Asymmetric Information, Two-Way Learning, and the Fed Information Effect*

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Abstract

How important is the information effect of monetary policy? We first show analytically that the reduced-form method of regressing forecast revisions on monetary policy surprises leads to a biased estimation, due to the correlation between monetary policy surprises and the unobserved shocks. We then develop a New Keynesian model in which learning is two-way: the central bank learns from lagged inflation and output, and the private sector learns from the interest rate. We calibrate our model parameters to match macroeconomic dynamics in the US and forecasting accuracy of the Federal Reserve and professional forecasters. Our calibrated model shows the information effect reduces the output gaps caused by demand shocks and noise shocks, but leads to a temporary rise in inflation after a contractionary monetary policy shock.

Keywords: asymmetric information, expectation formation, monetary policy
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 that an interest rate decision reveals the central bank's private information about the state of the economy, and use the interest rate as a signal to update beliefs about the state of the economy. 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. Bauer and Swanson (2023) 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 construct an analytic model to explain the reason for the different results between Nakamura and Steinsson (2018) and Bauer and Swanson (2023). Specifically, we show a reduced-form regression that measures the relationship between the private-sector's forecast revisions and monetary policy surprises yields a biased estimation of the information effect. This is because under asymmetric information, monetary policy surprises correlate with the unobserved fundamental shocks. This correlation means monetary policy surprises provide useful information about the economy and, at the same time, is hard to estimate in a reduced-form regression.

We then propose to structurally estimate the information effect using a quantitative New Keynesian model with asymmetric information. The key novelty of our model is the two-way learning mechanism: we assume that the central bank learns from decisions in the private sector (inflation and output) with one period lag, and the private sector learns from the interest-rate decisions by the central bank. We calibrate information precision to match moments of macroeconomic dynamics and expectations in the US economy. Our calibration suggests that exogenous signals about the current shock, both private and public, are noisy. However, the central bank quickly gets precise information by learning from lagged equilibrium variables, and this precise information is transmitted to the private sector through the information effect of monetary policy. Our baseline calibration suggests that the information effect dominates the direct effect of monetary policy: a 1 percent exogenous policy shock leads to a 0.8 percent rise in inflation. The size of the information effect would decrease if the central bank has observation errors or there is large exogenous variation in the policy rate.

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. There is a public signal that is available to both the central bank and all professional forecasters. In addition to the public signal, the central bank also observes a private signal. Each professional forecaster gets an individual-specific signal, and the noise components of all individual-specific signals cancel out in aggregation.

The central bank sets the interest rate following a targeting rule that makes the interest rate respond to the central bank's expected output. We assume that the interest rate also contains a policy shock, which 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 average of pre-FOMC expected interest rate across all forecasters. This definition corresponds to the definition of monetary policy surprises using the high-frequency identification method in the empirical literature.

Our analytic model provides a micro-foundation for monetary policy surprises under asymmetric information. In our framework, the fundamental shock, the noise shock in the central bank's private and public information, and the exogenous interest-rate shock all contribute to a monetary policy surprise. After a positive fundamental shock, professional forecasters underestimate the realization of the shock due to imperfect information, and thereby underestimate the response by the central bank. Hence, the actual interest rate is greater than the expected interest rate, leading to a monetary policy surprise. Notice that if the central bank does not have private information about the fundamental shock, a fundamental shock will not cause any monetary policy surprise, even if the public information is still imperfect. This is because without central bank private information, the endogenous responses in the interest rate are perfectly predictable. In this case, surprise in the interest rate is solely driven by the exogenous policy shock.

The correlation between monetary policy surprises and the fundamental shock implies that monetary policy provides valuable information. 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 relative to professional forecasters. The information effect exhibits a non-linear relationship between the precision of public information and the policy rule coefficient. Connecting our model to the empirical literature, we argue that if one regresses post-FOMC expected output on only monetary policy surprises, without controlling for the fundamental shock and the noise shock, the

estimated coefficient is biased upward. This result is consistent with the argument made in Bauer and Swanson (2023).

However, we also argue that results shown in Bauer and Swanson (2023) cannot conclude that monetary policy has no information effect for two reasons. First, the estimated coefficient measures the combination of the information effect and the direct effect of monetary policy. A negative coefficient only suggests that the direct effect dominates the information effect, and the information effect could still be singificant. Second, both Nakamura and Steinsson (2018) and Bauer and Swanson (2023) measure the expectations formed by professional forecasters, but interest rates may have a larger information effect on expectations of firms and households. Their expectations are more important than those of professional forecasters, considering firms and households are the ones making pricing and demand decisions in the economy.

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 in our calibrated model. We assume that there are two aggregate fundamental shocks: a persistent demand shock and a transitory cost-push shock. Since the demand shock directly affects the household's preference, we assume the household has perfect information about it. Each firm observes its own marginal cost, which include the aggregate cost-push shock and an idiosyncratic shock, which give each firm a private signal.

Capturing information asymmetry is the key to our model. We assume there are two exogenous signals: one public signal available to all agents and one private signal only available to the central bank. In addition to the exogenous signals, the central bank also learns from endogenous signals of inflation and output with a time lag. On the other hand, firms use their real marginal costs as their private signal. 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 directly assign values to the parameters commonly used in the New Keynesian literature (parameters of the household's utility function, Calvo parameter, and the coefficients of the monetary policy targeting rule). We then internally calibrate the parameters that govern the degree of information friction. 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. We calibrate the standard deviation of individual firms' real marginal costs using empirical evidence of price changes. According to empirical estimates, conditional on price changes, the average absolute size of price changes is large, which implies a sizeable idiosyncratic shock in firms' marginal costs. To calibrate the precision of external signals, we choose the standard deviation of the central bank's private and the public signals to match the inflation and output nowcast accuracy in the Greenbook. 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 first analyze the effect of imperfect information by comparing the perfect information benchmark and the economy in which the private sector does not learn from the interest rate. In this case, the imperfect information economy has larger output gaps but smaller inflation deviation. This is because as the demand shock directly change the household's utility, the household has better information than the firms.

With the information effect, the equilibrium under imperfect information converges to the full information benchmark faster, suggesting that the information effect of monetary policy significantly reduces the degree of information friction in the economy. This is because the interest rate facilitates a two-way learning 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 the next period, when the central bank learns from past inflation and output, the central bank, in turn, gets more precise information, which makes the interest rate more informative about the underlying economy. After a policy shock, whether as a result of the noise in the central bank's private information or an exogenous policy shock, the information effect leads to larger inflation deviations, as firms mistakenly believe the change in the interest rate to be a real demand shock.

Related Literature

Our paper builds on the growing literature on the information effect of monetary policy. Romer and Romer (2000) first proposes the concept, which shows 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) argues 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.

Motivated by the empirical relevance of the information effect of monetary policy, economists start 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 a few exceptions, the existing literature on the information effect studies the case of one-way learning: the private sector learns 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). By modeling a two-sided learning process, Kohlhas (2022) shows that releasing the central bank's information is beneficial even for inefficient shocks, such as cost-push shocks. The difference is that we focus on quantifying the degree of the information effect on the US economy.

