

Term Structure, Forecast Revision, and the Signaling Channel of Monetary Policy

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Abstract

Monetary policy shocks affect interest rates at long horizons (10 years or more). Furthermore, the private sector's real GDP forecasts are revised upward in response to a monetary tightening. These facts challenge the prevailing theories in academic and policy circles. In this paper, I propose a micro-founded model to rationalize those facts, based on the signaling channel of monetary policy. I consider a framework where the central bank has private information about future economic conditions. Agents update their beliefs according to Bayes' theorem. Policy actions play a signaling role, and may therefore rationalize the above empirical findings. (JEL: E32, E43, E44, E52, E58)

1. Introduction

Two facts are often used to reject the standard New Keynesian (NK thereafter) model. The first is the well known excess sensitivity of long-term interest rates to monetary surprises. Since the long-term rate is the weighted average of the current and expected future short-term rate, the significant impacts of monetary policy shocks on long-term rates imply that those shocks have highly persistent effects on the real economy for more than 10 years. Clearly, this is contradictory to conventional NK models, which are based on the paradigm that monetary policy has limited long-run impacts. The second is

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that the private sector's real GDP forecasts are revised upward in response to a monetary tightening. A sign that is the opposite of what a conventional NK model predicts. Both facts point towards puzzling movements in the market's expectations in response to a monetary surprise.

In this paper, I revisit those empirical findings and I provide one single mechanism to rationalize those puzzles within an NK framework based on the signaling channel of monetary policy (Melosi 2017). The model features an unobserved stochastic trend. And, the central bank holds private information regarding the trend of the economy, by allocating an abundant resource on the investigation of current and future economic conditions. Therefore, monetary actions serve as a signal regarding the long-term growth. This is consistent with the evidence provided by Ang et al. (2006): the short-term interest rate predicts real GDP growth in the far future both in terms of within-sample fit and out-of-sample forecast. I provide evidence that further supports this underlining mechanism: the counter-intuitive response of consumer's expectations at a *longer horizon* (5 years) to a monetary shock. The model is estimated using the Bayesian method. Two main results stand out.

First, the model rationalizes the excess sensitivity of long-term interest rates to monetary shocks and the counter-intuitive response of households' expectations to a monetary shock. In the model, private agents might interpret an expansionary (negative) monetary surprise in two different ways. First, it can be interpreted as the Fed's endogenous response to a worse than expected long-term productivity trend. If this is the case, private expectation regarding the productivity trend decreases and, consequently, the market's expectation regarding the long-term natural real interest rate drops. Thus, the long-term rate, which is the weighted average of the current and expected future short-term rate responds significantly to a monetary surprise. Alternatively, an expansionary monetary surprise can be interpreted as a pure monetary shock. If this is the case, it contains no information about the unobserved productivity trend, and therefore expectations about the trend and the natural real interest rate are not affected. In my framework, since private agents cannot distinguish a shock to productivity trend from a monetary policy shock, optimal belief updating (Bayes' rule) requires that agents assign weights to both interpretations. Thus, in response to a negative monetary surprise (driven by an exogenous monetary shock or a shock to productivity trend) both the perceived trend and the perceived natural real rate drop. Hence agents become more pessimistic, long-term interest rates decrease and expected real GDP in the next quarters drop.

Second, the signaling channel dampens the traditional effect of monetary policy via an inter-temporal substitution effect. On the one hand, via the conventional channel, a higher interest rate leads to a higher saving rate by reducing aggregate consumption. On the other hand, a positive monetary shock is partially interpreted, as the future economic condition will be better than previously expected. Through the second channel, consumers have the desire to

consume more. Overall, the aggregate impact of a monetary shock is smaller as compared to an NK model with perfect information. This result suggests that an intended expansionary monetary deviation (monetary shock) that aims to stimulate the economy might not work as expected.

One implication of the model is a monetary action that comes out as a surprise to the private agents (denote it as a monetary surprise) is not necessarily an exogenous monetary shock. The current state-of-art measures of monetary surprise are constructed using High Frequency Identification (HFI thereafter) strategy.¹ The basic idea behind the HFI strategy is that financial contracts reflect the market's beliefs about future monetary actions. Thus, the tick-by-tick data on Federal Funds futures and Eurodollar futures enable us to construct monetary surprises within 30-minute surrounding the Federal Open Market Committee's (FOMC thereafter) announcements. The tight window (30 minutes) ensures that those identified measures are true surprises to the market. However, monetary surprises are not necessarily monetary shocks. A monetary action might turn out as a surprise to the market when the central bank observes/anticipates a change in economic condition that is not fully understood by the market. Whereas, a monetary shock is defined as the central bank's exogenous deviation from a monetary policy rule that is unrelated to economic conditions. Thus, the HFI monetary surprises measures might be confounding with the Fed's private information regarding the state of the economy.

In the empirical section of the paper, I revisit the empirical exercises conducted by Nakamura and Steinsson (2017)² taking into account the confounding problem discussed above. Following Romer and Romer (2004), I control for Greenbook forecasts,³ which is a proxy for the central bank's information set. The identification assumption is that, once those variables are controlled for, the HFI monetary surprises are exogenous. Campbell et al. (2016) and Miranda-Agrippino (2016) take a similar approach to clean the endogenous components contained in HFI monetary surprises and use them as instruments in a Proxy VAR. I confirm that the excess sensitivity of long-term rates and the counter-intuitive response of private forecasts to a monetary *surprise* documented in Nakamura and Steinsson (2017) are present in response to a monetary *shock*. The results are robust to the use of Romer and Romer (2004)(R&R thereafter) monetary shocks. Those facts are consistent with the prediction of the model, based on the mechanism that private agents revise their

1. See the seminal work of Kuttner (2001) and Gürkaynak et al. (2005a) for the construction of monetary surprises.

2. They looked at how HFI monetary surprises affect long-term interest rate and real GDP forecast revisions.

3. The Fed's internal forecasts that are only available with a lag of five years. A similar approach is taken by Romer and Romer (2004) to construct R&R monetary shocks from fed funds rate

expectations about long-term economic growth in response to an exogenous monetary shock.

In addition, I provide direct evidence that further supports the underlying mechanism. Using data from the Michigan Survey of Consumers, consumers' expectations about the economic condition in the medium run (5 years) are improved in response to a contractionary monetary shock.

The ability of the model to rationalize those facts relies on the degree of information frictions. A simulation exercise suggests that in the estimated model, the degree of information advantage held by the Fed is not higher than that implied by Romer and Romer (2000)'s estimates.

To the best of my knowledge, this is the first paper that attempts to build a micro-founded model to rationalize the counter-intuitive response of households' expectations about real GDP growth and the excess sensitivity of long-term interest rates to monetary shocks. A vast literature that studies the volatility of long-term yield has emphasized the importance of risk premia (see, for instance, Dai and Singleton 2002). One limitation of the current paper, given its highly stylized model, is that the paper does not allow for risk premia shocks that are one of the main drivers of long-term interest rate. To address the concern about whether risk premia being the main channel through which monetary shocks affect long-term rates, I use risk-neutral rates and term premia decomposed by Kim and Wright (2005). The excess sensitivity to a monetary shock is found for risk-neutral measures of interest rates.

1.1. Literature review

This paper contributes to the literature on the signaling channel of monetary policy actions. Earlier works include Cukierman and Meltzer (1986), Ellingsen and Soderstrom (2001). Erceg and Levin (2003), Kozicki and Tinsley (2005) and Gürkaynak et al. (2005b). And recent studies include Baeriswyl and Cornand (2010), Tang (2015), Melosi (2017) and Falck et al. (2017).⁴ Melosi (2017) builds and estimates a DSGE model that features information frictions on the firm's side and the central bank holds superior information. In contrast, I study the information frictions on the household's side. This is crucial to rationalize the empirical facts that I discuss in this paper since the term structure of

4. Those papers, including this paper, assume that the central bank has superior information as compared to the private market. Romer and Romer (2000) provides supporting empirical evidence. D'Agostino and Whelan (2008) provides an opposing one. Note that in a rational expectation framework, the results discussed in this paper would hold as long as the central bank holds private information regarding the state of the economy. Empirical findings in Tang (2015), Miranda-Agrippino (2016), Miranda-Agrippino and Ricco (2017) are consistent with the hypothesis that the Fed has private information (see also Jarociński and Karadi (2018)). Moreover, even if the central bank has the same or an inferior information set, the signaling channel would arise if the market believes that the central bank knows more.

interest rate relies on consumers' Euler equation. Moreover, I focus on the long-term trend. In another closely related paper, Nakamura and Steinsson (2017) emphasize the information effects of FOMC statements. Unlike in their work, I build a model that endogenizes the signal extraction process and I use it to assess the role of the signaling channel of *monetary actions* in explaining the two empirical puzzles.⁵

Edge et al. (2007), Boz et al. (2011), Kuang and Mitra (2016) and Cao and L'Huillier (2018) study the effects of a trend shock when the later is not perfectly observed. This paper proposes that monetary actions act as an endogenous signal about the underlining trend. And, I focus on the implications for the transmission of monetary policy shocks.

More broadly, this paper adds to the literature that has focused on the implications of information frictions on business cycle. In his island model, Lucas (1972) shows that money non-neutrality arises from the imperfect knowledge regarding those nominal disturbances. Woodford (2002), Mankiw and Reis (2002), Sims (2003), Adam (2007) and Mackowiak and Wiederholt (2009) provide alternative frameworks in which the real effect of a monetary shock emerges from information friction. In contrast, in this paper, money non-neutrality arises from price stickiness and the presence of information asymmetry dampens the impacts of monetary shocks.⁶ This paper relates to the literature that studies information frictions on the household side: Mankiw and Reis (2006), Lorenzoni (2009), Angeletos and La'O (2013), Maćkowiak and Wiederholt (2015) and Wiederholt (2015). In contrast to those works, in this paper households learn from monetary policy actions. Coibion and Gorodnichenko (2012, 2015) provide empirical evidence that households are subject to information frictions.

