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

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Abstract

We study the information effect of monetary policy when the central bank and the private sector have imperfect and asymmetric information about the economy. We first show analytically that a reduced-form regression leads to biased estimation of the Fed's information effect, because the unobserved shock correlates with monetary policy surprises. We then develop a New Keynesian model in which the learning is two-sided: the central bank learns from lagged inflation and output, and the private sector learns from the interest rate. Our calibrated model suggests that imperfect information enlarges output gaps but reduces inflation fluctuations. The two-sided learning mechanism makes the central bank better informed over time, and the more sensitive interest-rate responses reduces output gaps but amplifies inflation deviations after demand shocks.

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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 decisions reveal 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. 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). Namely, why estimation of the information effect may be biased for a reduced-form estimation that measures the relationship between the private sector's forecast revisions and monetary policy surprises. We show that with asymmetric information, monetary policy surprises correlate 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. Information about the fundamental shock is asymmetric between the central bank and the private sector. 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 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 central bank sets the interest rate in response to its expected output, conditional on its private and public signals. We assume that the interest rate also contains a pure 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 pre-FOMC expected interest rate averaged across all forecasters. This definition corresponds to constructing monetary policy shocks using the high-frequency identification method in the empirical literature.

We provide a micro-foundation for monetary policy surprises under asymmetric information. In our framework, monetary policy surprises constitute the fundamental shock, the noise shock in the central bank's private and public information, and the exogenous interest-rate shock. Suppose the central bank's private information is observable by the private sector, even if the information is still imperfect. In that case, the interest rate becomes perfectly predictable by the private sector, in which case any surprise in the interest rate results from the exogenous policy shock.

Monetary policy surprises increase with the fundamental shock and the noise in the central bank's private signal and decrease with the noise in the public signal. The reason is that professional forecasters understand the interest rate is set conditional on the central bank's private signal and form expectations about this private signal the same as they form expectations about the underlying fundamental shock. Due to imperfect information, professional forecasters underestimate the fundamental shock in the absence of noise shocks and overestimate the fundamental shock after a positive noise shock. As a result, professional forecasters, on average, expect a smaller interest rate than the actual one after a positive fundamental shock and a larger interest rate than the actual one after a positive noise shock. Since professional forecasters do not observe the central bank's private signal, it surprises the professional forecasters when the central bank increases the interest rate due to a positive noise in its private signal.

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 degree 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 private information. 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 agrees with the argument made in Bauer and Swanson (2023). In addition, even if an unbiased estimation yields a negative coefficient, i.e., a positive monetary policy surprise leads to a downward revision of output forecasts, the information effect could still be quantitatively important. This is because the coefficient measures the combination of the information effect and the direct effect of monetary policy. Therefore, a negative coefficient only suggests that the direct effect dominates the information effect. In summary, our simple model shows that it is difficult to conclude the importance of the information effect by a reduced-form regression analysis.

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 the demand shock is the only fundamental shock that drives economic fluctuations. 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.

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 (2017a), 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

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

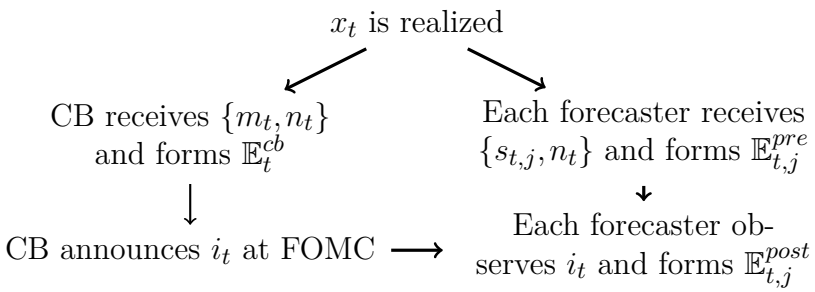
where $\phi_y > 0$. The central bank chooses the value of ϕ_y and is perfectly known by the private sector. e_t is the traditionally modeled "monetary policy shock", which captures any exogenous variation in the interest rate that cannot be explained by the endogenous response to $\mathbb{E}_t^{cb} y_t$.

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

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

Figure 1: Sequence of Events



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

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

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

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

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).*

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

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

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 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 $\mathbb{E}^{pre}_{t,j} m_t = \mathbb{E}^{pre}_{t,j} x_t$, and forms $\mathbb{E}^{pre}_{t,j} x_t$ 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 $\mathbb{E}^{pre}_{t,j} m_t = m_t$. 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.