In addition, another critical novelty in our model is the rich information asymmetry between different agents. Incomplete information models often pose technical difficulties due to the infinite regress of expectations that arises when agents need to "forecast the forecasts of others" (see Townsend (1983)). Asymmetric information acerbates the issue as higher-order beliefs also exist among groups of agents of different types. Frequency-domain methodologies (see Kasa (2000), Huo and Takayama (2018), Rondina and Walker (2021), and Jurado (2021)) effectively circumvents the infinite regress problem. We advocate the "`z-Tran`" toolbox developed in Han, Tan, and Wu (2022) as it is tailored to endogenous and exogenous signals and asymmetric information sets.

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 implications on 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 the 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. Section xx will relax this assumption and allow equilibrium output and inflation to depend on the private sector's expectations.

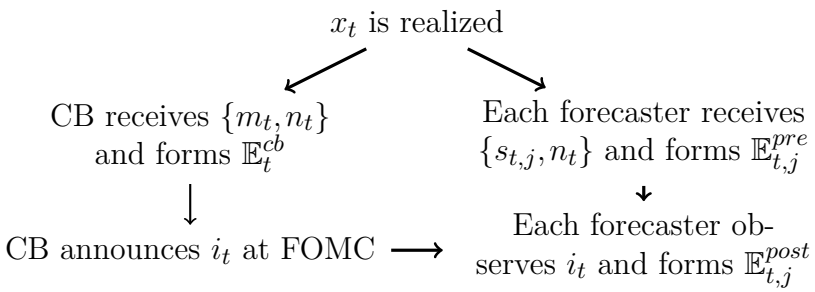
The central bank sets the interest rate following a targeting rule conditional on its expectation, given by

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

where $\phi_y > 0$. The central bank chooses the value of ϕ_y and 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 $\mathbb{E}_t^{cb} y_t$.

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

Figure 1: Sequence of Events



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 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 and makes announcements in FOMC meetings. 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 (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

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

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

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

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

In addition to forming expectations about x_t, the professional forecasters also form expectations about the interest-rate decisions. Individual forecasters understand that the interest rate is set conditional on the central bank's imperfect information according to Equation (4). In addition, as 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

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

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

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

$$\hat{i}_t = \frac{i_t - \frac{\phi_y}{1+\kappa\phi_y}\frac{\nu_n}{\nu_x+\nu_n+\nu_m} n_t}{\frac{\phi_y}{1+\kappa\phi_y}\frac{\nu_m}{\nu_x+\nu_n+\nu_m}} = x_t + \varepsilon_t^m + \frac{1}{\phi_y \frac{\nu_m}{\nu_x+\nu_n+\nu_m}} e_t \quad (7)$$

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

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

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).*

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

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

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 close-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

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

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

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

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 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 decision. 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 public to the private sector, then $\mathbb{E}_{t,j}^{pre} m_t = m_t$. In this case, a monetary policy surprise is only a 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 by the Greenbook and Survey of Professional Forecasters data.

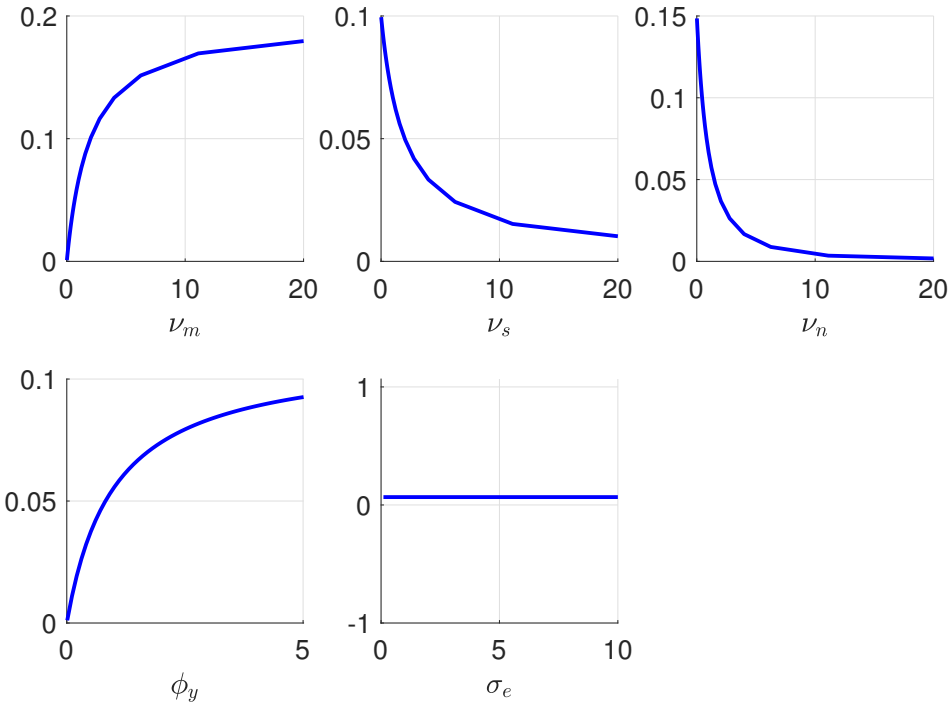
Proposition 1 shows that mps_t positively correlates with x_t. In the following proposition, we characterize how the effect of x_t on mps_t depends on the degree of information frictions and the parameters of the interest rate rule.

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 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

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 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 Predict 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 the monetary policy surprise is not exogenous and correlates 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 by economic news. To make our results comparable to 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., $news_t = x_t - \int \mathbb{E}_{t,j}^{pre} x_t$, where $\mathbb{E}_{t,j}^{pre} x_t$ 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 by 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 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 that the central bank has more precise information, Furthermore, the latter requires that the private sector has precise information.

Monetary policy surprises are predictable by 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. Instead, we assume that the private sector has 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 by 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, do not correlate with the state of the economy, and are not predictable by economic news. Also, notice that mps_t still correlates with x_t and is predictable by economic news if perfect information is only available 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 by $news_t$ still holds.

2.2.3 The Information Effect of Monetary Policy

Because monetary policy surprises correlate 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 friction.

To make our model implied information effect comparable to the ones measured in the empirical literature, we express the post-FOMC expectation 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 the average post-FOMC expectation

of economic output is given by

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

The value 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 the size of it 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 the size of it*

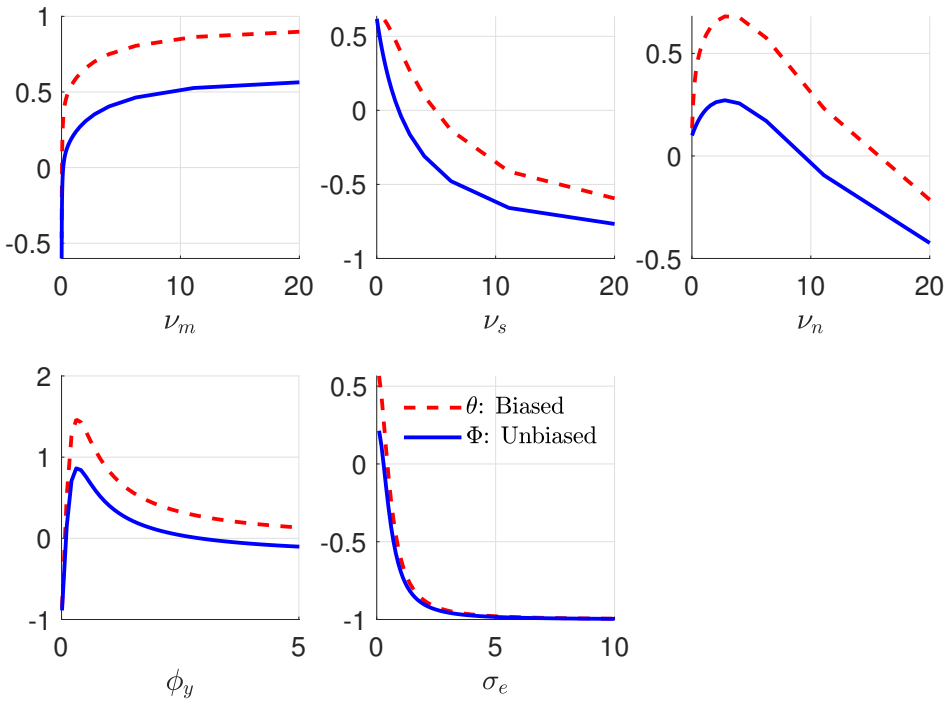
- *increases with the precision of the central bank's private information (ν_m),*
- *decreases with the precision of the forecasters' private information (ν_s),*
- *has a non-linear relationship with the precision of the public information (ν_n) and the policy rule coefficient (ϕ_y),*
- *and decreases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