The empirical part of the paper is related to the literature that studies the impacts of FOMC announcements on the yield curve and private agents' forecasts. See for example Romer and Romer (2000), Gürkaynak et al. (2005b), Hanson and Stein (2015), Nakamura and Steinsson (2017), Gilchrist et al. (2015) and Campbell et al. (2012).⁷ Unlike in the existing literature, I employ relevant control variables to address the confounding problem discussed above.

5. The signaling channel that I emphasize in the current paper is about long-term economic conditions. In contrast, a seemly apparent alternative approach is to model the central bank's private information about its policy rule, such as the inflation target emphasized by Gürkaynak et al. (2005b). However, the empirical facts that I emphasize in this paper are inconsistent with the interpretation of the monetary instrument revealing information about the Fed's inflation target. Therefore, I abstract from this discussion and whether the Fed's 2% inflation target, which was implicit before 2012 and explicit since then, was or not common knowledge is beyond the scope of the current paper.

6. See also Nimark (2008, 2014, 2017), Huo and Takayama (2015a,b), and Ou et al. (2021) for recent applications of information frictions for business cycle dynamics.

7. Hansen et al. (2019) has also contributed to the debate on why monetary announcements affect long-term interest rate.

This allows us to interpret the estimated responses as the market's reactions to exogenous monetary shocks (actions). Gertler and Karadi (2015), Miranda-Agrippino (2016), Lakdawala (2019) and Campbell et al. (2016) clean those HFI monetary surprises in a similar fashion. The use of R&R shocks as alternative measures reinforces the argument that even an exogenous monetary shock can generate the puzzling facts mentioned above. In addition, I provide novel evidence on the counter-intuitive response of consumer's expectations at the medium horizon (5 years) that further supports the channel that I emphasize in this paper.

The remainder of the paper is organized as follows. Section (2) presents empirical facts. Section (3) introduces the model. Section (4) estimates the model and discusses implications of the model as compared to the basic New Keynesian model. And Section (5) concludes.

2. Empirical Facts

This section discusses empirical facts in details. Section (2.1) presents the impact effects of monetary shocks on the yield curve. Section (2.2) discusses the impact effects of monetary policy shocks on real GDP forecasts. Section (2.3) presents evidence on the counter-intuitive response of consumer's expectations at the medium horizon (5 years) to monetary shocks that further supports the channel that I emphasize in this paper.

2.1. Fact 1: Impact Effect of Monetary Policy on Yield

I estimate regressions of the following form:

$$Y_{t+1d}^h - Y_{t-1d}^h = \alpha^h + \beta^h \Delta MP_t + \gamma^h X_t + \varepsilon_{h,t}, \quad (1)$$

where, $Y_{t+1d}^h - Y_{t-1d}^h$ are the two-days changes in nominal yield surrounding monetary policy decision dates. The superscript h denotes the maturity of the yield. ΔMP_t is the daily changes in the monetary policy instrument, three-month treasury bill rate,⁸ surrounding the monetary policy decision date. It is debatable whether the daily change in the monetary instrument or the change in a tighter window (ex: 30-minute window surrounding FOMC announcement) is a better proxy for monetary surprise. Hanson and Stein (2015) argue in favor of the daily change to allow for the market to have sufficient time to digest the new information. Gürkaynak et al. (2005a) argue that the use of a tighter window (30 minutes) surrounding the FOMC announcement is desirable to minimize the noise. To combine the advantages of those two, I instrument the

8. I obtain qualitatively similar and quantitatively more significant result using 1-year or 2-year interest rate as monetary policy instrument.

daily changes of ΔMP_t by monetary surprises constructed within a 30-minute window surrounding the FOMC announcements using data on the financial future.

However, due to the asymmetric information of the central bank and private agents, the HFI monetary surprises are subject to a confounding problem. To see this, in a world with asymmetric information, a non-monetary shock that is observed by the central bank but is not seen by private agents will be included in the HFI monetary surprises because the central bank's reaction to this unobserved shock comes as a surprise to private agents.

To address this confounding problem, I control for Greenbook forecasts, which is a proxy for the central bank's information set. Following Romer and Romer (2004)'s specification, both the Fed's internal forecasts of inflation, real output growth, the unemployment rate and the change in forecasts since the previous meeting are also included in vector X_t .⁹ The underlying identification assumption is that those HFI monetary surprises are exogenous once controlled for Greenbook forecasts. Intuitively, this IV approach is equivalent to the two-step approach: first, clean those HFI monetary surprises using Greenbook forecasts; and second, use those cleaned monetary surprises as instruments.¹⁰ The one-step approach employed in this paper has the advantage that the standard errors are free of construction error, which would arise in the two steps approach. Gertler and Karadi (2015) and Miranda-Agrippino (2016) take the two-step approach and use the cleaned HFI monetary surprises in a proxy VAR.

For each h , I estimate a regression of the form (1) using HFI monetary surprises as instruments for the variable of interest ΔMP_t . There are eight measures of HFI monetary surprises that are constructed based on fed funds futures and futures on Eurodollar deposits. In the baseline, I include all of them as instruments. Results are robust to the use of alternative sets of instruments. The F-statistics from the first-stage regression is 16.5, which is greater than the rule-of-thumb value 10 proposed by Stock and Yogo (2005). This suggests strong relevance of these instruments. The sample ranges from 1990M2 to 2012M12 due to the availability of HFI monetary surprises and Greenbook forecasts.

Figure (1) plots the estimates of $\hat{\beta}$ s from estimating separate regressions. The lines are the 95% confidence interval constructed using standard errors that are robust to serial correlation and heteroskedasticity. As one can see, monetary shocks have persistent positive and significant effects on the entire yield curve. For instance, the nominal rate with maturity of 20 years increases by roughly 0.5 basis points in response to a 1 basis point exogenous increase in monetary instrument.

9. See equation (1) in Romer and Romer (2004) for the exact set of controls.

10. See in the Online Appendix A for a detailed discussion.

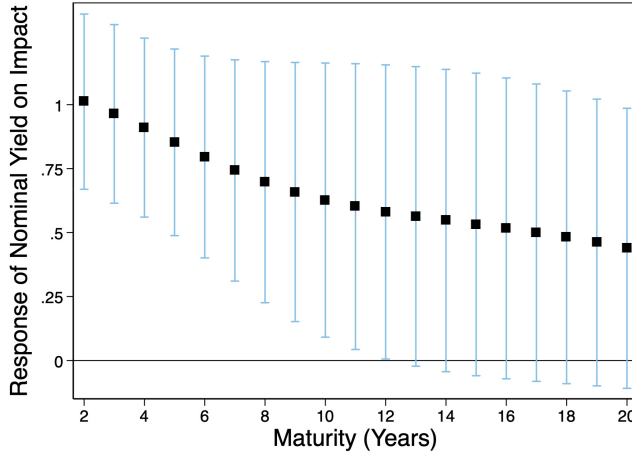


FIGURE 1. This figure plots the responses of nominal yields at different maturities to monetary shocks. The square dots represent the estimated $\hat{\beta}^h$ from separated regressions: $Y_{t+1d}^h - Y_{t-1d}^h = \alpha^h + \beta^h \Delta MP_t + \gamma^h X_t + \varepsilon_{h,t}$ using HFI monetary surprises as instruments for the variable of interest ΔMP_t . The blue lines are the 95% confidence interval constructed using standard errors that are robust to serial correlation and heteroskedasticity. Sample: 1990M2 to 2012M12.

2.1.1. Robustness Checks. To address the concern about whether risk premia being the main channel through which monetary shocks affect long-term rates, I use risk-neutral rates constructed by Kim and Wright (2005). Figure (B.1) shows the estimation result: the excess sensitivity to a monetary shock survives when risk-neutral measures of nominal interest rates are used. In light of this result, in the model that I present below, I will abstract from risk premia.

Those results are robust to the use of R&R monetary shocks: an alternative measure of monetary shock that is often used in the literature. Those shocks are identified at monthly frequencies, to be comparable with the baseline, I use R&R shocks to instrument MP_t in the following regression model:

$$Y_t^h = \alpha^h + \beta^h MP_t + \gamma^h X_t + \varepsilon_{h,t}, \quad (2)$$

with MP_t denotes the monetary instrument, three-month treasury bill rate which is instrumented by R&R monetary shocks and Y_t^h is the nominal yield with maturity h . X_t includes the four lags of MP_t , Y_t^h , industry production and CPI. Data are in monthly frequency. Note that those controls are included to improve the relevance of the instrument.¹¹ The first stage F-statistic is equal to 17.5. The sample ranges from 1969M1 to 2007M12 due to the availability of R&R monetary shocks.

11. Intuitively, R&R Monetary Shocks are strong instruments to the reduced form innovations (of the monetary instrument) but not relevant to the endogenous component of three-month treasury bill rate.

Figure (B.2) plots the estimation results: an R&R monetary shock has a big impact on yields at the long horizons.

In addition, the results discussed in this section are robust to: i) the use of alternative instrument sets ii) excluding the recession periods iii) the use of daily changes in nominal yields instead of a two-day window iv) the use of inflation indexed interest rate. See online appendix for detailed explanations and figures.