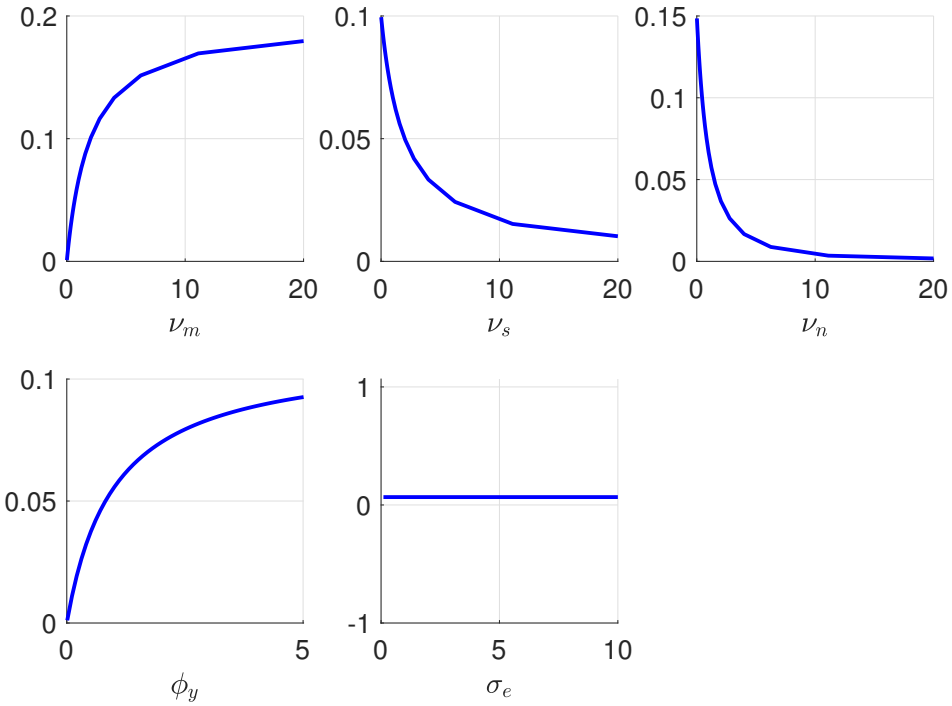
Proposition 1 shows that mps_t positively correlates with x_t. In the following proposition, we characterize how the effect of x_t on mps_t depends on the degree of information frictions and the parameters of the interest rate rule.

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 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

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 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*

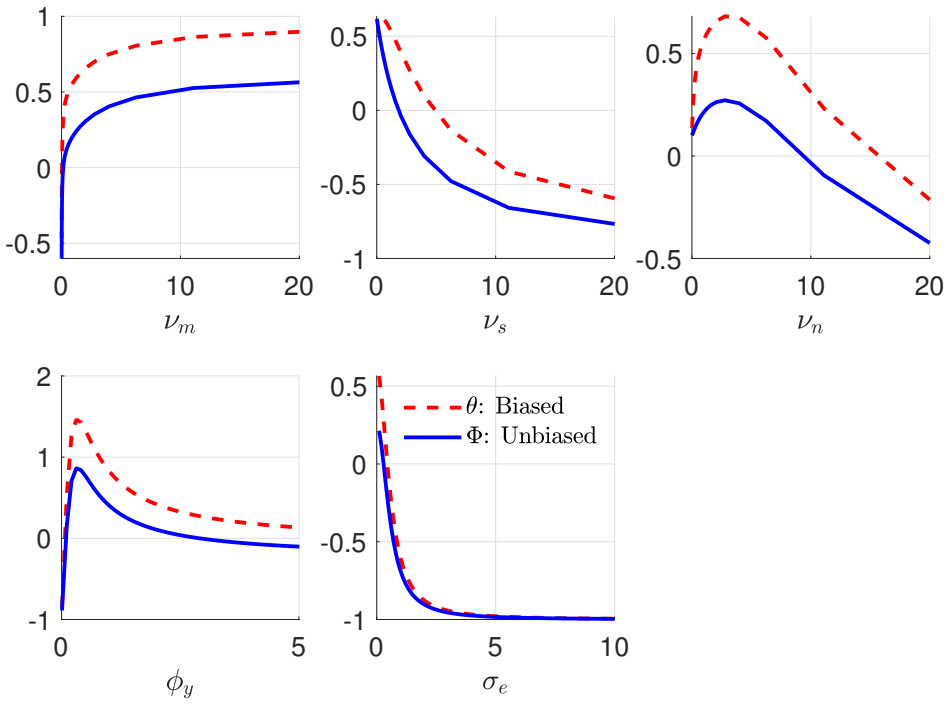
- *increases with the precision of the central bank's private information (ν_m),*
- *decreases with the precision of the forecasters' private information (ν_s),*
- *has a non-linear relationship with the precision of the public information (ν_n) and the policy rule coefficient (ϕ_y),*
- *and decreases 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 of the size of the information effect may be biased, and cannot disentangle the information effect from the combined effect. 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 (2017b). 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, it features different effects of information frictions on inflation and output. Second, instead of assuming that private-sector's expectations are formed by professional forecasters who do not make economic decisions, we now model that private-sector's expectations are formed by firms and households, and thereby expectations affect equilibrium inflation and output. 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 set prices and produce intermediate goods, and a central bank that decides the interest rate following a targeting rule. We first describe the optimization problems of the household and the firms, and the interest rate rule. We then specify the information structure in the economy. Lastly, we write out the aggregate equilibrium variables in terms of the IS curve and the Phillips curve, and compare them with the ones in the traditional New Keynesian literature under FIRE.