We illustrate how Φ changes with different parameters by the solid blue line in Figure 3. 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 changes 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 update 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

Figure 3: The Information Effect of Monetary Policy



Notes: The blue solid line plots the value of Φ in Equation (16), and the red dashed 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 $\phi_y = 1.5$.

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 correlate with mps_t and determine $\mathbb{E}_t^{post} y_t$.

To calculate the size of the omitted variable bias in our model, we re-write 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 red dashed lines and compare it with the actual size of the information effect (Φ). All four panels suggest that the omitted variable bias leads to an overestimation of the size of the information effect.

Bauer and Swanson (2023) suggests 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 $news_t$ in 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 correlates with mps_t and affects $\mathbb{E}_t^{post} y_t$, the estimation of the coefficient on mps_t will still be biased.

Summary. There are three key takeaways from the simple model. First, asymmetric information between the central bank and private agents leads to the information effect of monetary policy. Second, the size of the information effect crucially depends on the information structure and the signal precision. Third, a reduced-form estimation that measures the correlation between forecast revisions and monetary policy surprises is not a good way to study the size of the information effect. The estimation is likely to be biased due to the correlation between monetary policy surprises and unobserved shocks, and the estimated coefficient captures the combined effect of monetary policy rather than the information effect alone. Therefore, we turn to a structural model to study the information effect of monetary policy.

3 A New Keynesian Model

To quantify the information effect of monetary policy in the real world, we develop a New Keynesian model under information frictions, building on Nimark (2008) and Melosi (2017). The key innovation of our model is to assume that signals used by the central bank and the private sector also include endogenous variables in the equilibrium.

Our quantitative model has two extensions from our analytic model in Section 2. First, instead of equating the private-sector's expectations with the expectations of professional forecasters, we model the private sector consists of different agents, including households, firms, and professional forecasters Each agent has different information set and forms different expectation. Therefore, in contrast to Nakamura and Steinsson (2018) or Bauer and Swanson (2023), where the information effect is measured on the expectations of professional forecasters, our model can potentially capture different information effect on different agents. Second, as firms make pricing decisions conditional on their expectations of the aggregate economy, the information effect can change equilibrium inflation and output, which in turn, changes the interest rate decisions by the central bank. These two features allow us to compare model predictions with empirical moments of macroeconomic dynamics and survey expectations in the US economy.

3.1 Model Set-up

The economy consists of a representative household that demands consumption goods and supplies labor, a continuum of firms that produce intermediate goods and set prices, and a central bank that sets the interest rate according to a targeting rule. We first describe the optimization problems of the household and the firms, as well as the interest rate rule. We then specify the information structures of all agents. Lastly, we express the aggregate equilibrium variables in terms of the IS curve and the Phillips curve and compare them with those in the traditional New Keynesian literature under FIRE.

3.1.1 Household

The representative household chooses aggregate consumption, C_t, relative to an external habit stock hC_{t-1}, and labor supply, N_t, to maximize its lifetime utility.

$$\mathbb{E}_0^{HH}\sum_{t=0}^{\infty}\beta^t U(C_t,N_t)=\mathbb{E}_0^{HH}\sum_{t=0}^{\infty}\beta^t\exp(d_t)\left[\log(C_t-hC_{t-1})-\frac{N_t^{1+\psi}}{1+\psi}\right], \tag{20}$$

where $\beta \in (0,1)$ is the deterministic discount factor, $h \in (0,1)$ governs the strength of habits, 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 later.

The preference of the household is subject to a stochastic demand shock d_t, which is assumed to follow an AR(1) process:

$$d_t = \rho d_{t-1} + \varepsilon_t, \quad \varepsilon_t \sim N(0, \sigma_d^2). \tag{21}$$

Since the demand shock directly affects the household's preference, we assume that it is perfectly observable by the household. The aggregate good, C_t, consists of a continuum of intermediate goods in the form of $C_t = \left(\int_{[0,1]} C_{t,j}^{(\nu-1)/\nu} dj \right)^{\frac{\nu}{\nu-1}}$, where ν is the elasticity of substitution between different intermediate goods $C_{t,j}$.

The intra-temporal labor supply decision sets the marginal rate of substitution between leisure and consumption euqal to the real wage, which is given by[2]

$$w_t = \frac{1}{1-h}(c_t - hc_{t-1}) + \psi n_t. \tag{22}$$

Using the intertemporal consumption decision and the goods market clearing condition, we derive the following expression for aggregate output,

$$y_t = \frac{1}{1+h}\left(\mathbb{E}_t^{HH} y_{t+1} + h y_{t-1}\right) - \frac{1-h}{1+h}\left(i_t - \mathbb{E}_t^{HH}\pi_{t+1}\right) + \frac{1-h}{1+h}\left(d_t - \mathbb{E}_t^{HH} d_{t+1}\right), \tag{23}$$

where i_t and π_t denote the nominal interest rate and the inflation rate.

3.1.2 Firms

A continuum of competitive monopolistic firms is indexed by $j \in [0,1]$ and produces intermediate goods under the Calvo type of 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

$$max_{P_t^*(j)} \Sigma_{k=0}^{\infty} \theta^k \mathbb{E}_{t,j}^{Firm} \left\{ Q_{t,t+k} \left[P_t^*(j) Y_{t+k}(j) - MC_{t+k}(j) N_t(j) \right] \right\}, \tag{24}$$

[2]We use the lowercase variables to denote the logarithmic deviations from their deterministic steady-states.

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, $I_{t,j}^{Firm}$. The stochastic discount factor is $Q_{t,t+k}$ and $MC_{t+k}(j)$ denotes the firm-specific nominal marginal cost.

The optimal price for a firm j who can re-optimize at time t is determined by the discounted sum of its current and expected future nominal marginal costs

$$p_{t,j}^{*} = (1-\beta\theta)\mathbb{E}_{t,j}^{Firm}\sum_{k=0}^{\infty}(\beta\theta)^{k}(p_{t+k}+mc_{t+k,j}), \tag{25}$$

where $mc_{t,j}$ is firm j's real marginal cost at time t. Following Nimark (2008), we assume $mc_{t,j}$ is a linear combination of the equilibrium real wage and some supply-side shocks. In particular, there is an *i.i.d.* aggregate cost-push shock $u_t \sim N(0,\sigma_u^2)$, and an idiosyncratic wage bargaining shock $\eta_{t,j} \sim N(0,\sigma_\eta^2)$, such that

$$mc_{t,j} = w_t + u_t + \eta_{t,j}. \tag{26}$$

The idiosyncratic components of $mc_{t,j}$ are canceled out in aggregation, i.e., $\int_{[0,1]}\eta_{t,j}dj = 0$.

