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*To My Family*

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# Abstract

### Essays on Monetary Policy

In a standard New Keynesian model, the central bank moves the real rate when it changes the nominal interest rate since the price level responds sluggishly to change in nominal rates due to nominal rigidity. Monetary policy is non-neutral, for it moves the real rate, thus alters agents' intertemporal consumption decisions. The standard model is a simplified world without information frictions or regional heterogeneity. In a world with information frictions, monetary policy actions communicate to the public about the central bank's private information. Monetary policy can generate additional effects by shaping agents' beliefs about the true state of the economy or the future monetary policy path. In a world with regional heterogeneity, monetary policy can have interesting interactions with local characteristics. This dissertation investigates regime-dependent, state-dependent, and heterogeneous regional effects of monetary policy.

Chapter 1 introduces a new regime dependence of monetary policy due to information frictions: the effects of monetary policy shocks depend on the type of the fundamental macro shock in the economy. Specifically, output responses to monetary policy shocks are amplified relative to their counterparts in perfect information models when the fundamental macro shock is a productivity level shock or a demand shock. In contrast, output responses are dampened when the fundamental macro shock is a productivity growth rate shock. Households observe the overall fundamental in the economy but cannot distinguish its persistent part from its temporary part. The central bank sets the interest rate tracking a function of the persistent fundamental plus a monetary policy shock, so the interest rate is a noisy signal about the persistent fundamental with the monetary policy shock as the noise. Exogenous monetary policy shocks lead households to update their perceptions about the persistent fundamental differently facing varying types of fundamental macro shocks, thus generating heterogeneous effects on output.

Chapter 2 introduces the position effect: the effects of a monetary policy shock depend on its relative position in the monetary policy sequence. I use both event study and local projections methods to investigate how the effects of monetary policy depend on the relative position of monetary policy shocks in monetary policy sequences. The effects of monetary policy are less potent in the first half of monetary policy sequences, which I phrase as the position effect. Possible explanations include different implicit forward guidance, different information effects, and Fed's different interest rate smoothing behavior at different positions in the monetary policy sequence. I provide supporting evidence for the interest rate smoothing behavior: less interest rate smoothing in the first half of a monetary policy sequence shortens the shock duration, thus weakening the effect.

Chapter 3, joint work with Ninghui Li, investigates the regional heterogeneity of monetary policy on local house prices. House prices in growing urban areas are more sensitive to monetary policy. We first define urban growth and urban decline using CBSA level population data and then test local house prices to monetary policy shocks using local projections. The housing supply elasticity does not drive our results, although it plays a role in house price dynamics. We find evidence supporting that the effect of monetary policy interacts with the long-run expectations driven by local population growth.

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# Chapter 1

# Signaling Role of Monetary Policy Shocks

> *A given [monetary] policy action. . . can have very different effects on the economy, depending (for example) on what the private sector infers from that action about likely future policy actions,* ***about the information that may have induced the policymaker to act****, about the policymaker's objectives in taking the action, and so on.*
>
> Bernanke (2003)

## 1.1 Introduction

Do policy interventions by the central bank always have the same effects? If the answer is a yes, central bankers can back-engineer the policy interventions needed for certain policy targets. If the answer is a no, central bankers need to carefully evaluate all states that can influence the effectiveness of monetary policy before policy decisions. Unfortunately for central bankers, the answer to this question may be a no. Existing literature provides both theoretical and empirical support for different types of state-dependent monetary policy. For example, the effects of monetary policy can depend on the distribution of savings from refinancing mortgages, the sign of monetary policy shocks, and whether the economy is in an expansion or a recession.[1] This paper adds a new type of regime dependence into the literature: the effects of policy interventions can depend on the type of the fundamental macro shock[2] in the presence of information frictions.[3]

Information frictions may have important implications for monetary policy effects, as is evidenced by the Bernanke quote. Information about future policy actions and policymakers' objectives can influence the effects of monetary policy actions. In this paper, I focus on *variation in the information that may have induced the policymaker to act*. The central bank is sometimes countering a demand shock, sometimes a productivity shock. Suppose the central bank is raising the policy rate upon observing a positive demand shock, and it should raise the policy rate by 20 basis points based on the observed size of the demand shock. However, suppose the central bank raises the policy rate by 25 basis points instead. The extra five basis points reflect that the central bank intends to counter the demand shock more aggressively for the current period. Households have no idea about the decomposition of the 25 basis points increase in interest rate. However, they know that it reflects a combination of an endogenous reaction to the demand shock and an exogenous monetary policy shock. They update their perceptions of the demand condition after observing the 25 basis-points movement. This perception revision affects output. When the central bank is countering a different fundamental shock, do the extra five basis points generate the same effects?

To answer this question, I construct a unified framework with multiple regimes and focus on the cross-regime comparison. The unified framework is a New Keynesian model with information frictions in which the interest rate signals the information known by the central bank to the private sector. The interest rate signaling the central bank's private information distinguishes this paper from the literature on Fed information effect where the central bank

[1] Eichenbaum et al. (2018): the distribution of savings from refinancing mortgages, Angrist et al. (2018): the sign of monetary policy shock, Tenreyro & Thwaites (2016): expansions or recessions, Alpanda et al. (2019): the interest rates cycle and credit cycle.

[2] The fundamental macro shocks in this paper are shocks that drive macroeconomic fluctuations but are not policy shocks.