3.1.1 Household

The representative household chooses aggregate consumption, C_t, and labor supply, N_t, to maximize its lifetime utility subject to the inter-temporal budget constraint. The preference of the household is defined as check

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

where $\mathbb{E}_t^{HH}(\cdot)\equiv\mathbb{E}(\cdot|\mathcal{I}_t^{HH})$ is an expectation operator conditional on the household's information set, $\mathcal{I}_t^{HH}$. $\beta\in(0,1)$ is the deterministic discount factor and $1/\psi>0$ is the Frisch elasticity of labor supply. d_t is a demand shock.

We assume that the demand shock consists of an persistent component and a transitory

component, denoted by

$$d_t = u_t^{\beta} + e_t^{\beta}, \qquad e_t^{\beta} \ N(0, \sigma_{e,\beta}^2), \tag{20}$$

where the transitory component, e_t, is an *i.i.d.* process, given by $e_t^{\beta} \ N(0, \sigma_{e,\beta}^2)$. and the persistent component follows an AR(1) process, given by

$$u_t^{\beta} = \rho u_{t-1}^{\beta} + \varepsilon_t^{\beta}, \qquad \varepsilon_t^{\beta} \sim N(0, \sigma_{\epsilon,\beta}^2) \tag{21}$$

Since the demand shock directly affects the household's utility, we assume that the household observes d_t perfectly. However, the household cannot disentangle the persistent and transitory components of the two shocks.

The aggregate good, C_t, consists of a continuum of intermediate good 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 inter-temporal consumption decision yields the following Euler equation:[2]

$$c_t = \mathbb{E}_t^{HH} c_{t+1} - \left(i_t - \mathbb{E}_t^{HH} \pi_{t+1}\right) + \left(d_t^C - \mathbb{E}_t^{HH} d_{t+1}^C\right), \tag{22}$$

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

The intra-temporal labor supply decision sets the marginal rate of substitution between leisure and consumption equal to the real wage, given by

$$w_t = c_t + \psi n_t \tag{23}$$

3.1.2 Firms

A continuum of monopolistic competitive firms is indexed by $j \in [0,1]$. All firms are subject to two types of frictions: the Calvo type of price rigidity (Calvo (1983)) and information frictions. Each firm produces an intermediate good under a linear production function, given by $Y_{t,j} = N_{t,j}$.

Under the assumption of the Calvo-type price rigidity, 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 future profits while $P_t^*(j)$ remains effective. The profit-maximization problem for firm j is given by

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

where θ is the probability that the current price does not change from this period to the next.

[2]Lowercase variables denote the log deviations from their non-stochastic steady states levels.

$\mathbb{E}_{t,j}^{Firm}$ denotes the expectation formed by firm j, and $\mathbb{E}_{t,j}^{Firm} \equiv \mathbb{E}_t\left[\cdot|\mathcal{I}_{t,j}^{Firm}\right]$, i.e., individual firms form expectations conditional on its information set. The stochastic discount factor is determined as $Q_{t,t+k} = \beta^k \frac{U'(C_{t+k})}{U'(C_t)} \frac{P_t}{P_{t+k}}$ and $MC_{t+k}(j)$ denotes the firm-specific nominal marginal cost.

