between case 2 and case 3.

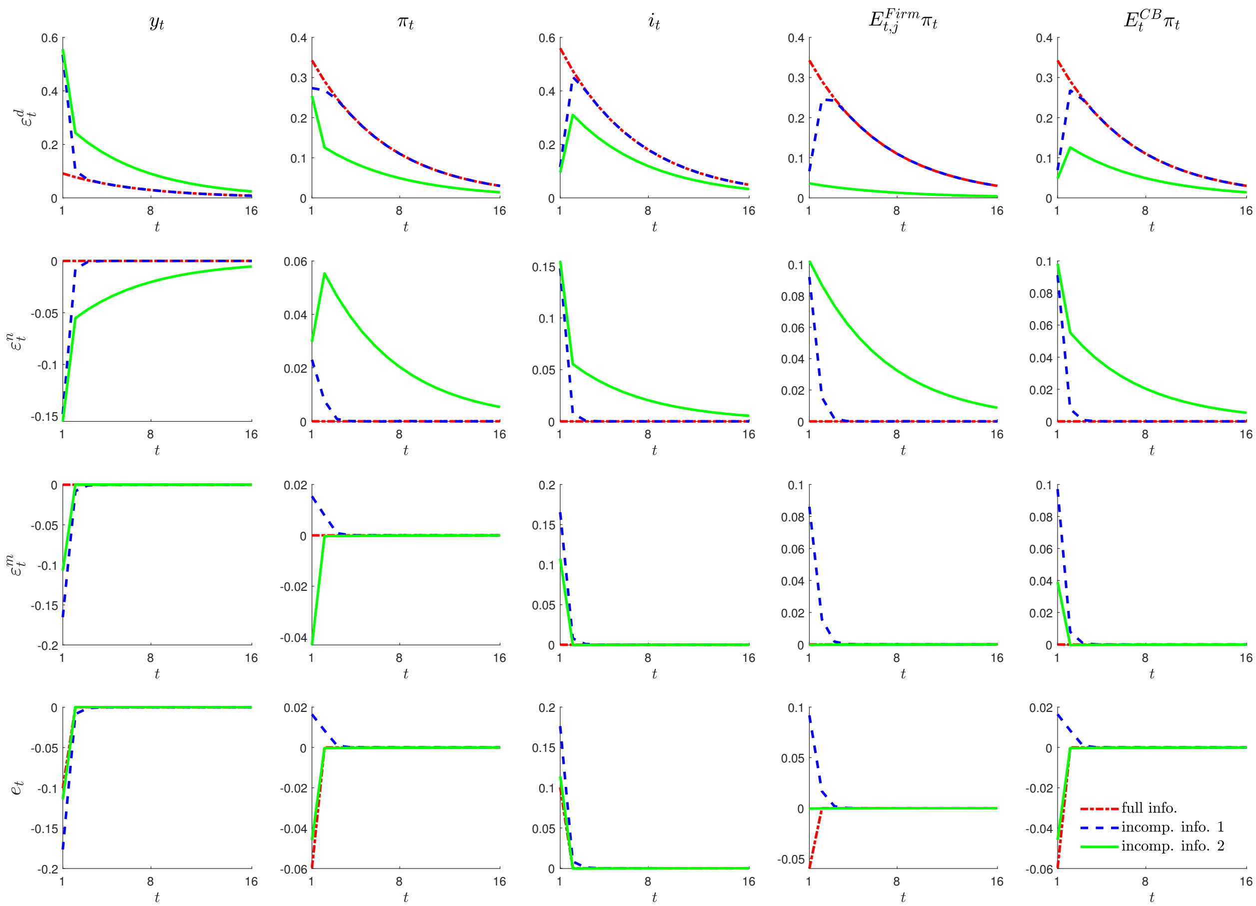
We first discuss the effect of imperfect information by comparing case 1 and case 3. The first row of Figure 4 illustrates the dynamics after a positive demand shock. The positive change in the output level is much larger under imperfect information than under perfect information. The reason is that the increase in the interest rate is much smaller in case 3 because the central bank underestimates the changes in inflation and output due to having imperfect information about the demand shock. A smaller increase in the interest rate leads to a higher demand for consumption.