[3] There is a slight difference between regime dependence and state dependence. Regime dependence emphasizes the differences between several parallel economies, while state dependence emphasizes differences between different states within the same economy.

sends out information through FOMC (Federal Open Market Committee) announcements (e.g. Romer & Romer (2000), Gürkaynak et al. (2005)). The only difference across the three regimes is the type of the fundamental macro shock: I consider a productivity level shock, a demand shock (discount factor), and a productivity growth rate shock.[4] Households are assumed to know the fundamental shock type in the economy but do not know how persistent it will be. A more realistic assumption might be that households are not sure about the type of fundamental shock in the economy. Under the latter assumption the general results should be a combination of the extreme cases I investigate here.[5]

Cross-regime comparison shows that monetary policy shocks can generate different effects: output responses are amplified when the underlying macro shock is a productivity level shock or a demand shock. On the contrary, output responses are dampened when the underlying macro shock is a productivity growth rate shock. This is different from Nakamura & Steinsson (2018) where the signaling role of monetary policy shocks has a uniform effect by assumption.[6] Importantly, "amplified" and "dampened" are relative to the traditional effects of monetary policy shocks in perfect information models. A positive exogenous monetary policy shock increases the real interest rate due to nominal rigidity,[7] and the increase in the real rate will decrease households' current consumption. Besides the traditional effects, monetary policy shocks in my model have additional effects through shaping households' perceptions about the underlying fundamental shock in the presence of information frictions. When the additional effects further decrease output, we say the effects are amplified. When the additional effects increase output, partially offsetting the traditional effects, we say the effects are dampened.

[4]A productivity level shock means a transitory but persistent movement in the log level of productivity while the growth rate shock means a transitory but persistent movement in the first difference of the log level.

[5]Due to the signal-extraction problem, the uncertain case will not be a simple linear combination of extreme cases here.

[6]The output gap and inflation responses are dampened in their model. The output gap and inflation responses depend on the future path of real rate gaps (real interest rate minus real natural rate). The same monetary policy shock moves the real rate gaps less than its counterpart in perfect information models, thus generating dampened effects.

[7]Inflation response is less than the change in the nominal interest rate.

The model in each regime is a New Keynesian model with information frictions based on Lorenzoni (2009). It has several ingredients. First, households observe the fundamental but cannot distinguish a persistent part from a temporary part. Households' expectations about future fundamental depend only on the persistent part because the temporary parts at different periods are independent of each other. Second, the central bank correctly observes the persistent part of the fundamental and sets the interest rate tracking a function of the persistent fundamental plus a monetary policy shock.[8] Depending on regimes, the central bank tracks a positive function of the persistent productivity growth rate and the persistent demand level, but a negative function of the persistent productivity level.[9] Households know the rule by which the central bank sets the interest rate, but they do not know the size of the monetary policy shock. Monetary policy shocks are assumed to be independent across time. If they know the size of the monetary policy shock, they can infer the persistent fundamental perfectly from the interest rate movement.

Under this setting, the interest rate serves as a noisy signal from which households can extract information about the persistent fundamental, while the monetary policy shock functions as the noise. Exogenous monetary policy shocks will lead households to overestimate or underestimate the persistent fundamental depending on regimes. The informational role of the monetary policy shock is similar to a noise shock in the business cycle literature (Lorenzoni (2009)), as they both generate overestimates or underestimates of the persistent fundamental. However, Lorenzoni (2009) focuses on how noise shocks around permanent productivity generate a demand shock. In contrast, I focus on a new regime-dependence of monetary policy arising from the fact that monetary policy shocks are noise around varying macro fundamentals in different regimes.[10]

The key mechanism behind the results works through the household's consumption de-

[8]One possible reason for this monetary policy shock is measurement error on the central bank's side. See Orphanides (2003).

[9]The detailed justification for this monetary policy rule is in Section 1.2. In short, the central bank is tracking a variation of the natural real interest rate.

[10]Investigating effects of noise shocks around a different fundamental is interesting by itself. For example, Benhima & Poilly (2020).

cision.[11] This is different from the literature on the signaling role of monetary policy which focuses on firms' price-setting behavior and hump-shaped inflation responses such as Melosi (2017), Berkelmans (2011), and Falck et al. (2019).

The different effects arise from the fact that households interpret the same monetary policy shock as containing different information in different regimes. In the productivity level shock regime, the central bank sets the interest rate tracking a negative function of the persistent productivity (the persistent part of productivity) plus a monetary policy shock. When there is a positive exogenous monetary policy shock, what households observe is an increase in the interest rate. Households do not know if the interest rate movement is purely caused by an exogenous monetary policy shock. They attribute this interest rate increase partially to the fact that the central bank observes a much lower persistent productivity than they do. Since the households know that the central bank observes perfectly the persistent productivity, they revise downward their perceptions of the persistent productivity and their expectations of future productivity. This belief updating leads to a negative output response since current consumption depends positively on expected future productivity.

In the regime of productivity growth rate shock, the central bank tracks a positive function of the persistent productivity growth rate. A positive exogenous monetary policy shock now leads to an upward revision in perceptions of the productivity growth rate, thus increasing output. As for the demand shock regime where the central bank tracks a positive function of the persistent demand condition, a positive exogenous monetary policy shock leads households to revise upward their perceptions about the persistent demand and expectations of future demand. Output decreases because higher expected future demand leads to lower current consumption since households save more for consumption next period.

**Related literature.** This paper adds a new type of regime dependence into the state-

[11] Generally, current consumption depends negatively on the real rate, negatively on future discount factor and positively on future income. The real rate is the relative price of today's consumption to tomorrow's consumption. Thus, a higher real rate leads to lower consumption today. If households expect the discount factor to be higher tomorrow relative to today, they want to save more for tomorrow's consumption. Future productivity determines the future income, and higher future income leads to higher consumption today.

dependent monetary policy literature. Tenreyro & Thwaites (2016), Angrist et al. (2018), Eichenbaum et al. (2018), and Alpanda et al. (2019) introduce different types of state dependence, but none of these papers considers information frictions. Falck et al. (2019) is an exception. They investigate monetary policy effects depending on disagreements about inflation expectation, but they focus firm side information frictions and firms' price-setting behavior.