The profit maximization problem of Equation (24) yields the optimal price of firm j given by

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

where $mc_{t,j}$ denote the log approximated real marginal cost of firm j. Equation (25) indicates that a firm's optimal price equals the discounted sum of its current and expected future nominal marginal costs:

Following Nimark (2008), we assume $mc_{t,j}$ is a linear combination of the real equilibrium wage and a firm-specific wage bargaining shock, $\eta_{t,j}$, where $\eta_{t,j} \sim N(0, \sigma_\eta^2)$. Firm n's real marginal cost is given by

$$mc_{t,j} = w_t + \eta_{t,j} = (1+\psi)y_t + \eta_{t,j} \tag{26}$$

where the second equation is derived by substituting real wage with Equation (23) and imposing goods and labor market clearing conditions.

Equation (26) implies that when a firm observes a higher marginal cost, it cannot perfectly tell whether it is due to a higher real demand that drives up equilibrium wage, or a positive firm-specific shock to the bargaining power of its workers that drives us its own labor cost.

Since firms set prices before production, the firm j does not know the aggregate demand or the real marginal cost of production when $p_{t,j}^*$ is chosen. Instead, we follow the literature to assume that the equilibrium wage clears the labor market. In other words, firms sign contracts with workers specifying higher hourly wages for aggregate overtime.

3.1.3 Central Bank

The central bank sets the interest following a Taylor-type targeting rule. Due to imperfect information, the central bank sets the interest rate responding to its expected inflation and its expected output.[3] Specifically, the interest rate follows

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

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

where $\mathbb{E}_t^{CB} \equiv \mathbb{E}(\cdot|\mathcal{I}_t^{HH})$ denotes the central bank's expectation operator. The policy coefficients satisfy $\phi_\pi > 1, \phi_y > 0$.

3.1.4 Time Protocol and Information Structure

To capture the information effect of monetary policy, we assume in a given period, the interest is set before the household and firms make consumption and pricing decisions. Any period t is divided into three stages. At stage 1, the demand shocks (including both ϵ_t^β and e_t^β and the exogenous signals are realized. At stage 2, the central bank sets the interest rate based on its expectation of the current inflation and output. At stage 4, firms that get the Calvo lottery reset their prices. At stage 3, the household demands goods and supplies labor.

We assume that each agent's information set includes both exogenous and endogenous signals. For exogenous signals, we assume there is a public signal observed by all agents about the current innovation of the persistent demand shock.

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

On top of the public signal, the central bank also observe a private signal of the current innovation of the persistent demand shock,

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

For endogenous signals, we assume that the central bank extracts information from past inflation and output. This is motivated by the fact that, in practice, major central banks, including the Federal Reserve and the European Central Bank, pay close attention to aggregate economic conditions, and describe their policy decisions to be data dependent. Since data on aggregate economy often come with a lag, we assume the central bank observes lagged inflation and lagged output.

We also assume that the private sector does not use lagged inflation and output as signals. This assumption is motivated by recent survey evidence (see Coibion, Gorodnichenko, and Kumar (2018)) that points to firms having less information about aggregate economic conditions, especially inflation, and having more information about their industry-specific prices. We thereby assume that firms use their firm-specific marginal cost (with one-period lag) as a signal. We assume that the household observe the discount factor perfectly, as the discount factor directly enters its utility function. However, it cannot distinguish the persistent component and the transitory component. Both firms and the household observe the interest rate, allowing the interest rate to have an information effect.

To sum up, the central bank's information set includes the history of exogenous public signal, its private signal, and inflation and output up to $t-1$. Each firm's information set includes the history of the public signal and the interest rate up to t, and its own marginal cost up to $t-1$. The household's information set includes the history of the demand shock, the public signal and the interest rate up to t.

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

$$\mathcal{I}_t^{HH} = \{d_{t-k}, n_{t-k}, i_{t-k} | k \geq 0\}, \tag{31}$$

$$\mathcal{I}_{t,j}^{Firm} = \{n_{t-k}, mc_{t-k-1,j}, i_{t-k} | k \geq 0\}, \tag{32}$$

3.1.5 Equilibrium

We follow the tradition in the New Keynesian literature to write the equilibrium of aggregate variables in the form of an IS curve and a Phillips curve.