Firms observe their own marginal costs perfectly, but cannot separately observe the economy-wide shocks $\{d_t, u_t\}$ and the firm-specific bargaining shock $\eta_{t,j}$. Equation (26) implies that when a firm observes a higher real marginal cost, it cannot perfectly tell whether it is due to a higher real demand that drives up equilibrium wage, a greater aggregate cost-push shock, or a positive firm-specific shock to the bargaining power of its workers.

Aggregate price level p_t is the weighted average between firms who cannot re-optimize and firms who re-optimize their prices, *i.e.*, $p_t = \theta p_{t-1} + (1-\theta)\int p_{t,j}^{*}dj$. Inflation is defined as $\pi_t = p_t - p_{t-1}$.

3.1.3 Central Bank

We assume the central bank is also subject to incomplete information and sets the nominal interest rate i_t following a Taylor-type targeting rule. To capture the potential information effect of monetary policy, we assume that in each period, the central bank sets the interest rate before the private sector makes consumption and pricing decisions.

The central bank sets the interest rate responding to the central bank's expected, not

actual, inflation and output.[3] Specifically, the interest rate follows

$$i_t = \phi_\pi \mathbb{E}_t^{CB} \pi_t + \phi_y \mathbb{E}_t^{CB} y_t + e_t. \tag{27}$$

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

3.1.4 Exogenous Signals

There are three aggregate shocks in the economy: a persistent demand shock d_t, a transitory cost-push shock u_t, and a monetary policy shock e_t. To avoid introducing too many exogenous stable variables, which adds computation complexity, we assume that there is only two exogenous signals (one public and one central bank's private), both of which reveals information about the aggregate demand shock.

The notation for signals also closely follows the simple model. First, there is an unbiased public signal is available to all agents. Denote the public signal as

$$n_t = d_t + \varepsilon_t^n, \quad \varepsilon_t^n \sim N(0, \sigma_n^2). \tag{28}$$

In addition to n_t, the central bank also receives a private signal, m_t, which follows

$$m_t = d_t + \varepsilon_t^m, \quad \varepsilon_t^m \sim N(0, \sigma_m^2). \tag{29}$$

Since both the aggregate cost-push shock and the idiosyncratic wage bargaining shock are *i.i.d.*, each firm's real marginal cost serves as a private signal about the aggregate demand shock. We do not introduce any other private signals to the firms.

3.1.5 Timing Protocol and Information Sets

The timing protocol is standard in the literature on the information effect of monetary policy. We that any period t is divided into three stages. At stage 1, all shocks are realized. At stage 2, the central bank sets the interest rate based on its information set, which will be specified later. At stage 3, households makes consumption and labor supply decisions. At the same time, firms make pricing decisions.

The model structure (including all structural parameter values and equilibrium conditions) is common knowledge to households, firms, and the central bank. All economic agents

[3] Since we do not model technology shocks, there are no fluctuations in the natural level of output. Hence, equilibrium output equals the output gap in our model.

also form conditional expectations (i.e., $\mathbb{E}_t^{HH}(\cdot|I_t^{HH})$, $\mathbb{E}_{t,j}^{Firm}(\cdot|I_{t,j}^{Firm})$, $\mathbb{E}_t^{CB}(\cdot|I_t^{CB})$) rationally.

We now describe the information sets for each economic agent. Since the demand shock directly enters the household's utility function, we assume that the household's information set includes the history of the demand shocks. It turns out that the model's quantitative predictions are not sensitive to whether or not the household observes the temporary cost-push shock. This is because as the central bank does not have information about the cost-push shock, the interest rate does not response to the cost-push shock. Consequently, a temporary cost-push shock results in a one-time increase in inflation while the output stays the same both in the current period and in future periods. Therefore, without loss of generality, we assume that the household has perfect information on all shocks.

We assume that the central bank's information set includes the exogenous signals of the demand shock and endogenous signals of lagged inflation and output. This assumption is motivated by the fact that, in practice, most central banks, including the Federal Reserve and the European Central Bank, closely monitor statistics of the aggregate economy, which often comes with a time lag. For this reason, we set

$$\mathcal{I}_t^{CB} = \{n_{t-k}, m_{t-k}, e_{t-k}, \pi_{t-1-k}, y_{t-1-k} | k \geq 0\}. \tag{30}$$

Due to the scarcity of surveys of firm expectations, it is difficult to gauge how firms form expectations. We therefore hypothesis three types of firms' information sets, $\mathcal{I}_{t,j}^{Firm}$.

$$\textbf{Type I:} \quad \mathcal{I}_{t,j}^{Firm} = \{mc_{t-k,j}, n_{t-k} | k \geq 0\}; \tag{31}$$

$$\textbf{Type II:} \quad \mathcal{I}_{t,j}^{Firm} = \{mc_{t-k,j}, n_{t-k}, i_{t-k} | k \geq 0\}; \tag{32}$$

$$\textbf{Type III:} \quad \mathcal{I}_{t,j}^{Firm} = \{mc_{t-k,j}, n_{t-k}, i_{t-k}, \pi_{t-1-k} | k \geq 0\}. \tag{33}$$

Of all $\mathcal{I}_{t,j}^{Firm}$ considered, firms always learn from the histories of their real marginal cost and the public signal. Type I firms are the least informative ones among the three types, as their information sets do not have additional aggregate equilibrium variables. On top of the signals contained in Type I firms, the information set of Type II firms also includes the nominal interest rates, which allows for the possibility that monetary policy has an information effect. Type III firms are the most informative ones, because on top of the signals observed by Type II firms, Type III also learn from the history of realized inflation.[4] In our calibration and main analysis, we consider the case in which all firms are of the same type. By doing so,

[4]We omit the case where $\mathcal{I}_{t,j}^{Firm} = \{mc_{t-k,j}, n_{t-k}, i_{t-k}, \pi_{t-1-k}, y_{t-1-k} | k \geq 0\}$, because as as we show later, the economy with Type II firms and Type III firms are very similar, and thus the alternative specification of adding both lagged inflation and lagged output to firms' information set would yield similar results.

we measure the maximum and minimum size of the information effect. We will discuss the situation in which firms are of different types in Section ??.

Besides households, firms, and the central bank, there is also a professional forecaster, allowing us to connect our model to the SPF data and the literature on the high frequency identification of monetary policy surprises. Importantly, the professional forecaster forms expectations twice in a given period, once before and once after the FOMC meeting. We specify the pre-FOMC and post-FOMC information sets of the professional forecaster as:

$$\mathcal{I}_t^{PF,pre} = \{n_{t-k}, i_{t-k-1}, \pi_{t-1-k}, y_{t-1-k} | k \geq 0\}. \tag{34}$$

$$\mathcal{I}_t^{PF,post} = \{n_{t-k}, i_{t-k}, \pi_{t-1-k}, y_{t-1-k} | k \geq 0\}. \tag{35}$$

Compared to $\mathcal{I}_t^{CB}$, the professional forecaster has same information of lagged aggregate equilibrium variables, but does not have access to the private signals of the central bank m_t and the exogenous monetary policy shocks e_t. Instead, he tracks the central bank's interest rate decisions. The only difference between $\mathcal{I}_t^{PF,pre}$ and $\mathcal{I}_t^{PF,post}$ is the inclusion of the latest interest rate decision i_t in the latter.