This paper is closely related to the literature about the signaling role of monetary policy. The existing literature either focuses on one type of fundamental macro shock or assumes a homogenous effect of the signaling role to explain certain empirical findings (e.g., the price puzzle, hump-shaped inflation responses, and long-end real term structure responses.). This literature includes Berkelmans (2011), Zhang (2017), and Nakamura & Steinsson (2018). I introduce multiple regimes to capture the time-varying effects of monetary policy shocks across different historical periods. While Melosi (2017) and Berkelmans (2011) focus on inflation dynamics and firms' price-setting behavior with information frictions, I instead focus on information frictions on the households side. Baeriswyl & Cornand (2010) and Tang (2013) focus on optimal monetary policy with information frictions but in different settings to this paper. However, optimal monetary policy is beyond the scope of this paper. The central bank, in my setting, tracks a specific function of the persistent fundamental with inflation targeting.

This paper is also related to the literature on the Fed information effect. Empirical literature on the Fed information effect includes the seminal work Romer & Romer (2000), following by Gürkaynak et al. (2005), Nakamura & Steinsson (2018), and Jarociński & Karadi (2020). Papers on the theoretical side include Cukierman & Meltzer (1986) and Ellingsen & Soderstrom (2001).

Since the monetary policy shock has a noise role in this paper, it is also related to the literature about the role of news and noise in business cycles (Lorenzoni (2009), Barsky & Sims (2012) , Blanchard et al. (2013), among others).

The structure of the paper goes as follows: In Section 1.2, I show the general setup, solve the solutions analytically, and analyze the effects of exogenous shocks under different regimes. Section 1.3 compares the different effects of monetary policy shocks across regimes on endogenous variables. Section 1.4 discusses monetary policy shocks' noise role, and the relation between interest rate surprises and monetary policy shocks in this paper. Section 1.5 concludes.

## 1.2 A New Keynesian Model with Information Frictions

This section lays out micro-foundations for the New Keynesian model à la Woodford (2011) and Galí (2015) with information frictions. The innovation is the information structure included: expectation terms in the optimization problem now depend on the information the private sector and the central bank have when making decisions. The information structure is a variation of Lorenzoni (2009) to allow the interest rate to carry information about the fundamental macro shocks in the economy. The focus is on the effects of monetary policy shocks when the interest rate serves as a noisy signal. To be specific, there are persistent and temporary parts of the fundamental that households cannot distinguish. The central bank sets the interest rate according to the persistent fundamental plus a monetary policy shock. The households extract information from the interest rate about persistent fundamentals. The monetary policy shock serves as *noise* to prevent the households from learning fully the persistent fundamental. It also has traditional effects on output and inflation, as it has in the perfection information model. Section 1.2.1 builds the common framework shared by different regimes. Sections 1.2.2-1.2.4 show the analysis for different regimes, respectively.

### 1.2.1 The Model

**Households**

The representative household seeks to maximize their utility given by

$$E_0 \sum_{t=0}^{\infty} \beta^t [U(C_t, N_t)]$$

where $\beta$ denotes the household's subjective discount factor, $C_t$ denotes household consumption of a composite consumption good, and $N_t$ denotes hours of work or employment. The specific period utility form is given by:

$$U(C_t, N_t, Z_t) = \left( \frac{C_t^{1-\sigma}}{1-\sigma} - \frac{N_t^{1+\varphi}}{1+\varphi} \right) Z_t$$

where $\sigma \geq 0$ and $\varphi \geq 0$ determine, respectively, the curvature of the utility of consumption and the disutility of labor. Later in the discussion, I set $\sigma = 1$ to use log utility for simplicity and then discuss the implications of $\sigma \neq 1$. The composite consumption good in the following expression is an index given by:

$$C_t = \left[ \int_0^1 (C_t(i))^{\frac{\epsilon-1}{\epsilon}} di \right]^{\frac{\epsilon}{\epsilon-1}}$$

with $C_t(i)$ denoting the quantity of variety $i$ consumed by the household. The parameter $\epsilon > 1$ denotes the elasticity of substitution between different varieties.

Households face a flow budget constraint given by

$$P_t C_t + Q_t B_t \leq B_{t-1} + W_t N_t + \Pi_t - T_t$$

where $P_t$ is a price index that gives the minimum price of a unit of the consumption good $C_t$, $B_t$ is the government bond the households hold at $t$ and delivers unit consumption at $t+1$, $Q_t$ is the price of the bond in period $t$, $W_t$ denotes the wage rate received by households in period $t$, $\Pi_t$ denotes all the profits of firms in period $t$, and $T_t$ is a lump-sum tax levied by the government. To rule out Ponzi schemes, household debt cannot exceed the present value of future income in any state of the world.