The IS curve

Imposing the goods market equilibrium condition, $y_t = c_t$, aggregate demand in Equation (22) can be written as the following IS curve:

$$y_t = \mathbb{E}_t^{HH} y_{t+1} - \left(i_t - \mathbb{E}_t^{HH} \pi_{t+1}\right) + \left(d_t - \mathbb{E}_t^{HH} d_{t+1}\right). \tag{33}$$

The key difference between Equation (33) and the traditional IS curve under FIRE is that in our setting the household has imperfect information on the *persistence* of the demand shock. This is because although the household can observe the current demand shock perfectly, and hence, the actual d_t enters the IS curve, it has imperfect information on the persistent component of the shock. The household use the combined demand shock as a signal of the persistent demand shock, and the transitory component of the demand shock acts like a noise shock. When a transitory demand shock hits the economy, the household mistakenly expects a part of the increase in the demand shock is persistent, and thereby expects a higher demand shock in the next period. ($\mathbb{E}_t^{HH} d_{t+1} > 0 = \mathbb{E}_t^{FIRE} d_{t+1}$) In addition, because $\mathbb{E}_t^{HH} d_{t+1} \neq \mathbb{E}_t^{FIRE} d_{t+1}$, its expectations of future inflation and output are different from the ones formed under perfect information.

The Phillips curve

Inflation is the difference between the current and the previous aggregate price, level, i.e., $\pi_t = p_t - p_{t-1}$. The aggregate price level, p_t, is the weighted average between firms that re-optimizes their prices and firms that cannot re-optimize in this period, i.e., $p_t = \theta p_{t-1} + (1-\theta) \int p_{t,j}^* dj$. It is well known in the literature that under FIRE, that aggregating

the intermediate firms' optimal prices leads to the following forward-looking Phillips curve:

$$\pi_t = \beta \mathbb{E}_t^{FIRE} \pi_{t+1} + \frac{(1-\beta\theta)(1-\theta)}{\theta}(1+\psi) y_t, \tag{34}$$

where $\mathbb{E}_t^{FIRE}$ is the expectation formed under full information and rational expectations.

However, in our model, due to firms use their firm-specific marginal cost as private signals, expectations are heterogeneous. Therefore, aggregating individual prices is a non-trivial 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

$$z_{t,j} = (1-\beta\theta)(1-\theta)\mathbb{E}_{t,j}^{Firm} mc_{t,j} + (1-\theta)\mathbb{E}_{t,j}^{Firm}\pi_t + \beta\theta \mathbb{E}_{t,j}^{Firm} z_{t+1,j}, \tag{35}$$

Notice that since firms set prices before the household demand goods and supplies labor, firms do not know their actual marginal cost when setting prices, i.e., $\mathbb{E}_{t,j}^{Firm} mc_{t,j} \neq mc_{t,j}$ in Equation (35).

To derive the aggregate price level, notice that Equation (35) suggests that firms need to infer aggregate equilibrium variables that are functions of expectations formed by others. The equilibrium conditions (33), (35) and (27) contain three types of non-nested 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 and its accompanying "z-Tran" toolbox 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 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

I have not worked on this section. 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 $\phi_\pi = 1.5$ 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

$$\mathcal{P} = \{\rho, \sigma_\beta, \sigma_\varepsilon^C, \sigma_\varepsilon^N, \sigma_e, \sigma_n, \sigma_m, \sigma_\eta, \sigma_s\}.$$

We calibrate these parameters internally to match the moments of realized macro series and the nowcast and forecast accuracies in the Greenbook data set and the Survey of Professional Forecasters (SPF)

Table 1 lists the calibrated parameters and Table 2 compares the model-simulated moments with their data counterparts. 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 set the persistence parameter ρ to match the first auto-correlation of quarterly inflation. Second, we choose the standard deviation of demand shock, σ_β, to match the standard deviation of quarterly inflation. Third, since the monetary policy shock e_t enters the monetary rule directly, we calibrate σ_e to match the standard deviation of the nominal interest rate. The sizes of the transitory shocks, σ_ε^C and σ_ε^N, are pinned down to match the forecast errors of inflation in Greenbook and SPF data. We calibrate the standard deviation of individual firm's wage-bargaining shock $\eta_{t,j}$ (i.e., σ_η) to match 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% by Klenow and Kryvtsov (2008). The standard deviations of the public and private signals $\{\sigma_n, \sigma_m, \sigma_s\}$ jointly determine how far away the central bank and the firms' expectations are from the ones under full information. We calibrate them jointly to match the standard deviations of the monetary policy surprises and the inflation nowcast errors of Greenbook and SPF data. Table 2 shows that the model-implied moments match their data counterparts well. Without adding interest rate inertia on the monetary policy rule, our calibration slightly underestimates the nominal interest rate's auto-correlation (0.86 *v.s.* 0.97).