3.1.6 Solution to the Aggregate Equilibrium

To derive aggregate inflation, one needs to integrate prices of all firms. Prices of individual firms include firm-specific expectations of the aggregate price, as specified in Equation (25). However, expectations are heterogeneous in our model, because firms use their firm-specific marginal cost $mc_{t,j}$ as private signals, making aggregating individual prices a nontrivial task.

To address the issue, we first follow Han, Ma, and Mao (2023) and reformulate the individual firm's optimal pricing problem with 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 (25) recursively in terms of $z_{t,j}$ leads to

$$z_{t,j} = (1-\beta\theta)(1-\theta)mc_{t,j} + (1-\theta)\mathbb{E}_{t,j}^{Firm}\pi_t + \beta\theta\mathbb{E}_{t,j}^{Firm} z_{t+1,j}, \tag{36}$$

Equation (36) suggests that firms' expectations have a contemporaneous effect on actual inflation. If there is a public noise shock that drives up firms' expectations of current inflation, $\mathbb{E}_{t,j}^{Firm}\pi_t$, they increase their prices in addition to their actual real marginal costs $mc_{t,j}$, which leads to a higher actual inflation.

The equilibrium conditions (23), (36) and (27) contain three types of nonnested conditional expectations $\mathbb{E}_t^{HH}$, $\mathbb{E}_{t,j}^{Firm}$, and $\mathbb{E}_t^{CB}$, resulting in a breakdown of the law of iterated expectations and leads to the infinite regress problem of "forecasting the forecast of others"

(see Townsend (1983)). Solving the equilibrium in the time domain requires including many higher-order expectations to form a suitable state space. We solve this problem using the analytic policy function iteration (APFI) method developed in Han, Tan, and Wu (2022). APFI is built upon 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) shows how to apply the inverse discrete-time Fourier transform to calculate 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 prespecified criterion.[5]

3.2 Calibration

We calibrate the model to the US economy at a quarterly frequency. First, for parameters that are commonly used in the New Keynesian literature, we directly assign them values that are standard in the literature. Specifically, the discount factor, β, is set 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. The habit formation parameter, h, is set to 0.75. The Taylor rule coefficients are $\phi_\pi = 1.5$ and $\phi_y = 0.5$. The AR(1) parameter of the demand shock is set to be $\rho = 0.9$.

The focus of our calibration is the set of parameters that determine the degree of the information effect and thereby, the size of the information effect of monetary policy. As illustrated by the simple model in Section 2, these parameters include

$$\mathcal{P} = \{\sigma_d, \sigma_u, \sigma_e, \sigma_\eta, \sigma_n, \sigma_m\}.$$

Given that we consider firms' information sets may be either Type I, Type II, or Type III, we perform three rounds of calibration.

In each round of calibration, parameters are jointly calibrated to match the standard deviation of inflation, cross-sectional price dispersion, the standard deviation of monetary policy surprises,[6] and the nowcast and forecast accuracies of inflation in Greenbook and the

[5] See Section 4 of Han, Tan, and Wu (2022) for a detailed description of the algorithm.

[6] We define the monetary policy surprise (mps_t) as the difference between the actual and the professional forecaster's pre-FOMC expected interest rate: $mps_t = i_t - \mathbb{E}_t^{PF,pre} i_t$. This definition corresponds to the definition in the literature on measuring monetary policy surprises using high frequency identification method.

Table 1: Data and model-simulated moments

Moment	Data	Type-I firms	Type-II firms	Type-III firms
$\sigma(\pi_t)$	0.59	0.59	0.59	0.59
$\sigma(mps_t)$	0.05	0.05	0.05	0.05
avg. $\lvert\Delta p_j\rvert$	9.7%	9.7%	9.7%	9.7%
$\sigma(\pi_t - \mathbb{E}_t^{CB}\pi_t)$	0.23	0.23	0.22	0.22
$\sigma(\pi_t - \mathbb{E}_{t-1}^{CB}\pi_t)$	0.28	0.31	0.32	0.32
$\sigma(\pi_t - \mathbb{E}_t^{PF}\pi_t)$	0.24	0.23	0.22	0.22
$\sigma(\pi_t - \mathbb{E}_{t-1}^{PF}\pi_t)$	0.31	0.31	0.33	0.33

Survey of Professional Forecasters (SPF).

The targeted moments, together with their model empirical and model-predicted values, are displayed in Table 1. Although targeted moments are determined simultaneously, in what follows, we discuss each of the moments in relation to the parameters for which the moment yields the most identification power. First, we choose the standard deviation of demand shock, σ_d, to match the standard deviation of quarterly inflation.[7] Second, intuitively, the exogenous monetary policy shock has the largest explanatory power of the high-frequency monetary policy surprises. We thus calibrate σ_e targeting the standard deviation of the high-frequency monetary policy surprises in the empirical literature.[8] Third, we calibrate the standard deviation of the individual firm's wage-bargaining shock $\eta_{t,j}$ to match the micro evidence of firms' pricing behaviors. Specifically, the target moment is the average of the absolute size of a price change conditional on a price change among firms, which is found to be 9.7 percent by Klenow and Kryvtsov (2008).

The rest of the parameters are calibrated to match the nowcast and forecast accuracies in the Tealbook and the SPF. First, the aggregate cost-push shock drives temporary inflation fluctuations that are unpredictable by the central bank. We thus calibrate the standard deviation of the cost-push shock by targeting the standard deviation of the forecast errors in the Tealbook. Finally, the standard deviations of the public and private signals, $\{\sigma_n, \sigma_m\}$, jointly determine how far away the central bank and the professional forecaster's expectations of the current economy are from the actual data. We calibrate them to match the standard deviations of the inflation nowcast (forecast of the current quarter) errors of inflation in the Tealbook and the SPF.

[7] We use GDP deflator to measure the inflation rate for both the actual and the forecast data. Data on actual GDP deflator are retrieved from FRED database for the sample period of 1970 Q1 – 2024 Q2.

[8] Acosta, Brennan, and Jacobson (2024) constructed a time series of monetary policy surprises using similar approaches as in Gürkaynak, Sack, and Swanson (2005) and in Nakamura and Steinsson (2018) for an updated sample period. Depending on different definitions, the standard deviations of the monetary policy surprises ranges from 0.032 to 0.098. We use 0.05 as a rough average.

Table 2: Calibrated Parameters $\mathcal{P}$

Shock description	std	Type-I firms	Type-II firms	Type-III firms
Demand shock d_t	σ_d	2.18	1.88	1.88
Cost push shock u_t	σ_u	1.85	1.85	1.85
Monetary policy shock e_t	σ_e	0.05	0.01	0.01
Firm j's wage-bargaining shock $\eta_{t,j}$	σ_η	33.8	29.1	29.1
Public noise ε_t^n	σ_n	6.56	6.02	6.03
CB's private noise ε_t^m	σ_m	10.5	11.3	11.3

Note: the unit is percent.