Households face a decision in each period about how much to spend on consumption, how many hours of labor to supply, how much to consume of each differentiated good produced in the economy and what portfolio of assets to purchase. Optimal choice regarding the trade-off between current consumption and consumption in different states in the future yields the following consumption Euler equation:

$$Q_t = \beta E_t \left[ (\frac{C_{t+1}}{C_t})^{-\sigma} \frac{P_t}{P_{t+1}} \frac{Z_{t+1}}{Z_t} \right]$$

as well as a standard transversality condition. Optimal choice regarding the intratemporal trade-off between current consumption and current labor supply yields a labor supply equation:

$$\frac{W_t}{P_t} = C_t^{\sigma} N_t^{\varphi}$$

Households optimally choose to minimize the cost of attaining the level of consumption $C_t$. This implies the following demand curves for each of the differentiated products produced in the economy

$$c_t(i) = \left( \frac{p_t(i)}{P_t} \right)^{-\epsilon} C_t$$

where $p_t(i)$ denotes the price of variety $i$ and

$$P_t = \left[ \int_0^1 (p_t(i))^{1-\theta} di \right]^{\frac{1}{1-\theta}}$$

**Firms**

A large number of identical firms are assumed to operate in the economy, producing a homogeneous consumption good. The representative firm's productivity is described by the production function:

$$Y_t(i) = A_t N_t(i)$$

where $A_t$ denotes aggregate productivity. Firm can re-optimize its price with probability $1-\theta$ as in Calvo (1983). With probability $\theta$, it must keep its price unchanged. Firm $i$ sets the price to $P_t^*$ to maximize its value,

$$max\{P_t^*\} : \sum_{k=0}^{\infty} \theta^k E_t \Lambda_{t,t+k} \frac{1}{P_{t+k}} \left( P_t^* Y_{t+k|t} - \Phi_{t+k}(Y_{t+k|t}) \right)$$

subject to the following constraint:

$$Y_{t+k|t} = (\frac{P_t^*}{P_{t+k}})^{-\epsilon} C_{t+k}$$

Then the aggregate price level evolves as:

$$P_t = \left[ (1-\theta)(P_t^*)^{1-\epsilon} + \theta P_{t-1}^{1-\epsilon} \right]^{\frac{1}{1-\epsilon}}$$

**Equilibrium Conditions**

The equilibrium conditions include three equations. The first equation links the current output with expected future output, the demand condition and the real interest rate (the IS curve). The second equation links current inflation with expected future inflation and current output (the Phillips Curve). And the third equation depicts monetary policy rule. These are the same three equations in perfect information New Keynesian models. The additional layer in this setting is that the central bank has perfect information and the private sector (households and firms share the same information set) has imperfect information. Now the interest rate set by the central bank not only moves the real rate but also has a direct effect on households' consumption decisions through affecting households' perceptions about the state of the economy.

Log-linearization of the Euler equation combining with the goods market-clearing condition delivers the IS curve:

$$y_t = E_t[y_{t+1}] - \frac{1}{\sigma}E_t[(i_t - \pi_{t+1} - \rho + (z_{t+1} - z_t))]$$

After log-linearization, the small letter denotes the log level for output, discount factor, and productivity. $\pi_t$ and $i_t$ are in levels. It shows that output positively depends on future output, negatively on the real rate and the expected expansion of demand conditions. All else equal, an expected stronger future demand decreases current consumption.

Log-linearization of the representative firm's profit maximization problem delivers the Phillips Curve:

$$\pi_t = \beta E_t[\pi_{t+1}] + \kappa(y_t - y_t^n)$$

where $\kappa \equiv \frac{(1-\theta)(1-\beta\theta)}{\theta}(\sigma + \varphi)$ and $y_t^n = \frac{1+\varphi}{\sigma+\varphi}a_t + \frac{1}{\sigma+\varphi}\mu$. It indicates that current inflation depends positively on inflation expectations, and the gap between current output and potential output.

Rewriting these two equations in the output gap form and ignoring the constant term:[12]

$$\tilde{y}_t = E_t[\tilde{y}_{t+1}] - \frac{1}{\sigma}E_t[i_t - \pi_{t+1} - ((z_t - z_{t+1}) + \frac{\sigma(1+\varphi)}{\sigma+\varphi}(a_{t+1} - a_t))]$$

$$\pi_t = \beta E_t[\pi_{t+1}] + \kappa\tilde{y}_t$$

where $\tilde{y}_t = y_t - y_t^n$. Define

$$r_t^n = E_t(z_t - z_{t+1}) + \frac{\sigma(1+\varphi)}{\sigma+\varphi}E_t(a_{t+1} - a_t)$$

[12] We focus on impulse responses which are percentage deviations from the steady-state after shocks. The constant term will not affect impulse responses.

as the natural real interest rate.

Further set $\sigma = 1$ to rewrite the IS curve and the Phillips Curve in forms of the output gap:

$$\tilde{y}_t = E_t[\tilde{y}_{t+1}] - E_t[i_t - \pi_{t+1} - ((z_t - z_{t+1}) + (a_{t+1} - a_t))] \tag{1.1}$$

$$\pi_t = \beta E_t[\pi_{t+1}] + \kappa \tilde{y}_t \tag{1.2}$$

I set $\sigma = 1$ for simplicity. $\sigma = 1$ corresponds to the case when the utility function for the household is log utility. Later I will discuss the effect this assumption has on the results. The natural real interest rate is now:

$$r_t^n = E_t(z_t - z_{t+1}) + E_t(a_{t+1} - a_t)$$

If the central bank sets the interest rate according to:

$$i_t = r_t^n + \phi_\pi \pi_t$$

This policy rule closes the output gap and inflation at the same time in a perfect information model. Whether the expectation term is based on the central bank's information or households' information is irrelevant in the perfect information model since they share the same information set. However, in an imperfect information model, the natural real rate is different in the households' and the central bank's eyes.