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. The central bank's private and public signals are noisy, as suggested by their large

Table 1: Internally Calibrated Parameters $\mathcal{P}$

Parameter	Value	Description
ρ	0.89	AR(1) of discount factor shock u_t^β
σ_β	2.12	Std. Dev. of discount factor shock ε_t^β
σ_ε^C	0.14	Std. Dev. of consumption utility shock ε_t^C
σ_ε^N	0.20	Std. Dev. of labor disutility shock ε_t^N
σ_e	0.24	Std. Dev. of monetary policy shock e_t
σ_n	4.42	Std. Dev. of public signal noise ε_t^n
σ_m	5.93	Std. Dev. of CB's private signal noise ε_t^m
σ_η	25.13	Std. Dev. of Firm j's wage-bargaining shock $\eta_{t,j}$
σ_s	6.32	Std. Dev. of Firm j's private signal noise $\varepsilon_{t,j}^s$

Table 2: Data and model-simulated moments

Moment	Data	Model	Moment	Data	Model
$\sigma(\pi_t)$	0.62	0.62	$\sigma(i_t)$	0.96	0.95
$corr(\pi_t, \pi_{t-1})$	0.78	0.79	$corr(i_t, i_{t-1})$	0.97	0.86
avg. $\lvert\Delta p_j\rvert$	9.7%	9.7%	$\sigma(mps_t)$	0.04	0.04
$\sigma(\pi_t - \mathbb{E}_t^{CB}\pi_t)$	0.23	0.23	$\sigma(\pi_t - \overline{\mathbb{E}}_t^{Firm}\pi_t)$	0.23	0.23
$\sigma(\pi_t - \mathbb{E}_{t-1}^{CB}\pi_t)$	0.29	0.30	$\sigma(\pi_t - \overline{\mathbb{E}}_{t-1}^{Firm}\pi_t)$	0.31	0.31

values relative to σ_β. The finding explains the sizable nowcast errors of the central bank. The standard deviation of the central bank's inflation nowcast errors from Greenbook is 0.23, over one-third of the standard deviation of realized inflation (0.59). If either the public or the private information is precise, the central bank would know the realized equilibrium well and thus have small nowcast errors. The individual firm's information is also noisy, as the firm-specific noise and wage-bargaining shocks have large standard deviations. In both the data (SPF and Greenbook) and our model, the standard deviations of inflation nowcast and forecast errors are very similar between the central bank and professional forecasters, resulting comparable precisions of the central bank and the firms' private noise signals on the demand shock ε_t^β (i.e., σ_m *v.s.* σ_s). Consequently and consistent with Bauer and Swanson (2023), we find the central bank does not have superior information compared to the firms in real time.

4 Quantitative Analysis

To analyze the information effect of monetary policy, we consider two benchmark scenarios. The first one is the full information economy, in which case all agents have the same infor-

mation set that includes the realization of all shocks up to t. The information set of this case is:

$$I_t^{FI} = \{\varepsilon_{t-k}^{\beta}, \varepsilon_{t-k}^{C}, \varepsilon_{t-k}^{N}, e_{t-k} | k \geq 0\},$$

The second one is the case in which agents have the same exogenous signals as the ones in Section 3. In addition, the central bank still learns from lagged inflation and output, but firms do not learn from the interest rate. The information set of this case is:

$$\mathcal{I}_t^{HH} = \{u_{t-k}^{C}, n_{t-k}, i_{t-k} | k \geq 0\}, \tag{36}$$

$$\mathcal{I}_t^{CB} = \{n_{t-k}, m_{t-k}, e_{t-k}, \pi_{t-1-k}, y_{t-1-k} | k \geq 0\}; \tag{37}$$

$$\mathcal{I}_{t,j}^{Firm} = \{n_{t-k}, s_{t-k,j}, i_{t-k} | k \geq 0\}, \tag{38}$$

4.1 The Effect of Imperfect Information

Figure 4 plots the impulse responses of output y_t, inflation π_t, and nominal interest rate i_t after a one-standard-deviation of the persistent demand shock, the transitory demand shock, a noise shock in the central bank's private signal, a noise shock in the public signal, and a exogenous monetary policy shock. The blue solid line denotes the case of full information, and the green dashed line denotes the case of no information effect. The difference between the two captures the effect of imperfect information.