The calibrated values are presented in Table 2. Across all specifications, the standard deviation of the monetary policy shock is much smaller than the values commonly used in the traditional New Keynesian literature, $\sigma_e \in [0.2, 1]$. Our calibration is more aligned with the general agreement that the Federal Reserve has precise control of the policy rate. It is also consistent with the recent empirical evidence that the average size of high frequency monetary policy surprises are just a few basis points. The calibrated standard deviations of demand and cost-push shocks are similar across three specifications. Consistent with both theoretical and empirical findings (see Mackowiak and Wiederholt (2009) and Andrade et al. (2022)), we also find that there is sizable variation in firms' idiosyncratic conditions. The calibrated standard deviation of an individual firm's wage bargaining shock, σ_η, is more than ten times larger than the standard deviations of the aggregate demand and cost-push shocks. Such a feature explains the empirical fact that individual price changes can be significant while aggregate inflation remains mild.

Finally, we find that, across all three cases, the public and the central bank's private signals are both noisy, as suggested by the large values of σ_n and σ_m relative to σ_d. The standard deviation of the central bank's inflation nowcast errors from the Tealbook is 0.23, which is over one-third of the standard deviation of realized inflation (0.59). If either the public or the private signal is precise, the central bank would know the realized equilibrium well and thus have close-to-zero nowcast errors. We find that the central bank's private information is even less precise than the public information, as $\sigma_m > \sigma_n$. This is consistent with the fact that the nowcast errors of professional forecasters (SPF) are very similar to the ones of the central bank (Tealbook). A very noisy central bank's private signal indicates that the central bank does not information advantage over professional forecasters in real time, which is consistent with Bauer and Swanson (2023).

4 Quantitative Analysis

In this section, we analyze the information effect of monetary policy by comparing aggregate economic variables and private-sector's forecast revisions under different information structures. We define two benchmark cases. The first benchmark is the full-information benchmark. The second benchmark is the "no-information-effect" benchmark, in which case the degree of information frictions is calibrated as in Section 3.2, and the interest rate is not used as a signal by firms. The differences between these two benchmarks highlight the role of imperfect information, which we explain in Section 4.1. Next, in Section 4.2, we illustrate the information effect of monetary policy by comparing how macroeconomic dynamics change from the no-information-effect benchmark. Third, in Section 4.3 we study how the size of the information effect depends on the firms' information structure.

4.1 Two Benchmark Cases: Full Information vs. Imperfect Information

In this section our analysis focuses on the comparison between the full-information benchmark (red dot dashed line) and the no-information-effect benchmark (blue dashed line). Figure 4 plots the impulse responses of output y_t, inflation π_t, and nominal interest rate i_t after a demand shock, a noise shock in the public signal, a noise shock in the central bank's signal, a policy shock, and a cost-push shock. The differences between the full-information benchmark (red dot dashed line) and the no-information-effect benchmark (blue dashed line) capture the effect of imperfect information on macroeconomic dynamics.

After a positive demand shock, output increases by a larger amount under the no-information-effect case (blue dashed line) than under the full-information case (red dot-dashed line). This is because with imperfect information, the central bank knows little about the demand shock on impact, and thereby the central bank fails to tighten the policy rate enough to offset the cool down demand, leading to a larger output gap than the one under full information.

Although the output gap is larger under the no-information-effect case, it does not feed into higher inflation. In contrast, inflation is lower in the no-information-effect case than in the full-information case. This is because firms underestimate the actual size of the output gap due to imperfect information about the persistent demand shock. Therefore, firms increase prices by a lesser amount than they would under full information. Inflation under imperfect information (blue dashed line) is persistently lower than that under full information (red dot-dashed line).

The second row of Figure 4 shows the dynamics after a positive cost-push shock. Under

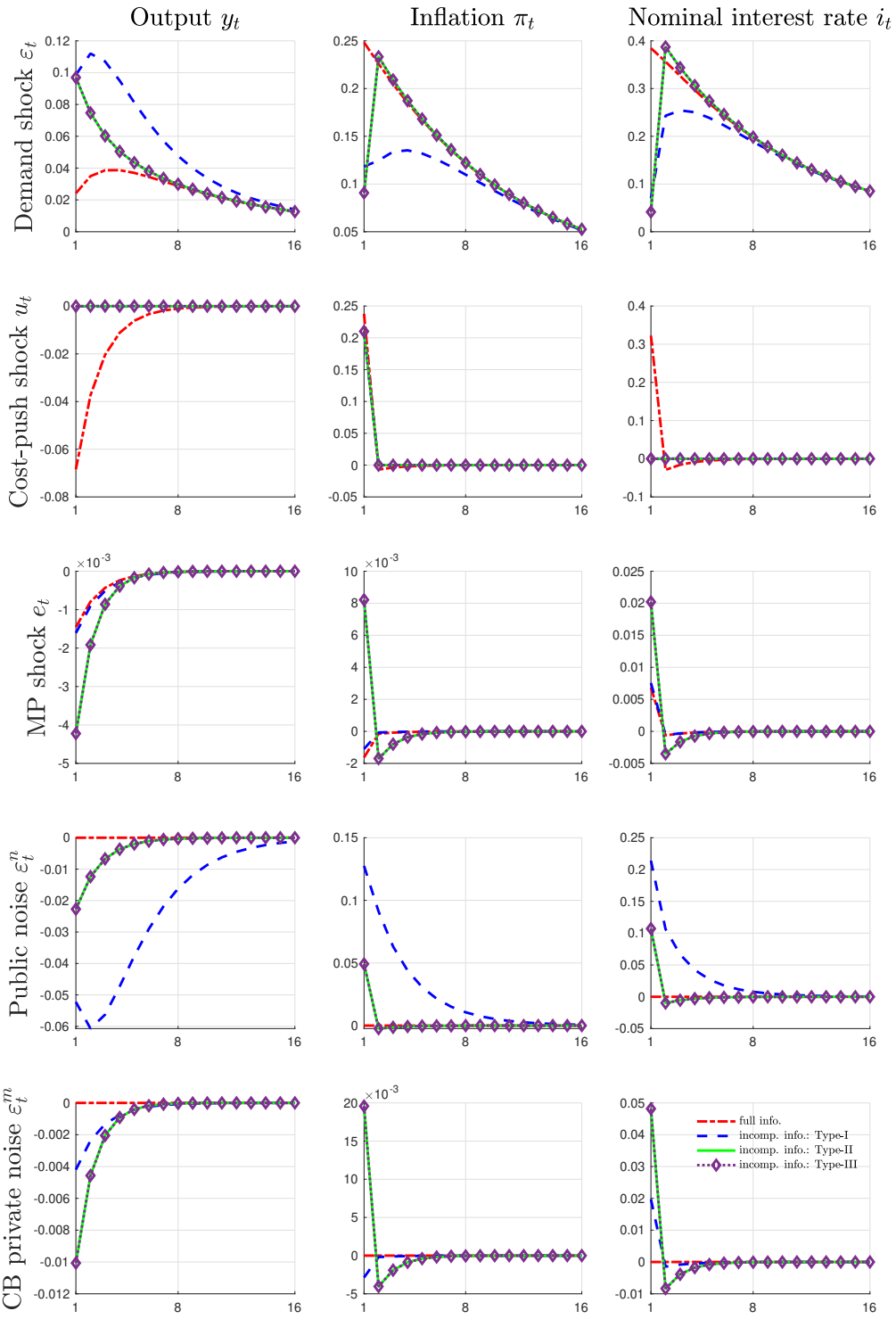


Figure 4: Impulse Responses

Note: In each row, the size of shock equals one standard deviation of the corresponding shock.