The central bank sets interest rule as:

$$i_t = \tilde{r}_t^n + \phi_\pi \pi_t + m_t \tag{1.3}$$

It is an interest rate rule tracking a function of the persistent fundamental with inflation targeting. The inflation term here also ensures the determinacy. $m_t$ is the monetary policy shock. $\tilde{r}_t^n$ corresponds to the natural real rate, but with only the persistent part. For example, when there is only a productivity level shock in the economy, productivity consists of a persistent part $x_t$ and a temporary part $\eta_t$.

$$a_t = x_t + \eta_t$$

The persistent part evolves:

$$x_t = \rho_x x_{t-1} + \epsilon_t$$

The central bank has perfect information, so

$$r_t^n = E_{cb,t}(a_{t+1} - a_t) = \rho_x x_t - (x_t + \eta_t)$$

Instead of tracking $r_t^n$, the central bank tracks a substitute for the natural real rate without the temporary part:

$$\tilde{r}_t^n = \rho_x x_t - x_t$$

This can be justified by the argument that the central bank does not want too much variation in the interest rate. Particularly they want to avoid flipping the direction of monetary policy actions too frequently.[13] This assumption holds for all the regimes discussed below. And the households know that the central bank sets the interest rate following this rule. The optimal monetary policy itself deserves exploration in this setting, but it is beyond the scope of this paper. This paper mainly focuses on how the effects of monetary policy shocks can vary with the type of fundamental macro shocks in the economy.

[13] The alternative explanation for tracking a substitute for the natural real rate comes from a corresponding dispersed information model. The temporary part in my model corresponds to the idiosyncratic part in the dispersed information model, the persistent part corresponds to the aggregate part. Since the idiosyncratic part adds to zero, the central bank only responds to the aggregate part in dispersed information models.

**The timing of the model**

Every period consists of three stages. At stage 1: Fundamental shocks are realized, and then the central bank sets the interest rate after observing the realized shocks. At stage 2: Households make their consumption decisions after observing the overall fundamental (without its composition) and the interest rate set by the central bank. At stage 3: Firms produce, and the markets clear. The interest rate serves as a signal about the true state of the economy to the households. The monetary policy shock has an additional signaling role since it enters the interest rate blocking the households from learning the true state perfectly. Next, I will analyze these separate regimes to check the effects of exogenous shocks with a special interest in monetary policy shocks.

### 1.2.2 Only Productivity Level Shocks

Suppose there is only a productivity level shock, and no other fundamental shocks in the economy. This is trying to capture certain periods when the main shock in the economy is the productivity level shock and agents know this. Households will think monetary policy interventions are trying to respond to the productivity level shock. Productivity $a_t$ consists of a persistent part $x_{a,l,t}$ and a temporary part $\eta_{a,l,t}$:[14]

$$a_t = x_{a,l,t} + \eta_{a,l,t} \tag{1.4}$$

The persistent component evolves as:

$$x_{a,l,t} = \rho_{a,l,x} x_{a,l,t-1} + \epsilon_{a,l,t} \tag{1.5}$$

while $\eta_{a,l,t}$ is i.i.d. across time, normal, with zero mean and variance $\sigma_\eta^2$. Different explanations can justify the $\eta_{a,l,t}$ here. It could be measurement error about productivity levels (see

[14]The subscripts $a,l$ here refer to *productivity* and *level* respectively. They are there to distinguish the productivity level shock case from later cases about a productivity growth rate shock and a demand shock.

Bomfim (2001)). It could be also uncertainty around $x_{a,l,t}$ in a dispersed information model but without explicitly modeling dispersed information with idiosyncratic shocks.[15]

The central bank observes perfectly $x_{a,l,t}$ and $\eta_{a,l,t}$. And it tracks the natural real interest rate, but only the persistent part. The inflation targeting term here is to guarantee determinacy:

$$i_t = -(1-\rho_{a,l,x})x_{a,l,t} + m_t + \phi_\pi \tilde{\pi}_t$$

The interest rate is set at the beginning of the period when true inflation is not yet realized. The central bank announces the nowcast of inflation $\tilde{\pi}_t$ it uses.

$$\tilde{\pi}_t = \pi_t + \xi_t$$

where $\xi_t$ is the nowcast error. $m_t$ is the monetary policy shock, which is orthogonal to the fundamental. Households have no idea of how large $m_t$ should be.

Households observe perfectly the interest rate set by the central bank and the nowcast inflation $\tilde{\pi}_t$ is announced by the central bank, thus households observe a noisy public signal about the persistent part of the productivity shock with the monetary policy shock $m_t$ as the noise around it.[16]

$$s_t = i_t - \phi_\pi \tilde{\pi}_t = -(1-\rho_{a,l,x})x_{a,l,t} + m_t \tag{1.6}$$

The interest rate rule can be rewritten as:

$$i_t = s_t + \phi_\pi \tilde{\pi}_t \tag{1.7}$$

The key idea in this paper is to see the effect of interest rate signaling information about the fundamentals. The potentially large nowcast errors around inflation stop agents from extracting information about the productivity shock from inflation. This is a simplification

[15] Similar justification is used in Tang (2013) for a different question and setting.

[16] Public signal is in the sense that the information is from a public institution. The model itself does not incur any strategic considerations about a public signal or a private signal.

to make the solution analytical. The results go through if $\tilde{\pi}_t$ also provides agents information about the true state of the economy.

Now we need to solve the model. Plugging the interest rate rule into the Euler equation, the economy system ends up as two equations.
The Euler equation:

$$y_t = E_t y_{t+1} - E_t[s_t + \phi_\pi \tilde{\pi}_t - \pi_{t+1}] \tag{1.8}$$

The Phillips curve:

$$\pi_t = \beta E_t \pi_{t+1} + \kappa(y_t - a_t) \tag{1.9}$$

These two equations look the same as in perfect information models. However, the additional channel is working behind the scenes. A positive monetary policy shock $m_t$ will increase $s_t$ here, thus increasing the relative price of current consumption, reducing output. This is the only channel in a perfect information model for monetary policy shock. An additional role arises in the imperfect information model here. A positive monetary policy shock leads to an increase in $s_t$, but households do not see the reason for the increase in $s_t$. What they do know is that $s_t$ is a negative function of $x_{a,l,t}$ plus $m_t$. An increase in $s_t$ can be due to either an increase in $m_t$ or a decrease in $x_{a,l,t}$. They interpret the increase in $s_t$ as partially due to a much lower $x_{a,l,t}$ than they previously thought. As they lower their perceptions about current persistent productivity, they believe productivity for the next period will also be lower, so they tend to reduce their current consumption. The additional role of the monetary policy shock works through affecting $E_t y_{t+1}$ directly. In a perfect information model, the $E_t y_{t+1}$ term is substituted recursively and then current output depends on the future path of real rate gaps (the real rate minus the natural real rate) to infinite periods ahead. However, in my setting the interest rate tracks a variation of the natural real rate using only the persistent productivity. It will close the expected real rate gap; thus, current output does not depend on the future real rate gap at all. Instead, the expected future output depends on the expected future productivity level, which is affected by the monetary policy shock.

**Model solution for only productivity level shocks**

Since the expected future output depends on the expected future productivity, which again depends on the current persistent productivity, the solution will depend on the perception of current persistent productivity. This system of equations now involves a signal extraction problem about the persistent part of productivity. The key idea of the solution method is undetermined coefficients with a signal-extraction built in. The solution method is used in Blanchard et al. (2013), and the logic for the equations to solve this model is shown in the appendix. I first solve the system of equations ignoring the $\xi_t$ in $\tilde{\pi}_t = \pi_t + \xi_t$, i.e. I replace $\tilde{\pi}_t$ with $\pi_t$. After solving the equation system, I readjust the solution to take into account the $\xi_t$. And I then verify the correctness of the solution.

If the exogenous state evolves according to:

$$X_t = AX_{t-1} + Bv_t$$

The private sector observes:

$$S_t = CX_t + Du_t$$

Let $Y_t = (y_t, \pi_t)'$ be the vector of endogenous variables. Suppose the economic model can be described in terms of the stochastic difference equation:

$$FE_t[Y_{t+1}] + GY_t + HY_{t-1} + MS_t + NE_t[S_{t+1}] = 0$$

Suppose there is a unique stable solution of the model:

$$Y_t = PY_{t-1} + QS_t + RX_{t|t}$$

The matrices P, Q, R can be found by solving the following equations:

$$FP^2 + GP + H = 0; (FP + G)Q + M = 0; (FP + G)R + [F(QC + R) + NC]A = 0$$

For the case of a productivity level shock, set $X_t = (x_{a,l,t}, x_{a,l,t-1})'$, $v_t = (\epsilon_{a,l,t}, 0)'$, $S_t = (a_t, s_t)'$ and $u_t = (\eta_{a,l,t}, m_t)'$. $S_t$ is a vector of signals while $s_t$ is the signal from the interest rate. So the matrices related with the states and signals are:

$$A = \begin{bmatrix} \rho_{a,l,x} & 0 \\ 1 & 0 \end{bmatrix}, B = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} C = \begin{bmatrix} 1 & 0 \\ -(1-\rho_{a,l,x}) & 0 \end{bmatrix}, D = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

And the matrices in the equation system are:

$$F = \begin{bmatrix} 1 & 1 \\ 0 & \beta \end{bmatrix}, G = \begin{bmatrix} -1 & -\phi_\pi \\ \kappa & -1 \end{bmatrix}, H = 0, M = \begin{bmatrix} 0 & -1 \\ -\kappa & 0 \end{bmatrix}, N = 0.$$

Solving the matrix equation system, I get

$$P = 0; Q = \begin{bmatrix} \frac{\kappa\phi_\pi}{1+\kappa\phi_\pi} & -\frac{1}{1+\kappa\phi_\pi} \\ -\frac{\kappa}{1+\kappa\phi_\pi} & -\frac{\kappa}{1+\kappa\phi_\pi} \end{bmatrix}; R = \begin{bmatrix} \rho_x \frac{1}{1+\kappa\phi_\pi} & 0 \\ \rho_x \frac{\kappa}{1+\kappa\phi_\pi} & 0 \end{bmatrix}.$$

Rewrite the solution as:

$$y_t = \frac{1}{1+\kappa\phi_\pi}(\kappa\phi_\pi a_t - s_t + \rho_{a,l,x} x_{a,l,t|t})$$
$$\pi_t = \frac{\kappa}{1+\kappa\phi_\pi}(-a_t - s_t + \rho_{a,l,x} x_{a,l,t|t})$$

Now I adjust the solution to take into account the $\xi_t$ in the inflation nowcast. $\xi_t$ appears where $m_t$ appears, so it should enter the solution similarly as $m_t$ but without affecting the perception of the persistent productivity. The solution should be as follows:

$$y_t = \frac{1}{1+\kappa\phi_\pi}(\kappa\phi_\pi a_t - s_t - \phi_\pi\xi_t + \rho_{a,l,x} x_{a,l,t|t}) \tag{1.10}$$
$$\pi_t = \frac{\kappa}{1+\kappa\phi_\pi}(-a_t - s_t - \phi_\pi\xi_t + \rho_{a,l,x} x_{a,l,t|t}) \tag{1.11}$$

Both output and inflation are functions of productivity, the signal from the interest rate, the inflation nowcast error, and the perception of the persistent productivity. This solution can be verified. First,

$$
\begin{aligned}
y_{t+1} &= \frac{1}{1+\kappa\phi_\pi}(\kappa\phi_\pi a_{t+1} - s_{t+1} - \phi_\pi\xi_{t+1} + \rho_{a,l,x}x_{a,l,+1|t+1}) \\
\pi_{t+1} &= \frac{\kappa}{1+\kappa\phi_\pi}(-a_{t+1} - s_{t+1} - \phi_\pi\xi_{t+1} + \rho_{a,l,x}x_{a,l,t+1|t+1})
\end{aligned}
$$

Simple algebra leads to

$$
\begin{aligned}
E_t y_{t+1} &= \rho_{a,l,x}x_{a,l,t|t} \\
E_t \pi_{t+1} &= 0
\end{aligned}
$$

Plugging these two expectations back into Equation 1.8 and Equation 1.9 delivers the solution as in Equation 1.10 and Equation 1.11. We solve the equations and verify the correctness of the solution.