After a persistent demand shock, the output deviation is larger under imperfect information. This is because the positive demand shock directly up consumption, but the central bank increases the interest rate by a lesser amount due to its imperfect information. The lower interest rate widens the output gap. Although the output gap is larger under the no information effect case, it does not feed into higher inflation. In contrast, inflation is lower under the no information effect case. This is because firms underestimate the actual size of the output gap due to having very noisy information about the persistent demand shock. Therefore, firms increase prices by a lesser amount.

Another important difference is the dynamics after an exogenous monetary policy shock. Under perfect information, a tightening policy shock leads to negative inflation and a negative output gap. In the case of no information effect, we assume that firms do not observe the interest rate when adjusting prices. Without price adjustments, the direct effect of the tightening of monetary policy have a larger effect on output. This case can be related to an earlier strand of the literature that models the real effect of monetary policy by assuming the central bank withhold information on policy changes. (Cukierman and Meltzer 1986, for example)

We summarize the effects of information frictions in the following results:

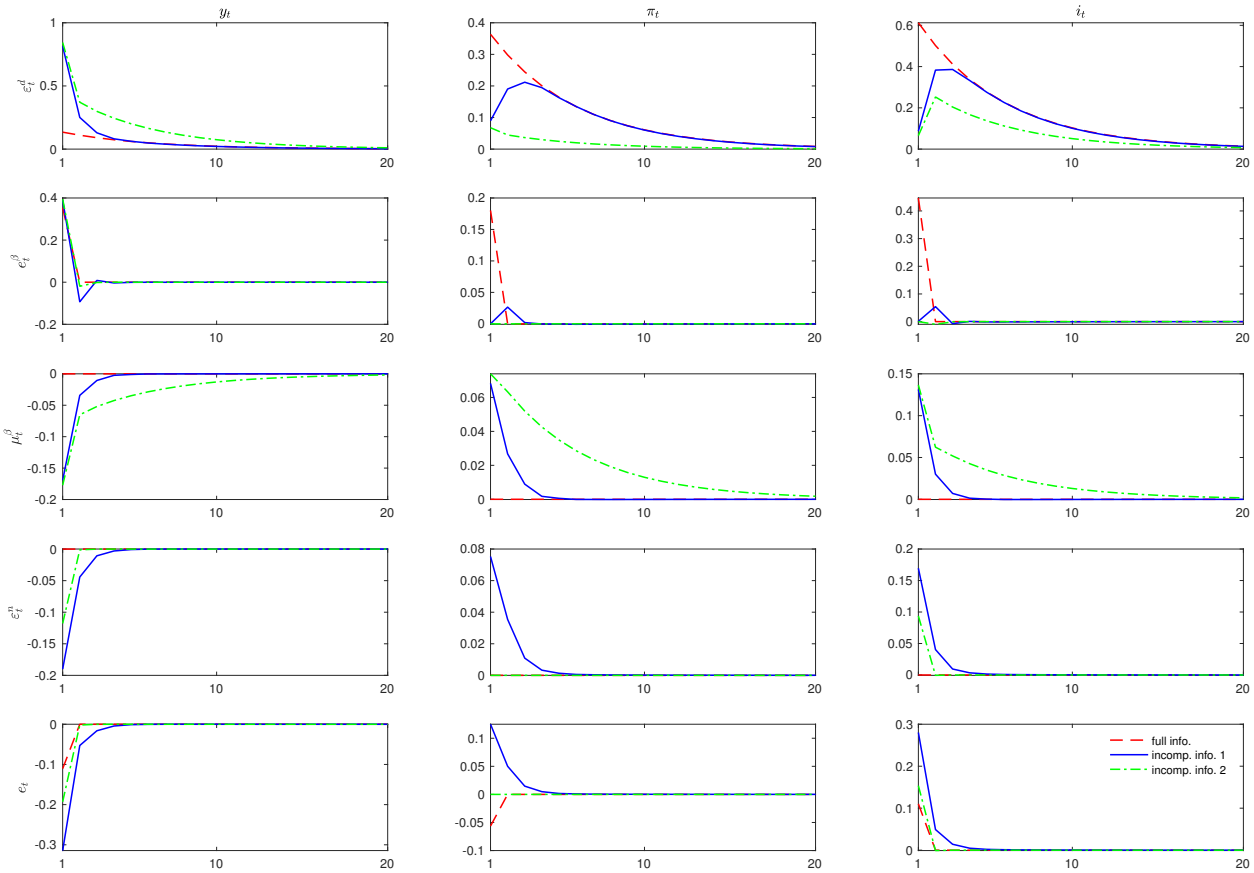


Figure 4: Impulse Responses

Proposition 4 *Imperfect information reduces inflation fluctuations and widens output gaps after demand shocks, and amplifies the real effect of monetary policy.*

4.2 The Information Effect of Monetary Policy

The information effect of monetary policy is shown by the difference between the baseline scenario (blue line) and the no information effect scenario (green line). These five rows of impulse responses can be grouped into three categories: responses to demand shocks, responses to noises in public information, and responses to policy shocks.

The first two rows show the impulse responses after a positive demand shock, with the first row showing the case of a persistent shock, and the second row showing the case of a transitory shock. In general, the information effect of monetary policy transmits the central bank's information to firms, reducing the information frictions in the economy. Therefore, the information effect brings the economy under information frictions closer to the full-information economy.

Importantly, learning is a gradual process. After a persistent demand shock, the two economies do not differ much on impact. This is because both the central bank and firms initial have noisy external information under our calibration. Over time, as firms learn more accurately about the persistent demand shock from the central bank's interest-rate decisions, it further increases prices in the following periods. As inflation increases due to the information effect of monetary policy, the positive output gap narrows. After around six quarters, the impulse responses of inflation and output converge to their full information case.