full information, the central bank tightens the interest rate in response, leading to a negative output gap and positive inflation. Under imperfect information, the central bank does

not have any information about the cost-push shock on impact, and therefore it does not adjust the interest rate. The household is also assumed to have no information about the cost-push shock or the rising inflation, and therefore, in the absence of interest-rate changes or information about price changes, output stays at the steady state level. Inflation rises on impact, because the cost-push shock increases production costs of all firms, and firms that get the Calvo lottery reset prices in response to the changes in production costs. However, although firms can see their own marginal cost, the firm-specific marginal cost provides very noisy information about the aggregate cost-push shock. each firm changes its price only in response to the change in its own production cost, while failing to optimize its price in response to the change in the aggregate price level. In other words, the strategic complementarity in price-setting is greatly reduced due to imperfect information. Consequently, inflation is lower in the no-information-effect case than under the full-information case,

The third row of Figure 4 shows that after a monetary policy shock, the full-information benchmark economy and the no-information-effect benchmark economy evolve similarly. The slightly difference between the red dot-dashed line and the blue dashed line is due to the fact that that the interest rate is not directly observable under the no-information-effect case, but rather, firms knows the direct effect of the interest rate through observing their marginal cost.

The last two rows show the impulse responses after a noise shock in the public information and in the central bank's information. The public noise shock works like a supply shock, driving positive inflation and negative output gaps. In this case, all firms and the central bank mistakenly believe that output would be higher, and therefore, firms increase prices and the central bank raises the interest rate. Both higher prices and the higher interest rate lower demand, in absence of an actual demand shock. Under imperfect information, the economy after a central bank's noise shock is similar to the one after a monetary policy shock. In both cases the tightening of the monetary policy lowers output and inflation at the same time.

By comparing the two benchmark cases, we summarize the effects of imperfect information as follows:

Proposition 4 *Compared with the full information case, imperfect information*

- *reduces inflation fluctuations and widens output gaps after demand shocks,*
- *reduces output gaps after cost-push shocks, and*
- *does not significantly change the effect of monetary policy shocks.*

Imperfect information Imperfect information reduces fluctuations in both inflation and output gaps after cost-push shocks. Imperfect information

4.2 The Information Effect of Monetary Policy

To analyze the information effect of monetary policy, we compare our baseline economy, in which the interest rate enters firms' information set (Type II in Equation (32)) and the no-information-effect benchmark (Type I in Equation (31)). The green solid line in Figure 4 shows the impulse responses under the information effect of monetary policy.

The first row shows that after on the impact of a positive demand shock, the economy with the information effect of monetary policy (green solid line) and the no-information-effect benchmark economy (blue dashed line) are the same. However, over time, the information effect of monetary policy brings the economy closer to the full-information benchmark. This is because after the first period, the central bank learns the realization of the demand shock from lagged inflation and output, and this information is transmitted to firms as the interest rate enters the firms' information sets. In turn, as firms become more informative in the following period, their pricing decisions are more similar to the ones under full information, and when the central bank learns from lagged inflation and output, the central bank's information becomes more precise over time. Although inflation almost converges to that under perfect information, the convergence of output takes about two years due to households' habit formation.

The second row show that the economy after a transitory cost-push shock does not differ much with or without the information effect of monetary policy. This is because when the cost-push shock hits the economy at $t = 1$, the output gap is zero and inflation is positive. In the following period, when the central bank learns from inflation and output with one-period lag, it understands that the shock was a transitory cost-push shock, and therefore, does not change the interest rate at $t = 2$. As the interest rate stays unchanged, there is no information revealed.

The third row shows that after a positive monetary policy shock, inflation rises and output decreases on impact, which is significantly different from the no-information-effect benchmark, in which case the positive policy shock lowers inflation. The reason for the rise in inflation is that firms mistakenly believe the increase in the interest rate reflects the central bank's private information about a positive demand shock, and thereby increase prices. Both positive inflation and the positive interest rate dampens demand, leading to a negative output gap.

The fourth row shows the responses to a positive noise shock in the public information.

On impact, inflation and output move in the same direction with or without the information effect of monetary policy. However, as economy under the information effect of monetary policy quickly converges to the full-information benchmark from $t = 2$. The reason is that by observing a negative output gap and a positive inflation in the last period, the central bank learns the public information reflect a noise shock instead of an actual demand shock. It then swiftly lowers the interest rate at $t = 2$, and subsequently, firms update expectations after observing the interest-rate change. The information effect of monetary policy helps stabilize inflation and output gap fluctuations due to public noise shocks.

The last row exhibits the economy after a positive noise shock of the central bank's private information. Contrary to the case of a public noise shock, the economy under the information effect of monetary policy experiences greater fluctuations in both inflation and output gaps after a noise in the central bank's private information. After a positive noise shock in its private signal, the central bank mistakenly believes that output will be higher and thus raises the interest rate. The information effect of monetary policy makes firms positively update their inflation expectations, and inflation rises as a result. Both a higher interest rate and higher prices lead to a negative output gap. At $t = 2$, the central bank observes the lagged output gap and realizes its previous private information was a noise. It then lowers the interest rate immediately, but it takes several quarters to stabilize the output gap due to habit formation in the households' utility.

comment Interestingly, except after a cost-push shock, the inflation rate and the interest rate move in the same direction. The output gap moves in the same direction only if the changes in the interest rate is a response to a demand shock, otherwise the output gap moves in the opposite direction. This is because under our assumption, as the demand shock directly affects households' preference, households have more accurate information than firms and the central bank. Therefore, the direct effect of monetary policy dominates the dynamics of output. i.e., in the absence of a real demand shock, output reduces in response to a tightening of monetary policy. The information effect of monetary policy dominates the dynamics of inflation. i.e., no matter what drives the changes in the interest rate, inflation increases with the interest rate.

We summarize the information effect of monetary policy in the following result:

Proposition 5 *Compared to the no-information-effect benchmark, the information effect of monetary policy*

- *increases inflation fluctuations and reduces output gaps after a demand shock,*
- *reduces fluctuations in both inflation and output gaps after a public noise shock, and*

- *leads to positive inflation after a tightening policy shock.*

Does the information effect change if firms' information sets also contain lagged equilibrium variables? That is, what if firms are Type III (Equation (33)? Figure 4 show that impulse responses of output, inflation, and the interest rate are the same whether firms' information sets include lagged inflation or not. This indicate that as the current interest rate contains the central bank's knowledge of lagged inflation, firms do not need to pay additional attention to lagged inflation. In other words, lagged inflation provide redundant information to firms as long as firms learn from monetary policy. It also suggests that whether firms learn from lagged inflation and output are not identifiable from impulse responses.

4.3 Determinants of the Information Effect

As implied by our analytic model, for monetary policy to have an important information effect on the economy, the central bank needs to have an information advantage than the private sector, and the exogenous variation in the interest rate needs to be small. In this section, we study how the size of the information effect may be reduced when the central bank has less precise private information and when the interest rate has larger exogenous variation.