Productivity $a_t$ affects the output positively, and inflation negatively. This is of no surprise given $a_t$ is the productivity level. The essential part of interest rate $s_t$ affects both output and inflation negatively. Both $a_t$ and $s_t$ affect output and inflation indirectly through $x_{a,l,t+1|t+1}$. $\xi_t$ is the nowcast error of inflation. A larger nowcast error leads the central bank to move the interest rate more than needed, thus decreasing output and inflation. $\rho_{a,l,x}x_{a,l,t+1|t+1}$ is the expected productivity of next period, and it affects output and inflation positively. The essential part of interest rate $s_t$ serves as the public signal about the fundamental. The monetary policy shock $m_t$ not only serves as the noise around the persistent part of productivity, preventing the households from knowing the exact level of persistent productivity, but also has a direct effect on output and inflation for the current period. The direct effect shows up in the second term of both equations ($s_t$ in Equation 1.10 and Equation 1.11, which contains $m_t$), and both output and inflation respond to the monetary policy shock negatively. The indirect effect of monetary policy shocks on output and inflation is through the last term, the perceived persistent productivity shock. Now we turn to how the monetary policy shock affects output by affecting the perception of persistent productivity. $\eta_{a,l,t}$ has a direct effect through $a_t$ and an indirect effect through $x_{a,l,t+1|t+1}$. $\epsilon_{a,l,t}$ has a direct effect through $a_t$ and $s_t$ and an indirect effect through $x_{a,l,t+1|t+1}$. We will come to the details of how the fundamental shock affects endogenous variables in the next subsection.

$\kappa$ captures the degree of nominal rigidity. When the price is fully flexible, i.e., $\kappa$ tends to infinity, moving the policy rate has no effect on output and inflation because the immediate jump in prices kills the movement in the real rate; and movement in the productivity expectation is absorbed by the real rate. $\phi_\pi$ captures the intensity of inflation targeting. The larger $\phi_\pi$ is, the lesser response of inflation to current productivity and the more response of output to current productivity. As $\phi_\pi$ tends to infinity, both the output gap and inflation are determined by the nowcast error for inflation. And if we ignore the second term $-s_t$ in both equations and set $\rho_{a,l,x} = 1$ and $\xi_t = 0$, these two equations then collapse to the solution as in Lorenzoni (2009).

**Effects of exogenous shocks**

The effects of exogenous shocks come from two channels. The first one is a direct effect. The second one is an indirect effect through the perception of persistent productivity and thus the expectations of future productivity. The model contains one persistent shock $\epsilon_{a,l,t}$ to productivity, two independent and identically distributed noise shocks $\eta_{a,l,t}$ and $m_t$ around two signals $a_t$ and $s_t$ respectively. Households' perceptions of persistent productivity depend on the last-period perceptions and the two signals in the current period. The perceived persistent part of productivity evolves as:[17]

$$x_{a,l,t|t} = \rho\rho_{a,l,x}x_{a,l,t-1|t-1} + (1-\rho)[\delta a_t + (1-\delta)\frac{s_t}{\rho_{a,l,x}-1}]$$

of which

$$\rho = \frac{\frac{1}{\sigma_x^2}}{(1-\rho_{a,l,x})^2\frac{1}{\sigma_m^2} + \frac{1}{\sigma_x^2} + \frac{1}{\sigma_\eta^2}}$$

and

$$\delta = \frac{\frac{1}{\sigma_\eta^2}}{(1-\rho_{a,l,x})^2\frac{1}{\sigma_m^2} + \frac{1}{\sigma_\eta^2}}$$

$\rho_{a,l,x}$ is the persistence of productivity. $\rho$ captures the relative importance of perceived persistent productivity of last period relative to the two signals of the current period. $\delta$ captures the relative importance of the signal $a_t$ to the signal $s_t$. The larger the precision of the private signal $a_t$ (smaller $\sigma_\eta^2$), the more weight is placed on the private signal $a_t$. $(1-\rho_{a,l,x})^2\frac{1}{\sigma_m^2}$ is the adjusted precision of public signal $s_t$. The larger the adjusted precision of the public signal $s_t$, the more weight is placed on the public signal. All else equal, a positive exogenous monetary policy shock $m_t$ will lead to a decrease in $x_{a,l,t|t}$ since $\rho_{a,l,x}-1$ is negative, and thus a decrease in both output and inflation (Both output and inflation are positive in in $x_{a,l,t|t}$.).

A few remarks here on the evolving of the perception of persistent productivity:

(i) When $\rho_{a,l,x}$ tends to one, $\delta$ tends to one. The weight on the signal from the interest rate $s_t$ is zero. Households update their perceptions about the persistent productivity without $s_t$. The interest rate loses its function as a signal about the persistent productivity. Under that situation, the monetary policy shock has its traditional role without affecting households' perceptions of productivity.

[17] The derivation is similar to the derivation of Kalman updating for discount factor shocks in the appendix. The $C$ matrices are slightly different for different regimes.