2.2. Fact 2: Expected Real GDP and Monetary Policy

One interpretation of the first set of facts is that a expansionary monetary surprise is perceived as news about future growth rate in consumption. The second set of facts provides evidence that is consistent with this hypothesis. Following Romer and Romer (2000), I estimate regressions of the following form:

$$y_{t+j|t} - y_{t+j|t-1} = \alpha^j + \beta^j MP_t + \gamma^j X_t + v_{j,t}, \quad (3)$$

where MP_t is instrumented by “cleaned” HFI monetary surprises that I will explain below. The first stage F-statistic is equal to 14.1. I add the following control variables, denoted as X_t : the lagged real GDP, price deflator, and monetary instrument. Data are in quarterly frequency, due to the data availability the number of lags is chosen to be two. $y_{t+j|t}$ denotes expected log real GDP at j quarters ahead that I take from the Survey of Professional Forecasters (SPF). Those surveys are normally conducted in the second month of a quarter with the exact date of the survey varies overtime. Therefore, a simple quarterly aggregation of monetary shocks might contain shocks that occur after the survey. In order to correctly identify the effect of monetary shock on forecast revision, one needs to adjust HFI monetary surprise as it occurred between the current survey ($y_{t+j|t}$) and the previous survey ($y_{t+j|t-1}$). This is possible since the exact dates of SPF and FOMC meetings are publicly available.

As it is discussed above, the HFI monetary surprises might contain the Fed’s information regarding the state of the economy. Previously, in monthly regressions, I controlled for the information set of the Fed. This is not desirable here in quarterly frequency, because aggregating the Fed’s information set from monthly to quarterly would generate information loss. As a solution, I clean the HFI monetary surprises in the spirit of Romer and Romer (2004) (the same approach is taken by Miranda-Agrippino 2016 and Miranda-Agrippino and Ricco 2017). In particular, I take the residuals from projecting HFI monetary surprises onto the Fed’s internal forecasts of inflation, real output growth, the unemployment rate and the change in forecasts since the previous meeting. I then use those “cleaned” HFI monetary surprises as instruments to estimate the coefficients of interest β^j in model (3).

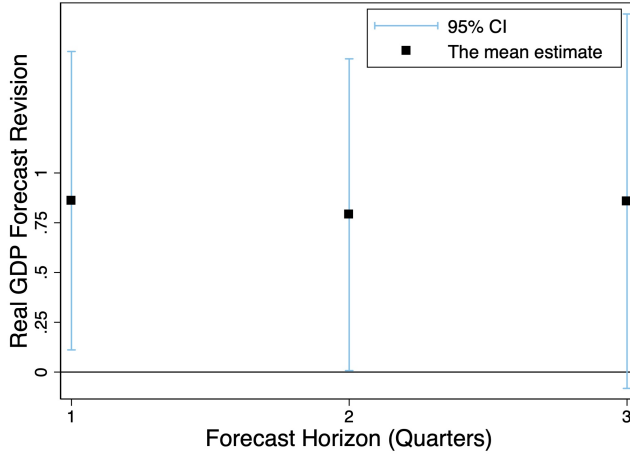


FIGURE 2. This figure plots the impact effect of a monetary shock on real GDP forecast revision. The square dots represent the estimated $\hat{\beta}_j$ s from separated regressions: $y_{t+j|t} - y_{t+j|t-1} = \alpha^j + \beta^j MP_t + \gamma^j X_t + v_{j,t}$, using HFI monetary surprises as instruments for MP_t . The forecast horizons are denoted in quarters and $y_{t+j|t}$ denotes the forecast made at time t about the real GDP at quarter $t+j$. The blue lines are the 95% confidence interval constructed using standard errors that are robust to serial correlation and heteroskedasticity. Sample: 1990Q1 to 2012Q4.

Figure (2) plots the instantaneous effect of monetary shock on real GDP forecast revision at 1 quarter, 2 quarters and 3 quarters ahead. In response to a monetary shock that increases the monetary instrument by 1basis point, professional forecasters revise their real GDP forecasts for the next quarters raising them by roughly 0.75 basis points. Qualitatively, this is the opposite of what the standard NK model predicts: monetary tightening should depress the expected real GDP.

2.2.1. Robustness Checks. The results discussed in this section are robust to: i) the use of alternative instrument set, ii) excluding the recession periods, iii) the use of raw HFI monetary surprises as instruments and iv) the use of R&R monetary shocks. See online appendix for detailed explanations and figures.

I emphasize that the results are robust to the use of R&R monetary shocks. As is evidenced by Figure (B.3), the use of R&R monetary shocks as exogenous instruments¹² generates the same puzzle.

12. The first stage F-statistic is equal to 11.6.

2.3. Monetary Policy and Consumers' Expectations at the Medium-run

The previous two facts are consistent with the interpretation that an expansionary monetary surprise is perceived as bad news about long-term economic conditions. Before moving to a structural model that builds upon this interpretation, I provide additional evidence that supports the mechanism that I emphasize in the next section.

Using data from the Michigan Surveys of Consumers, I investigate whether monetary shocks affect consumers' expectations about economic conditions in the following five years. Specifically, I use the index constructed from consumers' answers to the following questions: *"Looking ahead, which would you say is more likely – that in the country as a whole we'll have continuous good times during the next 5 years, or that we'll have periods of widespread unemployment or depression, or what?"* This index measures the relative fraction of consumers who report "Good Times". Using it as the dependent variable, I estimate the following model:

$$MSC_t = \alpha + \beta MP_t + \gamma X_t + v_t, \quad (4)$$

where MSC_t denotes the consumers' sentiment index described above, MP_t in the monetary instrument and X_t includes a set of control variables: four lags of MSC_t , MP_t , real GDP and inflation. Similar to previous regressions, for the identification of monetary shocks, I use the cleaned measure of HFI monetary surprises or R&R monetary shocks as instrumental variables for MP_t .

Estimation results are reported in Table 1, for both measures of instrumental variables across different samples, an exogenous increase in the short-term interest rate leads to a favorable revision in consumers' expectations about the economic condition in the next five years.

TABLE 1. Effects of Monetary Shocks on Medium-run Sentiment

	HFI (cleaned)	Instrumental Variables		
		HFI (cleaned)	R&R	R&R
MP_t	11.41 (6.76)	7.75 (4.26)	4.46 (2.61)	7.35 (2.67)
Controls:				
Lagged Sentiment	Yes	Yes	Yes	Yes
Lagged Macro Variables	Yes	Yes	Yes	Yes
F statistic	8.24	13.60	57.09	33.38
Sample Periods	90 - 2012	90 - 2007	78 - 2007	90 - 2007

Note: This table reports results from estimating: $MSC_t = \alpha + \beta MP_t + \gamma X_t + v_t$, using cleaned HFI monetary surprises or R&R monetary shocks as instruments for MP_t . Standard errors that are robust to serial correlation and heteroskedasticity are reported in parenthesis.

3. The Model

These facts challenge different varieties of NK models, which are based on the paradigm that monetary policy has limited long-run effects and a monetary policy tightening should depress agents' expectations regarding real GDP.

Figure (B.4) plots the impact effects of monetary shocks on nominal yields at different maturities and real GDP forecast revisions at different horizons predicted by a standard NK model with perfect information (a special case of the model discussed below). The circles and intervals are the mean estimates and 95% confidence intervals constructed based on posterior parameters' distributions. Details regarding the estimation of the model will be discussed in Section (4). As can be seen, the effect of a monetary shock on expected real GDP growth is clearly at odds with the Fact 2 discussed above. And quantitatively, a monetary policy shock has limited effect on long-term yield, which is inconsistent with Fact 1.

In this section, I build a model to rationalize those facts. The model consists of i) a representative household who makes consumption and labor supply decision to maximize her utility; ii) a representative firm operates in a monopolistic competitive market and sets price infrequently; iii) a monetary policy authority chooses interest rate following a Taylor rule. The household and the firm share the same information set, and the central bank holds private information regarding the trend of the economy—an assumption that is shared by Nakamura and Steinsson (2017)¹³ and supported by the facts presented above and those uncovered by Ang et al. (2006). This stylized model extends Melosi (2017) by introducing information asymmetry between household and the central bank.

3.1. Households

A representative household $j \in (0, 1)$ seeks to maximize the following utility function:

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t e^{\delta_t} U(C_t(j), N_t(j)), \text{ with } U(C_t(j), N_t(j)) = \left[\log(C_t(j)) - \frac{N_t(j)^{1+\varphi}}{1+\varphi} \right],$$

where δ_t is the preference shock that follows:

$$\delta_t = \rho_{\delta} \delta_{t-1} + \varepsilon_t^{\delta} \text{ with } \varepsilon_t^{\delta} \sim N(0, \sigma_{\delta}^2)$$

N_t denotes labour supply and C_t is a consumption index given by:

$$C_t = \left(\int_0^1 C_{j,t}^{(\gamma-1)/\gamma} dj \right)^{\gamma/(\gamma-1)}$$

13. They assume the Fed's announcements releases its private information about the natural rate of return, which is a function of consumption growth.

I have assumed a continuous supply of consumption goods $[0,1]$ with elasticity of substitution γ among them. The representative consumer faces a standard budget constraint:

$$\int_0^1 P_t(j)C_t(j)dj + Q_t B_{t+1} \leq B_t + W_t N_t + T_t$$

where, $P_t(j)$ denotes the price of good j , Q_t denotes the price at time t of one period bond that pays B_{t+1} at time $t+1$, W_t the wage and T_t the lump-sum transfer including profit from firms. Solving the consumer's optimization problem leads to the following Euler equation:

$$Q_t = \beta \mathbb{E} \left\{ \frac{\Lambda_{t+1}}{\Lambda_t} \frac{P_t}{P_{t+1}} \right\}$$

where, $P_t = \left(\int_0^1 P_{j,t}^{1-\gamma} dj \right)^{1/(1-\gamma)}$ is the aggregate price index and $\Lambda_t \equiv U_{c,t} e^{\delta t}$.