Under our calibration, the central bank's private exogenous signal, ϵ_t^m, provides imprecise information about the realization of the demand shock in the current period. However, the central bank still learns more precise information over time by extracting information from lagged equilibrium variables, including lagged inflation and lagged output, which is the source of the central bank's information advantage. To further illustrate this point, we simulate a counter-factual economy, in which the central bank observes past equilibrium variables with some observation errors. Specifically, the central bank's information set is given by,

$$\mathcal{I}_t^{CB} = \{n_{t-k}, m_{t-k}, e_{t-k}, \hat{\pi}_{t-1-k}, \hat{y}_{t-1-k} | k \geq 0\}. \tag{37}$$

where $\hat{\pi}_t = \pi_t + \epsilon_t^\pi$ and $\hat{y}_t = y_t + \epsilon_t^y$, and the observation errors follow $\varepsilon_t^\pi \sim N(0, \sigma_\pi^2)$, $\varepsilon_t^\pi \sim N(0, \sigma_\pi^2)$.

In Figure 5, we plot the economic dynamics when $\sigma_y = \sigma_\pi = 0.5$. Comparing the counter-factual economy in which the central bank has less precise private information due to observation errors (black dot-dashed line) and our baseline economy (green solid line), we find that when the central bank has less precise information about the past economy, the information effect is reduced: after demand shocks, it takes longer time for the economy to converge to the full-information benchmark. On the other hand, the output and inflation deviations

caused by the exogenous policy shock are also reduced. The last row in Figure 5 shows that fluctuations caused by the noise in the central bank's private exogenous information increase. After a positive ϵ_t^m shock, the size of the output gap and the inflation rate both become larger when the central bank has observation errors. This is because as the central bank's endogenous information becomes less precise due to the observation errors, it weighs more on its private exogenous signal, ϵ_t^m.

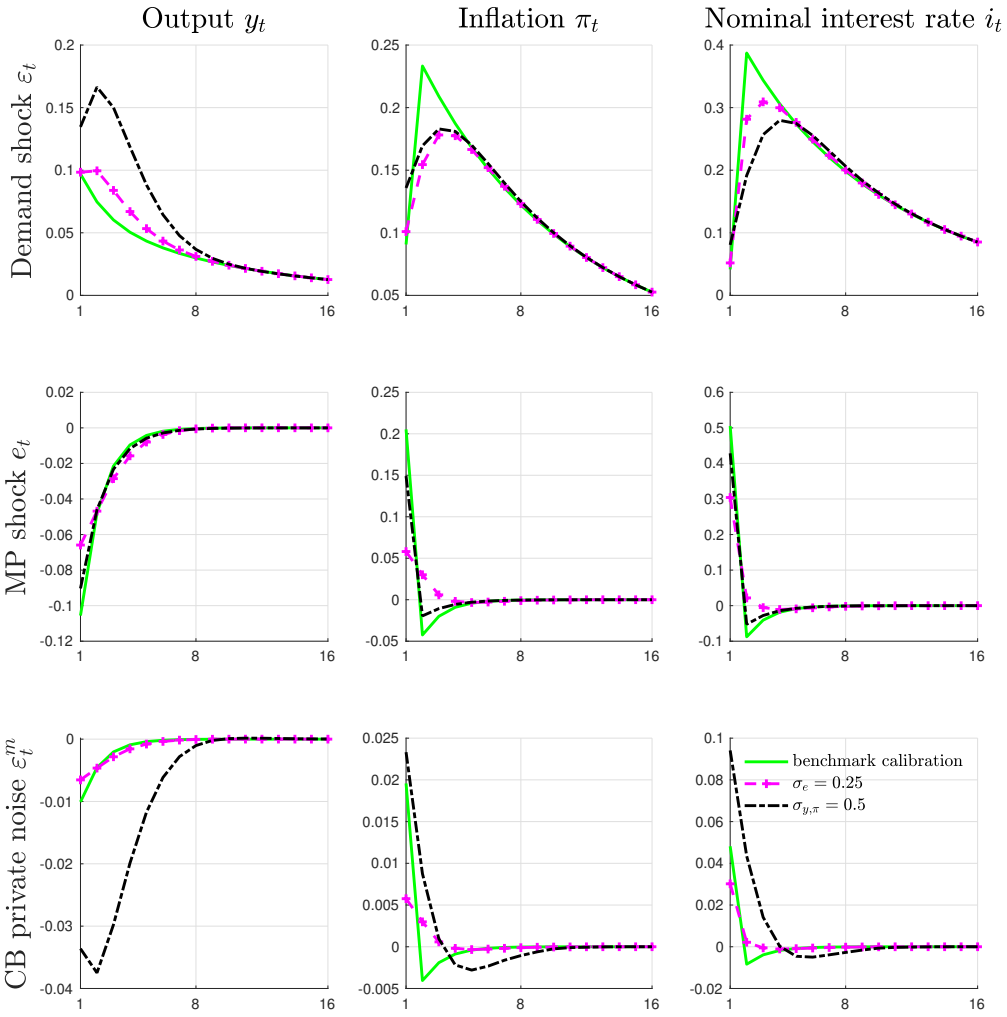


Figure 5: Impulse Responses

Note: In the first and the last rows, the size of shock equals one standard deviation of the corresponding shock. In the second row, to make the impulse responses comparable when σ_e changes, we fix $\sigma_e = 0.25$ for all three cases.

Another important determinants of the size of the information effect of monetary policy is the standard deviation of the policy shock. Intuitively, if the standard deviation of the policy shock increases, the interest rate reveals less precise information. In Figure 5, we plot the impulse responses in a counter-factual economy in which the standard deviation of the policy

shock increases to 0.25 (pink dashed line). It shows that a larger σ_e decreases the size of the information effect of monetary policy. After a demand shock, it takes longer time for the economy to converge to the full-information benchmark. On the other hand, the fluctuations caused by either a policy shock or a noise shock from the central bank's private exogenous information also become smaller when the information effect weakens. For a given size of a policy shock, inflation increases by less when the central bank has less precise information, since firms pays less attention to the interest rate when forming expectations.

The comparison between our baseline case and the two counter-factual economies (black dot-dashed line and pink dashed line in Figure 5), highlights the important mechanism of two-way learning: the central bank learns from the private-sector's demand and pricing decisions (with one-period lag), and the private sector learns from the central bank's interest-rate decisions. If the effectiveness of one side of the learning mechanism weakens, the information transmission of the other way is undermined, too.

For example, when the cental bank has observation errors, the information transmission from the private sector to the central bank becomes less precise. Consequently, the interest rate adjusts to a lesser extent to the demand shocks than it would in the baseline economy. Since the interest rate responds by less, the information transmission from the central bank to the private sector become less precise.

5 Conclusion

In this paper, we aim to quantify the size of the information effect of monetary policy. We first use an analytic model to highlight the problems of the reduced-form measure of the information effect by the correlation between monetary policy surprises and professional forecasters' forecast revisions. We then develop a New Keynesian model in which learning is two ways: the central bank learns from the demand and pricing decisions by households and firms, and firms learn from the central bank's interest rate decisions.

Under our calibration, the central bank's private exogenous signals are noisy, but the central bank can get more precise information by learning from lagged equilibrium variables. The information effect of monetary policy helps transmit the central bank's information to firms, reducing the output gaps caused by demand shocks or noise shocks. At the same time, the information effect also leads to positive information after a policy tightening shock. Under our baseline calibration, a monetary policy shock of one percentage point leads to a 0.8 percentage point increase in inflation. The size of the information effect depends on the degree of the central bank's information advantage and the standard deviation of the policy shock.

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