At the same time, the effect of the demand shock on inflation is smaller under imperfect information than under full information, which is due to firms having imperfect information. A positive demand shock drives up output and increases the real marginal cost for all firms. When firm j observes a higher $mc_{t,j}$, it cannot distinguish between whether it is due to the increase in aggregate demand, in which case aggregate inflation will go up, or due to having a positive idiosyncratic wage bargaining shock, in which case aggregate inflation stays the same. Therefore, as the firm weighs the possibility of the two cases, it increases its price by a lesser amount than it would under perfect information. Therefore, firms have lower expectations of aggregate inflation, which feeds into lower realized inflation.

The second and third rows of Figure 4 illustrate the effects of a positive public noise shock and a positive private noise shock, correspondingly. In both cases, a positive noise shock makes the central bank expect higher inflation (last column) and thus raise the interest rate. The higher interest rate reduces demand and leads to a negative output level. As for inflation, if the positive noise shock is public information, inflation increases. This is because when each firm expects higher inflation and thus increases prices, realized inflation increases as a result. If, on the other hand, the noise shock applies only to the central bank's private information, then each firm reduces prices due to lower demand, leading to a negative inflation rate.

The last row shows the dynamics after a positive monetary policy shock. The impulse responses are very similar between case 1 and case 3, as both the output level and inflation are negative. The difference lies in expectations. In case 3, firms only use their firm-specific marginal costs to infer information about the aggregate economy. Since the idiosyncratic wage bargaining shock has a very large variance, it provides very imprecise information about the average marginal cost in the economy. Therefore, each firm regards the decrease in its own marginal cost as a firm-specific shock and barely updates its expectation on inflation. Since each firm expects other firms to not change prices, the strategic complementarity in pricing decisions is absent. Thus, each firm adjusts its price by a lesser amount than it would

Figure 4: Impulse Responses



Notes: The dash-dotted red line is the full information case. The dashed blue line is our benchmark model, in which the interest rate has an information effect. The solid green line is our counter-factual model in which the interest rate does not enter firms' information sets.

under full information.

4.2 Two-Way Learning between the Central Bank and Firms

We now discuss the information effect of the interest rate by comparing case 2 and case 3. The first two rows of Figure 4 show that the information effect of monetary policy reduces the degree of information friction after a demand shock and after a public noise shock. In both cases, the blue lines (with information effect) lie in between the red lines (full information) and the green lines (no information effect). With the information effect of monetary policy, the dynamics quickly converge to the full information case.

This is due to the **two-way learning** mechanism between the central bank and firms. When firms learn from the interest rate, their pricing decisions are closer to the ones under perfect information. This, in turn, makes inflation and output closer to that under full information. Since aggregate inflation and output are endogenous signals to the central bank after a one-period lag, the central bank now has more precise information about the demand shock, making the interest rate a more precise signal to all the firms. This two-way learning mechanism further reduces the degree of information frictions over time. From around $t = 3$, the impulse responses are identical between the case under full information and the case with the information effect.

The information effect of monetary policy does not come without a cost. Although the information effect of monetary policy reduces fluctuations after the demand shock and public noise shock, it leads to larger fluctuations in output after a noise shock to the central bank's private information (the third row in Figure 4) and after a monetary policy shock (the fourth row in Figure 4). This is because the information effect of monetary policy transmits a wrong belief to firms, inducing firms to believe a positive demand shock and thus to increase prices. The combination of a tightening monetary policy and positive inflation leads to a further decline in output.

After all four shocks, inflation and the interest rate move in the same direction. This suggests that our model can explain the monetary policy price puzzle documented in the empirical vector autoregression (VAR) literature.[2] After a positive innovation in the interest rate, the information effect increases the prices due to the higher expected inflation, and the direct effect decreases the prices due to the lower demand of output. Under our calibration, the information effect dominates the direct effect, and therefore inflation rises after a positive interest rate.

5 Conclusion

This paper examines the quantitative importance of the information effect of monetary policy. To this end, we first use a simple model to show that under asymmetric information, monetary policy surprises are correlated with the state of the economy and thus theoretically provide useful information to private agents. In addition, this correlation also means that the existing evidence based on reduced-form regression analysis likely yields a biased estimation of the size of the information effect.

We then build a New Keynesian DSGE model under asymmetric information, and calibrate model parameters to match the macroeconomic dynamics and expectations data in the US economy. Under our calibration, the information effect is quantitatively important because it enhances a two-way learning process between the central bank and the private sector. When firms learn from the interest rate, they have more precise information about

[2] Sims (1992) finds that following a contractionary monetary policy shock, the price level increases initially.

the aggregate demand shock, and thus, their pricing decisions are more aligned with the fundamental shock. This, in turn, makes the central bank learn more precise information when firms extract information from inflation and output in the next period.

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