3.2. Firms

There is a continuum of firms indexed by $j \in [0, 1]$ which produce differentiated goods in a monopolistic competitive market according to the following production function:

$$Y_{t,j} = e^{a_t} N_{t,j}$$

Firms have access to the same technology with the latter follows the following process:

$$\begin{aligned} \Delta a_t &= g_t + \varepsilon_t^a \text{ with } \varepsilon_t^a \sim N(0, \sigma_a^2) \\ g_t &= \rho_g g_{t-1} + (1 - \rho_g) g^* + \varepsilon_t^g \text{ with } \varepsilon_t^g \sim N(0, \sigma_g^2). \end{aligned}$$

In words, the growth rate of productivity consists of a temporary component (ε_t^a) and a persistent component (g_t). Private agents observe the aggregate change in productivity (Δa_t). However, they cannot tell apart whether the change is a temporary or a persistent one.

Firms are subject to nominal rigidity *à la* Calvo (1983). Each period a fraction θ of firms cannot reset prices optimally, but choose their price according to the following indexation rule:

$$P_t(i) = P_{t-1}(i) \pi_{t-1}^\omega \pi^{1-\omega},$$

where π_{t-1} is the lagged inflation and π the steady state inflation. The fraction $1 - \theta$ of firms can reset their prices freely and will do so optimally to maximize the following equation:

$$\mathbb{E} \left[\sum_{k=0}^{\infty} \theta^k \beta^k \frac{\Lambda_{t+k}}{\Lambda_t} (P_t(i) \Pi_{t,t+k} - MC_t) Y_{t+k}(i) \right],$$

subject to constraint:

$$Y_{t+k}(i) = \left(\frac{P_{t+k}(i)\Pi_{t,t+k}}{P_{t+k}} \right)^{-\gamma} Y_{t+k},$$

where $\Pi_{t,t+k} \equiv \prod_{s=1}^k (\pi_{t+s-1}^\omega \pi^{(1-\omega)})$.

3.3. Log-linearized equilibrium conditions

I have log linearized the Euler equation around the steady state to get the dynamic IS equation:

$$\hat{y}_t = \mathbb{E}\hat{y}_{t+1} - [\hat{i}_t - \mathbb{E}\hat{\pi}_{t+1} - \rho_g \mathbb{E}\hat{g}_t + (\mathbb{E}\delta_{t+1} - \delta_t)]. \quad (5)$$

Since the model has a stochastic trend, to solve the model around a stationary steady state, I rescale the non-stationary variable by level productivity A_t . The variable with hat denotes its deviation from its steady state.

The log linearized Phillips curve is derived from firms' problem:

$$\hat{\pi}_t = \frac{\beta}{1 + \omega\beta} \mathbb{E}\hat{\pi}_{t+1} + \frac{\omega}{1 + \omega\beta} \hat{\pi}_{t-1} + \kappa \hat{y}_t + \varepsilon_t^\pi, \quad (6)$$

where $k \equiv \frac{(1-\theta\beta)(1-\theta)}{\theta(1+\omega\beta)}(\varphi + 1)$. Note that I have introduced shock to the Phillips curve: ε_t^π with mean 0 and variance σ_π^2 .

3.4. Monetary policy

The central bank sets the interest rate following a version of the Taylor rule that keeps track of the efficient real interest rate — the one that would prevail without frictions (Wicksell 1989). Cúrdia et al. (2015) show that the interest rate tracks an efficient rate of return that fits the U.S.'s data well. Formally, Woodford (2001) shows that such a rule is optimal.

I assume a Taylor rule of the following form:

$$\hat{i}_t = \rho_m \hat{i}_{t-1} + (1 - \rho_m)(\varphi_r r_t^e + \varphi_\pi \hat{\pi}_t + \varphi_y \hat{y}_t) + \varepsilon_t^m, \quad (7)$$

with $\varepsilon_t^m \sim i.i.d. N(0, \sigma_m^2)$. The persistent component $\rho_m \hat{i}_{t-1}$ is introduced to generate persistent impacts of monetary shocks. The theoretical argument for introducing this component is the following: in a framework with the presence of an output gap and inflation tradeoff, such as the current one, it is optimal for the central bank to conduct monetary policy with commitment in order to smooth the welfare loss over time. Consequently, the current policy rate depends on the previous one. Thus the lagged interest rate in the Taylor rule allows the simple policy rule to be able to approximate the optimal monetary policy under commitment.

The variable r_t^e denotes the efficient real interest rate.¹⁴ In this framework, the efficient real interest rate is the one that would prevail if the market were perfectly competitive and if there were no information frictions. To determine the efficient real interest rate, I solve the social planner's problem in this economy. The social planner makes intra-temporal consumption and labor decisions according to:

$$-\frac{U_{N,t}}{U_{C,t}} = MPN_t. \quad (8)$$

The inter-temporal optimality condition under efficient allocation is:

$$R_t = \beta \mathbb{E}^e \left\{ \frac{\Lambda_t}{\Lambda_{t+1}} \right\}. \quad (9)$$

Combine (8) with (9) and log-linearize :

$$r_t^e = \mathbb{E}^e g_{t+1} - \mathbb{E}^e \Delta \delta_{t+1}, \quad (10)$$

Lastly, ε_t^m in the Taylor rule is the exogenous monetary shock. In the literature, there are two main interpretations of these monetary policy shocks. First, ε_t^m reflects shocks in the FOMC's preference as committee members may prefer to respond more to inflation on one day than on another. Second, ε_t^m captures measurement error in the real time data that the FOMC has during the day of policy making. What matters is the assumption that ε_t^m is exogenous to policy decision and private agents do not observe monetary shocks. In the presence of unobserved monetary shocks, the central bank's action does not provide perfect information regarding the unknown g_t therefore agents' learning is persistent.

3.5. Belief updating and solution of the model

Private agents make decisions based on an uncertain environment. Namely, they do not observe the productivity trend g_t perfectly and cannot distinguish trend shocks (ε_t^g) from level productivity shocks (ε_t^a). Moreover, agents do not observe monetary shocks (ε_t^m). Since the trend is relevant for their optimal decisions, agents will infer g_t from observable variables. Let us denote agents' estimate of g_t by $g_{t|t} \equiv E(g_t|Z^t)$, where Z^t is the history of variables that are relevant for inference about g_t that agents observe up to time t .

I assume that agents understand the model and know the distributions of shocks as well as the parameters of the model. To update $g_{t|t}$, agents use the

14. An alternative interpretation of r_t^e in the Taylor rule is that the central bank reacts to its expected future economy or financial conditions, for instance the expected real GDP growth in the next period. The latter is proportional to the trend of the economy and is therefore similar to r_t^e .

up-to-date history of $Z_t = [a_t \ \hat{i}_t \ s_t]$ those are: the level of productivity, the policy rate and additional private signals about g_t summarized in s_t :

$$s_t = g_t + \varepsilon_t^p \text{ with } \varepsilon_t^p \sim i.i.d \ N(0, \sigma_p^2). \quad (11)$$

I introduce s_t for two reasons. First, it is more realistic to assume, apart from monetary action and level productivity, that agents receive additional information about the future development of the economy. For example, by reading newspapers. Second, with the introduction of s_t the NK model with perfect information is nested in this model by setting σ_p equal to zero. Thus, one approach to assess whether the signaling channel of monetary policy is empirically relevant or not is to check if the estimated σ_p is different from zero.

It is worth emphasizing that the realized short-run interest rate i_t provides information about the underlying trend g_t , because agents know the central bank's reaction function. Moreover, due to the fact that agents do not observe monetary shocks, they cannot infer g_t perfectly from monetary actions.

The signal extraction problem of agents is subject to a simultaneity problem. The monetary policy signal responds to endogenous variables $\hat{\pi}_t$, $\hat{y}_t$, and those are determined based on agents' posterior belief about g_t , which in turn depends on monetary policy. Svensson and Woodford (2004) provide a solution for optimal filtering under these settings.

The model's solution is derived in Online Appendix. In the model, agents update their beliefs about the unknown process $\hat{g}_t$ and ε_t^m using kalman filter. And naturally $g_{t|t}$ and $\varepsilon_{t|t}^m$ are state variables. Define $X_t \equiv \left(\varepsilon_t^m \ \hat{g}_t \ \hat{\delta}_t \ \varepsilon_t^\pi \ \hat{i}_{t-1} \ \hat{\pi}_{t-1} \ \varepsilon_{t|t}^m \ \hat{g}_{t|t} \right)'$, $U_t \equiv \left(\varepsilon_t^g \ \varepsilon_t^\delta \ \varepsilon_t^\pi \ \varepsilon_t^m \ \varepsilon_t^a \ \varepsilon_t^p \right)'$, and $X_t^f \equiv \left(\hat{y}_t \ \pi_t \right)'$ then the state space representation of the model's solution is:

$$X_{t+1} = AX_t + BU_{t+1}, \quad (12)$$

$$X_t^f = FX_t, \quad (13)$$

with matrix A, B and F specified in Online Appendix. Further more, the term structure of interest rates is derived in Appendix C.

4. Model Estimation and Results

I estimate the model using a Bayesian approach with quarterly data from the U.S. ranging from the first quarter of 1982 to the last quarter of 2016. Real GDP per capita, inflation, nominal yields with maturities of two, five and ten years are included in the measurement equations, see Online Appendix for detailed data descriptions.

It is well known that many DSGE models are subject to local identification issues, see Canova and Sala (2009) for potential reasons. Iskrev (2010) and

Komunjer and Ng (2011) provide algorithms to check for identification prior to estimation. It is standard practice in the literature that unidentified parameters are then calibrated. I follow Komunjer and Ng (2011)'s procedure and all parameters are verified to be locally identified.