The third row shows the responses to a positive noise shock in the public information. In this case, both firms and the central bank mistakenly believe a higher level of demand. Therefore, firms increase prices and the central bank tightens the interest rate. Both the higher inflation rate and the higher interest rate reduces current demand, leaning to a negative output gap. As the central bank gains more accurate information from lagged inflation and output, the information effect of monetary policy transmits the central bank's information to firms. Therefore, the effect of the public noise shock is reduced, inflation quickly reduces to the steady state level. As a result, the inflation-targeting central bank lowers the interest rate. Both a lower inflation rate and a lower interest rate helps demand, resulting in a narrower output gap than the one under no information effect.

The last two rows show the responses to a policy shock, either due to a noise shock in the central bank's private information (fourth row) or due to an exogenous shock to the interest rate (fifth row). In both cases, when monetary policy has an information effect, the positive innovation in the interest rate is regarded as a signal of higher demand, for which firms raise prices. Both positive inflation and the positive interest rate dampens demand, which is equivalent to a negative output gap. In comparison, when firms do not observe the interest rate, the changes in the interest rate do not drive inflation fluctuations, and thus the size of the negative output gap is smaller in the no information effect scenario.

Interestingly, after all five shocks, 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 *The information effect of monetary policy*

- *increases inflation fluctuations and reduces output gaps after demand shocks,*
- *reduces fluctuations in both inflation and output after public noise shocks, and*
- *leads to positive inflation after a tightening of monetary policy.*

5 Conclusion

This paper studies the information effect of monetary policy when the central bank and the private sector learn from each other. We first construct an analytic model to show that a reduced-form estimation of the information effect of monetary policy may yield a biased result. This is because due to asymmetric information, the unobserved state of the economy correlates with the monetary policy surprise.

We then develop a New Keynesian model in which the learning is two-sided: the central bank learns from lagged inflation and output, and the private sector learns from the interest rate. We calibrate the model parameters to match the macroeconomic and expectation data of the US economy. Our calibrated model suggests that, compared to the case in which the private sector does not learn from the interest rate, the information effect of monetary policy brings the economy closer to the perfect information benchmark. On the other hand, it also leads to more pronounced inflation after a monetary policy shock, either due to the noise in the central bank's private information or an exogenous policy shock, as firms mistakenly believe the change in the interest rate reflect a real demand shock.

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