Tables (2) and (A.1) report the prior and posterior estimates. Priors are reported in the first three columns. They are taken from the literature, see for example An and Schorfheide (2007). I estimate posteriors using the Random Walk Metropolis-Hastings algorithm. Posterior means and standard errors for both the model with asymmetric information and the one with perfect information (in which σ_p is imposed as zero) are reported. The key parameters that drive the main results are reported in Table (2): variances of monetary, level productivity, trend and private signal shocks — these are not only a measure of volatility but also a measure of precision of signals. In the model with asymmetric information, the posterior mean of σ_p — the private signal noise is much larger than monetary shock volatility (σ_m). This suggests that the information is indeed not perfect. In addition, σ_a , the noise of another source of private information, is relatively big and determines the magnitude of the signaling channel of monetary policy. The relative magnitude of σ_m and σ_g is another critical factor, my estimates are comparable to those estimated in the literature, see, e.g., Justiniano et al. (2010) and Herbst and Schorfheide (2015).

Table (A.1) reports the posterior estimates of other parameters. With few exceptions, estimated parameters between a model with asymmetric information and a model with perfect information are similar. The results discussed below are not driven by those differences.

TABLE 2. Prior and Posterior: Key Parameters

	Priors			Asymmetric Information		Perfect Information	
	Mean	s.d	Distribution	Mean	s.d	Mean	s.d
σ_m	4×10^{-3}	4	InvGamma	1.2×10^{-3}	0.7×10^{-4}	1.8×10^{-3}	1.3×10^{-4}
σ_a	4×10^{-3}	4	InvGamma	6.7×10^{-3}	4.6×10^{-4}	7.2×10^{-3}	4.7×10^{-4}
σ_g	4×10^{-3}	4	InvGamma	1.6×10^{-3}	0.1×10^{-3}	1.6×10^{-3}	0.1×10^{-3}
σ_p	4×10^{-3}	4	InvGamma	1.9×10^{-2}	1.1×10^{-2}	—	—

Note: Posterior means and standard deviations are estimated using the Random Walk Metropolis-Hastings algorithm

4.1. Results

4.1.1. Rationalizing Fact 1: the Impact Effects of Monetary Shocks on Long-term Yield. Figure (3) plots one of the main facts that I aim to capture: the

impact effects of monetary shocks on nominal yields. Those should be compared to their empirical counterpart: Figure (1).

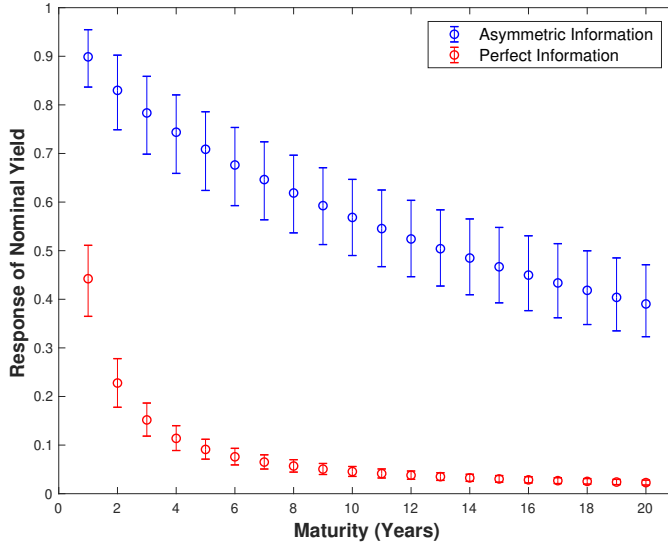


FIGURE 3. This figure depicts the impact effects of monetary shocks on nominal yield at different maturities predicted by the models. The circles and intervals are the mean estimates and 95% confidence intervals constructed based on posterior parameters' distributions. The blue lines plot the predictions of the model under asymmetric information. The red ones plot those for the perfect information case: all parameters are set to be the same as for the asymmetric case except for the private signal volatility σ^p , which is imposed as zero.

The circles and intervals are the mean estimates and 95% confidence intervals constructed based on posterior parameters' distributions. The blue lines plot the predictions of the model under asymmetric information. The red ones plot those for the perfect information case: all parameters are set to be the same as for the asymmetric case except for private signal volatility σ^p , which is imposed as zero. This choice of comparison is made to ensure that the signaling channel is the key mechanism driving the model's success.¹⁵

As one can see, while the model with perfect information fails to reproduce the empirical facts, the model with information asymmetry reflects the facts very well. As observed in the data, the model predicts that on impact nominal yields at all horizons respond to monetary shocks positively and significantly. In the model, private agents cannot distinguish a monetary shock from the central bank's endogenous response to the bank's information about the news shock. And agents know that the monetary policy responds positively to a news shock.

15. Alternatively, one can compare the predictions of the two models based on separate parameter estimates. The results are unchanged.

As a result, a positive monetary surprise that originates from a pure positive monetary shock is partially interpreted as the central bank has received good news about the economy's future development. Hence, the perceived natural real interest rate increases. Notice that the natural real interest rate is highly persistent ($\rho_g = 0.98$) in this economy, a magnitude that is shared in the long-run risk literature (Bansal and Yaron 2004), and therefore the expected natural real interest rate in the far future also increases. Consequently, the long-term yield, which is the weighted average of the current and expected future policy rate, increases in response to a positive monetary shock.

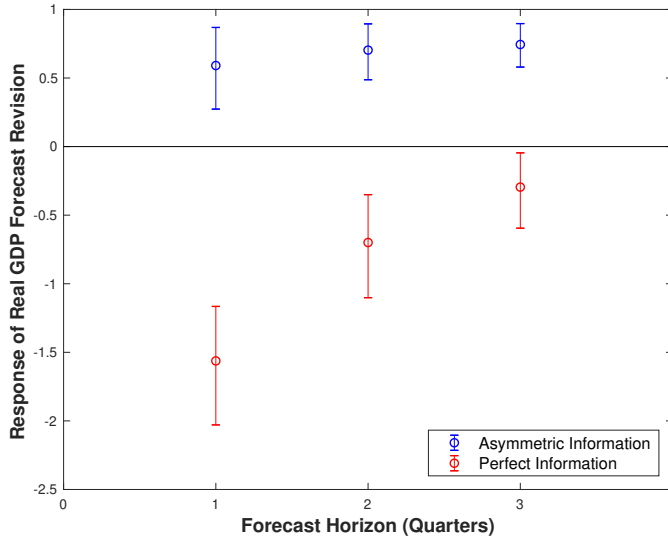


FIGURE 4. This figure depicts the impact effects of monetary shocks on real GDP forecast revision at different horizons predicted by the models. The circles and intervals are the mean estimates and 95% confidence intervals constructed based on posterior parameters' distributions. The blue lines plot the predictions of the model under asymmetric information. The red ones plot those for the perfect information case: all parameters are set to be the same as for the asymmetric case except for the private signal volatility σ^p , which is imposed as zero.

4.1.2. Rationalizing Fact 2: the Impact Effects of Monetary Shocks on Real GDP Forecast Revisions. Figure (4) shows the second fact that I aim to rationalize: the impact effects of monetary shocks on real GDP forecast revisions. These should be compared to their empirical counterparts: Figure (2). Again, the figure plots the mean estimates and 95% confidence intervals both for the model with information asymmetry (in blue) and with perfect information (in red). In contrast to the prediction of the standard NK model (the red lines), the model with asymmetric information fits the data well. In response to a positive monetary shock, agents, both in the model and data, revise upward their forecasts of log real GDP in the next quarters. This is due

to the signaling channel of monetary policy. A positive monetary shock is partly interpreted as the arrival of a positive news shock. As a result, agents become more optimistic.

4.1.3. Implication: the Signaling Channel Dampens the Conventional Effect of Monetary Policy. Figure (5) compares the IRFs of endogenous variables to a positive monetary shock in the model with asymmetric information with those in the model with perfect information. The solid and dashed lines are the mean estimates and 95% confidence interval of IRFs of the models constructed based on the posterior parameters' distributions. The ones in blue plot the predictions of the model under asymmetric information. The red ones plot those for the perfect information case: all parameters are set to be the same as for the asymmetric case except for the private signal volatility σ^p , which is imposed as zero.

As compared to the case with perfect information, the effects of monetary policy shock to output and inflation in the model with asymmetric information are more silent. Unlike in the perfect information case, in which monetary policy affects output only through the consumer's Euler equation and inflation adjusts according to the Phillips curve, with asymmetric information the signaling channel of monetary policy emerges. A contractionary monetary policy is perceived as a good news shock, thus agents become more optimistic and, as a result, they consume more. The signaling channel of monetary policy dampens the traditional channel. As a result, monetary policy shocks in the model with asymmetric information are less disturbing.

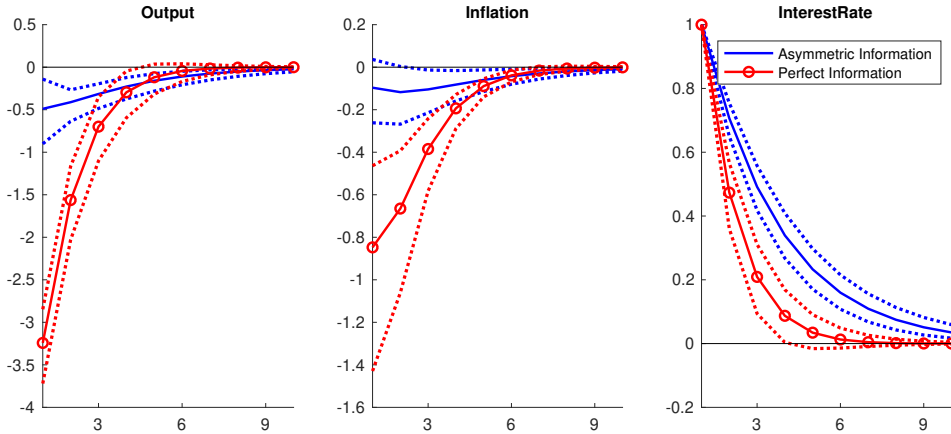


FIGURE 5. This figure plots IRFs after a positive monetary shock. The solid and dashed lines are the mean estimates and 95% confidence interval of IRFs of the models constructed based on the posterior parameters' distributions. The ones in blue plot the predictions of the model under asymmetric information. The red ones plot those for the perfect information case: all parameters are set to be the same as for the asymmetric case except for the private signal volatility σ^p , which is imposed as zero.

4.1.4. Discussion: How Plausible is the Estimated Degree of Information Frictions? The previous analysis shows that the estimated degree of information asymmetry is capable of rationalizing the aforementioned empirical puzzles. Yet we have not discussed whether the implied information asymmetry is reasonable or not. In the next exercise, I provide additional evidence.

Romer and Romer (2000) show that the FOMC staff's internal forecasts dominate commercial forecasts based on the estimation of the following regressions:

$$y_{t+h} = \alpha + \beta^P E_t^P(y_{t+h}) + \beta^F E_t^F(y_{t+h}) + e_t, \quad (14)$$

where $E_t^P(y_{t+h})$ denotes commercial forecasts (private agents' forecasts) at time t about variable y at h horizons ahead, and $E_t^F(y_{t+h})$ denotes the Fed's internal forecasts. They do the exercise both for real GDP forecasts and inflation forecasts. The null hypothesis is whether $\beta^F = \beta^P$. Under the null both private and the Fed's internal forecasts are equally precise. With $\beta^F > \beta^P$ meaning the Fed's information is superior to that of private agents. Estimation results are reported in Table (3) and Table (5) in their paper and I have copied those numbers to the last two columns of Table (3)¹⁶: overall $\hat{\beta}^P$ is not statistically different from zero and $\hat{\beta}^F$ is close to one. Those results suggest that the Fed has superior information about future inflation and real GDP and for the predictability of those variables it is enough to use solely the Fed's internal forecasts as predictors.

Using the structure model in this paper, I replicate their empirical results using the simulated data based on estimated parameters. I simulate the model 10 000 times for 65 periods each (the same sample size as in Romer and Romer (2000) regressions using SPF survey data). In each simulation, I construct the realized variables y_{t+h} : real GDP and Inflation; the private agents' forecasts of the corresponding variables at different horizons h denoted as $E_t^P(y_{t+h})$; and the central bank's forecasts denoted as $E_t^F(y_{t+h})$. For each simulation, I estimate the regressions of the form (14). The mean estimates are reported in Table (3), and the standard deviations are reported in parentheses. Those should be compared to the empirical results discovered by Romer and Romer (2000), i.e. the numbers contained in the fourth and fifth columns. As one can see, similar to Romer and Romer (2000)'s findings, the model predicts that the Fed's internal forecasts outperform the private forecasts in predicting future economic activities.

In addition, in each simulation, I calculate the ratio of mean square forecast error (RMSFE). The averages square forecast error (MSFE) is calculated as the average squared difference between the expected and actual GDP/inflation. The RMSFE is then obtained by taking the ratio between the MSFE of the Fed's forecasts and the MSFE of the private forecasts. An RMSFE smaller than one

16. The parameters are estimated using SPF data.

suggests that the Fed's internal forecasts are more precise than the private's forecasts. The means of simulated RMSFE are reported in the third column and the standard deviations are reported in parentheses. These should be compared to their empirical counterparts discovered by Romer and Romer (2000) that are reported in the last column. The simulated RMSFE are greater than their empirical counterparts, suggesting that the degree of the central bank's information advantage assumed in this model is smaller to that implied by the actual data. In practice, the central bank may have information advantage regarding other shocks in the economy and/or its monetary policy reaction function. Those features, that are assumed away in the current model¹⁷, may explain the gap between the simulated and actual RMEFE.

Overall, I interpret those as evidence suggesting that the implied information asymmetry in the model is realistic.

TABLE 3. Model Simulation: Romer and Romer (2000) Regressions

$$y_{t+h} = \alpha + \beta^P E_t^P(y_{t+h}) + \beta^F E_t^F(y_{t+h}) + e_t$$

	Model Simulations			Romer and Romer (2000)		
Forecast Horizon h	$\hat{\beta}^P$	$\hat{\beta}^F$	RMSFE	$\hat{\beta}^P$	$\hat{\beta}^F$	RMSFE
Real GDP						
1 Quarter	-0.04 (0.27)	1.00 (0.36)	0.79 (0.08)	0.56 (0.53)	0.81 (0.52)	-
2 Quarters	-0.11 (0.64)	1.00 (0.73)	0.94 (0.07)	0.66 (0.53)	1.07 (0.66)	-
3 Quarters	-0.18 (1.16)	0.98 (1.10)	0.97(0.06)	0.40 (0.28)	0.99 (0.44)	-
4 Quarters	-0.16 (1.95)	0.94 (1.54)	0.99 (0.05)	-1.07 (0.55)	2.33 (0.46)	-
Inflation						
1 Quarter	-0.02 (0.57)	0.97 (0.71)	0.95 (0.06)	0.39 (0.42)	0.57 (0.38)	0.72
2 Quarters	-0.10 (0.92)	1.07 (1.05)	0.97 (0.04)	-0.48 (0.33)	1.33 (0.29)	0.76
3 Quarters	-0.15 (1.30)	1.05 (1.34)	0.99 (0.04)	-0.65 (0.31)	1.55 (0.29)	0.74
4 Quarters	-0.19 (1.71)	0.99(1.69)	0.99 (0.03)	-0.72 (0.36)	1.53 (0.32)	0.70

Notes: I simulate the model 10 000 times for 65 periods each. In each simulation, I construct the realized variables y_{t+h} : real GDP and Inflation; the private agents' forecasts of the corresponding variables at different horizons h denoted as $E_t^P(y_{t+h})$; and the central bank's forecasts denoted as $E_t^F(y_{t+h})$. In each simulation, I estimate Romer and Romer (2000)'s regressions: $y_{t+h} = \alpha + \beta^P E_t^P(y_{t+h}) + \beta^F E_t^F(y_{t+h}) + e_t$. The mean estimates are reported in the first two columns of the table, and the standard deviations are reported in parentheses. In addition, in each simulation, I calculate the ratio of mean square forecast error (RMSFE). The means of simulated RMSFE are reported in the third column and the standard deviations are reported in parentheses. The last three columns report empirical results discovered by Romer and Romer (2000).

17. These information advantages cannot rationalize the aforementioned facts, therefore those features are assumed away for simplicity.

4.2. Robustness Checks

4.2.1. An Alternative Taylor Rule. The estimation results discussed above are based on a Taylor rule that responds to the efficient real interest rate. While keeping track of the efficient real rate is optimal, it is less clear how the central bank constructs the efficient real rate in practice. A more realistic assumption is to assume a monetary rule in which the central bank reacts to macroeconomic variables, such as current and expected inflation and output growth. In fact, Romer and Romer (2004) construct monetary shocks based on the assumption that the Fed reacts to current inflation and Real GDP growth as well as the Fed's internal forecasts of those variables. This section conducts a robustness exercise based on a rule of this type. In particular, I assume that the central bank reacts to inflation and expected real GDP growth:

$$\hat{i}_t = \rho_m \hat{i}_{t-1} + (1 - \rho_m)(\varphi_\pi \hat{\pi}_t + \varphi_y E^{Fed}(y_{t+1} - y_t) + \varepsilon_t^m), \quad (15)$$

where $E^{Fed}(y_{t+1} - y_t)$ denotes the Fed's internal forecast of real GDP growth in the next quarter. In practice, those are the FOMC staff's internal forecasts contained in the Greenbook, which is only available to the public with a lag of five years. Thus, according to this rule, the central bank reacts to its private information: the expected real GDP growth, which in turn depends on the underlying unobserved trend shock. Therefore policy action provides a signal regarding g_t .

The model with this alternative Taylor rule is estimated separately. Figure (B.5) plots the predictions of the model. Similar to the baseline, monetary shocks have significant impacts on long-term yield. And contractionary monetary shocks have expansionary impacts on private agents' real GDP expectations.

4.2.2. Persistent Monetary Shocks. Central banks might have only a vague knowledge about the long-run economic fundamentals in the real world. As a result, the monetary shocks can be partially driven by measurement errors made by the central bank in tracking the efficient rate. These measurement errors about the long-run dynamics are likely to be persistent. Consequently, monetary policy shocks can be persistent, too. To address this concern, I re-estimate the model allowing for persistent monetary shocks. Specifically, I assume that the exogenous deviation term ε_t^m in equation (7) follows the process: $\varepsilon_t^m = \rho_\varepsilon \varepsilon_{t-1}^m + e_t^m$ with $e_t^m \sim i.i.d N(0, \sigma_m^2)$.

Figure (B.6) shows that the baseline results are robust to this alternative specification. Monetary shocks have significant impacts on long-term yield. Moreover, contractionary monetary shocks have expansionary impacts on private agents' real GDP forecasts.

4.2.3. Replicating Empirical Facts using Simulated Data. Previously, the impacts of monetary shocks on the yield curve and real GDP forecasts are

derived using the state representation of the model. Thus, those are the exact responses of endogenous variables to exogenous monetary shocks. However, this is not the case in the empirical framework. In this section, I construct the model-implied impacts of monetary shocks closely following the empirical framework discussed in section (2).

To this end, I simulate the following variables: monetary surprises, R&R monetary shocks, yields with different maturities, real GDP forecast revisions and the central bank's internal forecasts of real GDP and inflation. Note that R&R monetary shocks are constructed as the residuals from projecting the monetary instrument on the current real GDP, Inflation, the central bank's forecast of real GDP and inflation, and the lagged short-term interest rate.

I construct the model-implied empirical evidence by estimating the empirical frameworks discussed in section (2) using those simulated variables. Figure (B.7) plots the simulated results by estimating regressions of the form (1) using monetary surprises as the instrumental variable and the central bank's forecast of real GDP and inflation as control variables. I simulate the model 10 000 times for 160 periods each (same as the empirical sample size). In each simulation, parameters of the model are drawn randomly from posterior parameters' distributions. The circles in Figure (B.7) report the simulated impacts of monetary shocks on the yield curve using the median of the posterior parameters' distributions and the lines plot the 95% probability intervals constructed based on posterior parameters' distributions. Similarly, Figure (B.8) plots the simulated results by estimating regressions of the form (2).

As one can see from Figure (B.7) and Figure (B.8), the model is capable of replicating the two empirical facts discussed in section (2): monetary shocks affect interest rates at long horizons and the private sector's real GDP forecasts are revised upward in response to a monetary tightening.

5. Conclusion

I have provided a micro-founded model based on the signaling channel of monetary policy that rationalizes: first, monetary policy shocks have an impact on interest rates at long horizons (10 years or more) and second, a contractionary monetary policy has an expansionary effect on agents' forecasts of real GDP. In the framework, the central bank holds superior information about future economic conditions. Policy actions partially reveal that information to the public, and thus the model is capable of generating the aforementioned facts. In the presence of the signaling channel, the impacts of monetary shocks on output and inflation are mitigated.

There are three lessons to be learned from this paper. First, in a world where the central bank has private information, the HFI monetary surprises are not necessary monetary shocks, and the former are subject to the confounding

problem. Thus, researchers, who are interested in identifying the impacts of monetary shocks using HFI monetary surprises, should clean those measures beforehand. Second, a deviation from the monetary policy rule that intends to stimulate real GDP may not be fruitful. In particular, an exogenous drop in the monetary instrument may have a limited impact on real GDP due to the presence of the signaling channel. Third, the degree of money non-neutrality that is estimated using a standard DSGE model might be biased if the true DGP features the information asymmetry among the central bank and the private market.

The signaling channel of monetary policy relies on i) the degree of uncertainty in the private market, and ii) the amount of private information that the central bank holds. Regarding the first, Falck et al. (2017) find that in periods when the private market is more uncertain, the signaling channel as emphasized by Melosi (2017) is more pronounced. Regarding the second, we have witnessed increased central bank transparency in recent decades. It might have improved the Fed's communication of its private information about future economic conditions, which in turn weakens the signaling channel of monetary policy and enhance the effectiveness of a monetary shock. Both the existence and the quantitative importance of such a change is a relevant and interest question that I reserve for future research.

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Appendix A: Table

TABLE A.1. Prior and Posterior: Remaining Parameters

	Priors			Asymmetric Information		Perfect Information	
	Mean	s.d	Distribution	Mean	s.d	Mean	s.d
σ_π	4×10^{-3}	4	InvGamma	2.5×10^{-3}	0.2×10^{-3}	3.0×10^{-3}	0.3×10^{-3}
σ_d	4×10^{-3}	4	InvGamma	1.3×10^{-2}	0.3×10^{-2}	3.8×10^{-2}	0.4×10^{-2}
σ_{y2}^e	4×10^{-3}	4	InvGamma	5.8×10^{-5}	4.4×10^{-5}	7.3×10^{-5}	5.5×10^{-5}
σ_{y5}^e	4×10^{-3}	4	InvGamma	4.3×10^{-5}	3.2×10^{-5}	6.1×10^{-5}	4.6×10^{-5}
σ_{y10}^e	4×10^{-3}	4	InvGamma	6.8×10^{-4}	4.7×10^{-5}	2.0×10^{-4}	4.8×10^{-5}
g^*	0.5×10^{-2}	0.5×10^{-2}	Gamma	0.4×10^{-2}	0.7×10^{-3}	0.4×10^{-2}	6.5×10^{-4}
π^*	0.5×10^{-2}	0.5×10^{-2}	Gamma	0.6×10^{-2}	0.4×10^{-3}	0.6×10^{-2}	0.3×10^{-3}
β	0.99	0.01	Beta	0.99	0.01	0.99	0.01
k	0.3	0.1	Beta	0.11	0.04	0.38	0.11
ω	0.3	0.1	Beta	0.34	0.08	0.32	0.08
ρ_g	0.5	0.2	Beta	0.98	0.003	0.99	0.3×10^{-3}
ρ_m	0.5	0.2	Beta	0.77	0.02	0.80	0.03
ρ_d	0.5	0.2	Beta	0.89	0.02	0.94	0.01
φ_π	1.5	0.25	Gamma	1.09	0.05	1.6	0.15
φ_y	0.25	0.05	Gamma	0.36	0.06	0.32	0.06
φ_r	1	0.05	Gamma	0.90	0.02	0.97	0.03

Note: Posterior means and standard deviations are estimated by Random Walk Metropolis-Hasting algorithm

Appendix B: Figures

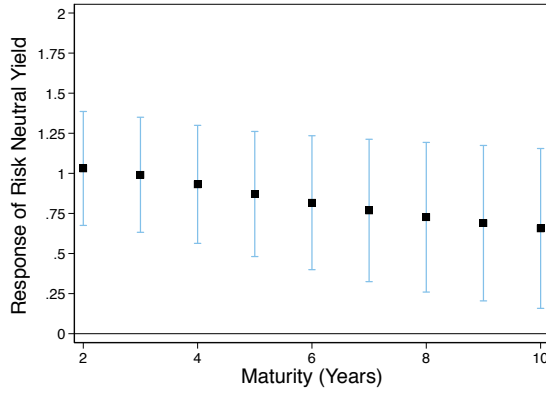


FIGURE B.1. This figure plots the impact effects of monetary shocks on risk-neutral measures of nominal yields. The square dots represent the estimated $\hat{\beta}^h$ from separated regressions: $Y_{t+1d}^h - Y_{t-1d}^h = \alpha^h + \beta^h \Delta MP_t + \gamma^h X_t + \varepsilon_{h,t}$ using HFI monetary surprises as instruments for the variable of interest ΔMP_t . Y_t^h are risk-neutral measures of nominal interest rates. The blue lines are the 95% confidence interval constructed using standard errors that are robust to serial correlation and heteroskedasticity. Sample: 1990M2 to 2012M12.

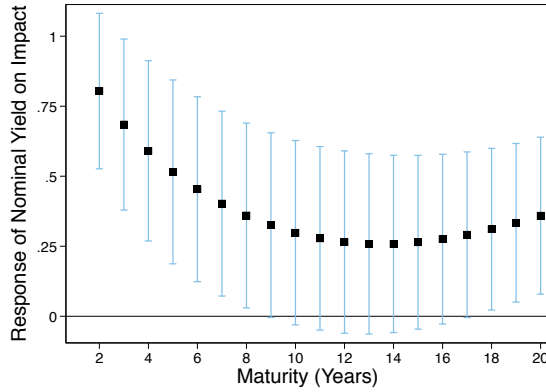


FIGURE B.2. This figure plots the impact effects of monetary policy on nominal yields, using R&R monetary policy shocks as instruments. The figure reports the results from estimating the following regressions: $Y_t^h = \alpha^h + \beta^h MP_t + \gamma^h X_t + \varepsilon_{h,t}$, where MP_t denotes the monetary instrument, three-month treasury bill rate which is instrumented by R&R Monetary Shocks. The blue lines are the 90% confidence interval constructed using standard errors that are robust to serial correlation and heteroskedasticity. Sample: 1969M1 to 2007M12.

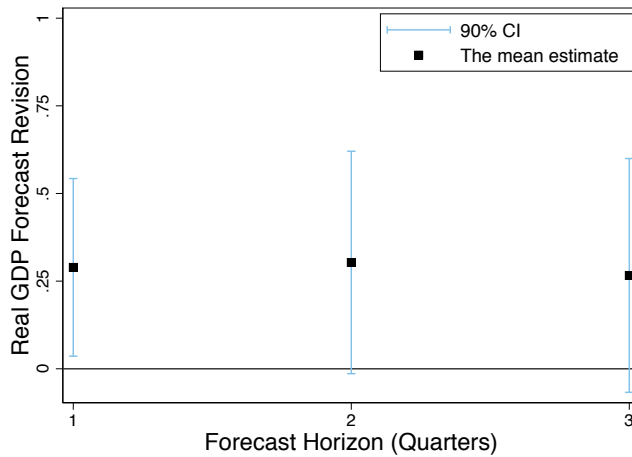


FIGURE B.3. This figure depicts the impact effects of monetary policy on real GDP forecast revisions, using R&R monetary policy shocks as instruments. The figure reports the results from estimating the baseline regressions: $y_{t+j|t} - y_{t+j|t-1} = \alpha^j + \beta^j MP_t + \gamma^j X_t + v_{j,t}$ using R&R monetary shocks as instruments for MP_t . The blue lines are the 90% confidence interval constructed using standard errors that are robust to serial correlation and heteroskedasticity. Sample: 1969Q1 to 2007Q4.

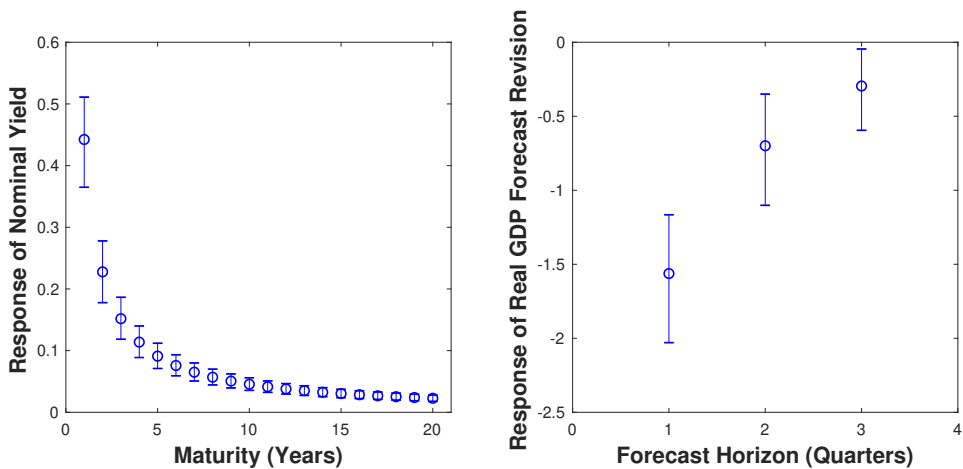


FIGURE B.4. This figure depicts the impact effects of monetary shocks on nominal yield at different maturities and real GDP forecast revisions at different horizons predicted by a standard NK model with perfect information. The circles and intervals are the mean estimates and 95% confidence intervals constructed based on posterior parameters' distributions.

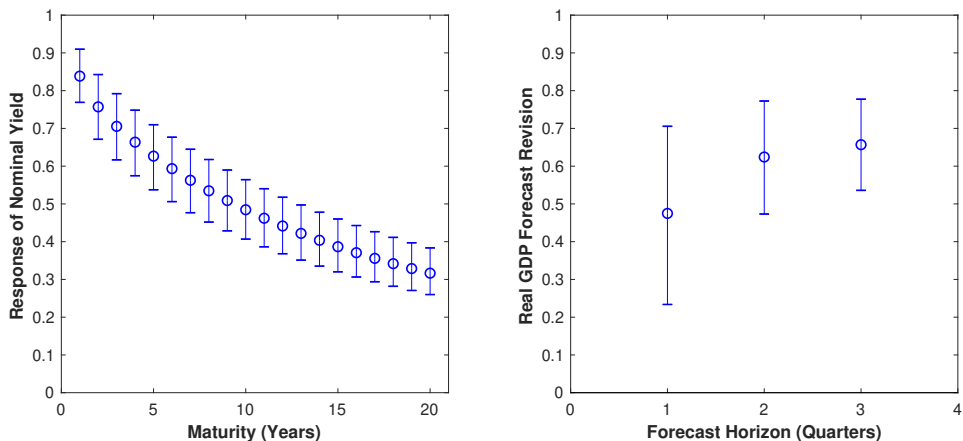


FIGURE B.5. Robustness Check: an Alternative Taylor rule. This figure depicts the impact effects of monetary shocks on nominal yield at different maturities and real GDP forecast revisions at different horizons predicted by the model. The circles and intervals are the mean estimates and 95% confidence intervals constructed based on posterior parameters' distributions.

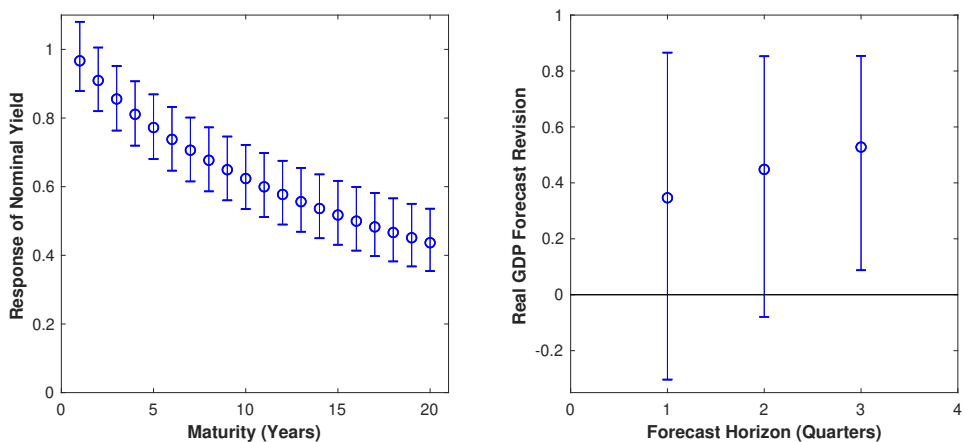


FIGURE B.6. Robustness Check: Persistent Monetary Shocks. This figure depicts the impact effects of monetary shocks on nominal yield at different maturities and real GDP forecast revisions at different horizons predicted by the model. The circles and intervals are the mean estimates and 95% confidence intervals constructed based on posterior parameters' distributions.

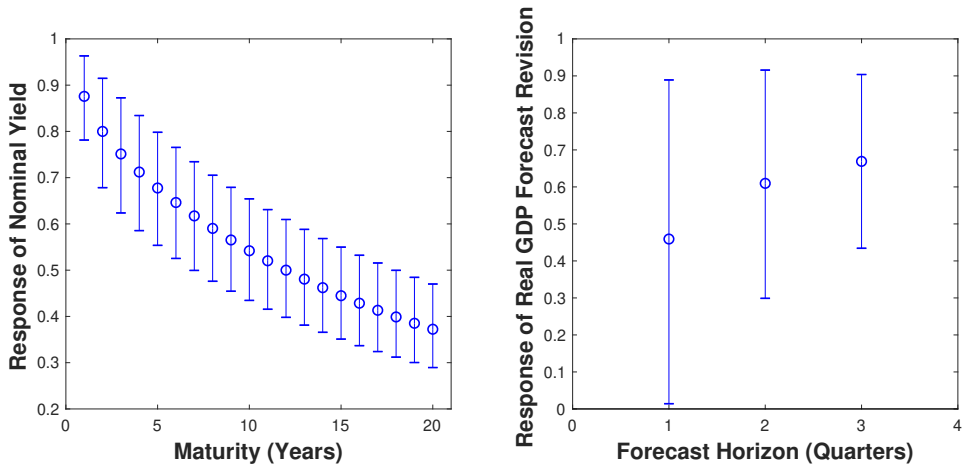


FIGURE B.7. Robustness Check: Simulated Responses using the HFI Approach. This figure depicts the impact effects of monetary shocks on nominal yield at different maturities and real GDP forecast revisions at different horizons predicted by the model. The circles and intervals are the mean estimates and 95% confidence intervals constructed based on posterior parameters' distributions.

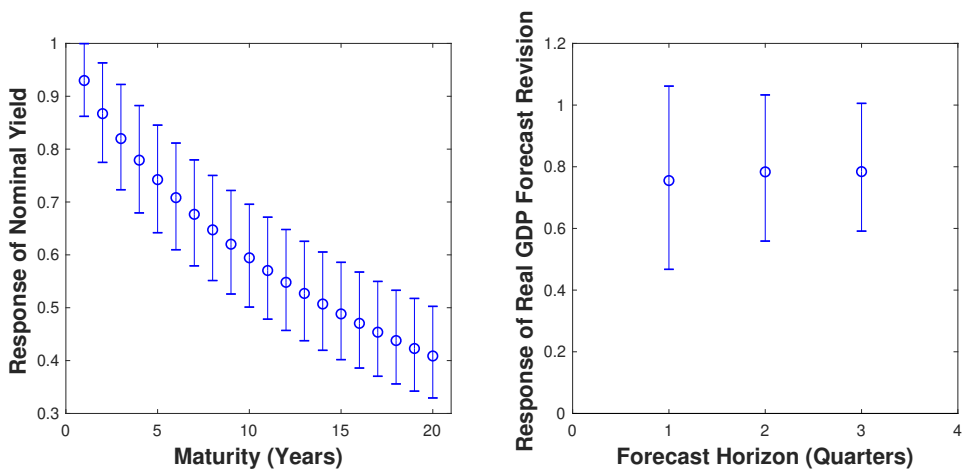


FIGURE B.8. Robustness Check: Simulated Responses using the R&R Approach. This figure depicts the impact effects of monetary shocks on nominal yield at different maturities and real GDP forecast revisions at different horizons predicted by the model. The circles and intervals are the mean estimates and 95% confidence intervals constructed based on posterior parameters' distributions.

Appendix C: Term structure

This section describes the term structure implied by the model. Following Bekaert et al. (2010) and Nimark (2008), yields of different maturities are

derived based on the following four equations together with the assumption that shocks are normal. The first equation characterizes the short-run yield, which is basically the monetary policy rule:

$$i_t = M_I X_t \quad (\text{C.1})$$

The second equation relates yields at different maturities with corresponding prices:

$$i_t^n = -\frac{1}{n} \log(P_t^n) \quad (\text{C.2})$$

In the third equation, I assume that there is no arbitrage condition:

$$P_t^{n+1} = E_t(M_{t+1} P_{t+1}^n) \quad (\text{C.3})$$

The fourth equation derives the stochastic discount factor from consumers' optimization problem:

$$M_{t+1}^n = \beta \frac{\Lambda_{t+1} P_t}{\Lambda_t P_{t+1}} \quad (\text{C.4})$$

Combining these equations one can write the yields in terms of state variable X_t as:

$$\begin{bmatrix} i_t \\ i_t^2 \\ \cdot \\ \cdot \\ i_t^n \end{bmatrix} = \begin{bmatrix} -A_1 \\ -\frac{1}{2}A_2 \\ \cdot \\ \cdot \\ -\frac{1}{n}A_n \end{bmatrix} + \begin{bmatrix} -B_1 \\ -\frac{1}{2}B_2 \\ \cdot \\ \cdot \\ -\frac{1}{n}B_n \end{bmatrix} X_t \quad (\text{C.5})$$

where i_t^n denotes the yield with maturity n at time t . A_n and B_n are derived recursively in Online Appendix. There are three key features that are absent in the previous literature. First in this model, agents' belief about trend $\hat{g}_{t|t}$ enters as a state variable and therefore affects the whole yield curve. Second, monetary policy acts as one of the signals, and as a consequence, monetary surprises affect the long end of the yield through their effects on $\hat{g}_{t|t}$ that standard models cannot capture. And third, if the process for g_t is highly persistent, which is verified in our estimation exercise shown later in this paper, current shocks would affect the yield curve at long horizons.