(ii) When $\rho_{a,l,x}$ tends to zero, the interest rate contains information about the current perception about persistent productivity. A positive exogenous monetary policy shock $m_t$ has its marginal effect on $x_{a,l,t|t}$, which is given by $(1-\rho)(1-\delta)\frac{1}{1-\rho_{a,l,x}}$. Since both $\rho$ and $\delta$ are decreasing as $\rho_{a,l,x}$ tends to zero, $(1-\rho)(1-\delta)$ increases, but $\frac{1}{1-\rho_{a,l,x}}$ decreases. So the overall effect of $(1-\rho)(1-\delta)\frac{1}{1-\rho_{a,l,x}}$ is nonlinear in $\rho_{a,l,x}$. Furthermore, its marginal effect on the next-period perception of persistent productivity $x_{t+1|t+1}$ is given by $\rho\rho_{a,l,x}(1-\rho)(1-\delta)\frac{1}{1-\rho_{a,l,x}}$. A near zero $\rho_{a,l,x}$ kills the interest rate signaling effect for future periods.

(iii) A medium level of $\rho_{a,l,x}$ will justify the interest rate's sizable signaling role not only to current output and inflation but also to future values. Similarly, a medium level of $\rho$ helps to delivers a sizable effect on the current and future values of output and inflation.

(iv) Variance of the fundamentals here $\sigma_x^2$ affects the value of $\rho$, all else equal. And the smaller $\sigma_x^2$ is, the larger $\rho$ is. In the extreme case where $\sigma_x^2$ tends to zero, $\rho$ tends to one. It makes sense since the perceived current period state will depend totally on the perceived past state if there is no variation across time. The current-period signals play no role in updating the perceived current state. When $(1-\rho_{a,l,x})^2\frac{1}{\sigma_m^2}$ and $\frac{1}{\sigma_\eta^2}$ are larger, which is to say the current signals are of high quality, the state will depend more on the current signals than on the past state. In a stationary process, $\sigma_x^2 = \frac{1}{1-\rho_{a,l,x}^2}\sigma_\epsilon^2$.

Now we explicitly check the effects of the three shocks on output and inflation. For the current period:

$$\begin{aligned}
\frac{\partial y_t}{\partial m_t} &= \frac{1}{1+\kappa\phi_\pi}\left(-\frac{\partial s_t}{\partial m_t} - \rho_{a,l,x}\frac{\partial x_{a,l,t|t}}{\partial s_t}\frac{\partial s_t}{\partial m_t}\right) \\
&= \frac{1}{1+\kappa\phi_\pi}[-1-\rho_{a,l,x}(1-\rho)(1-\delta)/(1-\rho_{a,l,x})] < 0 \\
\frac{\partial \pi_t}{\partial m_t} &= \frac{\kappa}{1+\kappa\phi_\pi}[-1-\rho_{a,l,x}(1-\rho)(1-\delta)/(1-\rho_{a,l,x})] < 0
\end{aligned}$$

The monetary policy shock has negative effects on both output and inflation for the current period. Again the first term on the right-hand side is the direct effect through $s_t$ and the second term is the indirect effect through affecting $x_{a,l,t|t}$. Specifically, the direct effect is due to an exogenous increase in the real rate and the indirect effect is due to a downward revision on the perception of persistent productivity. Both direct and indirect effects are negative.

$$
\begin{aligned}
\frac{\partial y_t}{\partial \eta_{a,l,t}} &= \frac{1}{1+\kappa\phi_\pi}(\kappa\phi_\pi + \rho_{a,l,x}(1-\rho)\delta) > 0 \\
\frac{\partial \pi_t}{\partial \eta_{a,l,t}} &= \frac{\kappa}{1+\kappa\phi_\pi}(-1 + \rho_{a,l,x}(1-\rho)\delta) < 0
\end{aligned}
$$

The temporary productivity shock has a positive effect on output and a negative effect on inflation. The first term on the right-hand side in both equations is the direct effect through increasing $a_t$ while the second term is the indirect effect through an upward revision on the perception of persistent productivity $x_{a,l,t|t}$. The direct effect outweighs the indirect effect.

$$
\begin{aligned}
\frac{\partial y_t}{\partial \epsilon_{a,l,t}} &= \frac{1}{1+\kappa\phi_\pi}[\kappa\phi_\pi + (1-\rho_{a,l,x}) + (1-\rho)\rho_{a,l,x}] \\
&= \frac{1}{1+\kappa\phi_\pi}[\kappa\phi_\pi + 1 - \rho\rho_{a,l,x}] > 0 \\
\frac{\partial \pi_t}{\partial \epsilon_{a,l,t}} &= \frac{\kappa}{1+\kappa\phi_\pi}[-1 + (1-\rho_{a,l,x}) + (1-\rho)\rho_{a,l,x}] \\
&= -\frac{\kappa}{1+\kappa\phi_\pi}\rho\rho_{a,l,x} < 0
\end{aligned}
$$

Overall, the persistent productivity shock has a positive effect on output and a negative effect on inflation. The first term on the right-hand side (first line of equations) is the direct effect through $a_t$, the second term is the direct effect through $s_t$, and the last term is through affecting the perception of persistent productivity $x_{a,l,t|t}$.

Now we switch to the dynamic responses of endogenous variables to exogenous shocks.

For future periods $h > 0$,

$$y_{t+h} = \frac{1}{1+\kappa\phi_\pi}(\kappa\phi_\pi a_{t+h} - s_{t+h} - \phi_\pi \xi_{t+h} + \rho_{a,l,x} x_{a,l,t+h|t+h})$$
$$\pi_{t+h} = \frac{\kappa}{1+\kappa\phi_\pi}(-a_{t+h} - s_{t+h} - \phi_\pi \xi_{t+h} + \rho_{a,l,x} x_{a,l,t+h|t+h})$$

Thus, taking derivatives delivers:

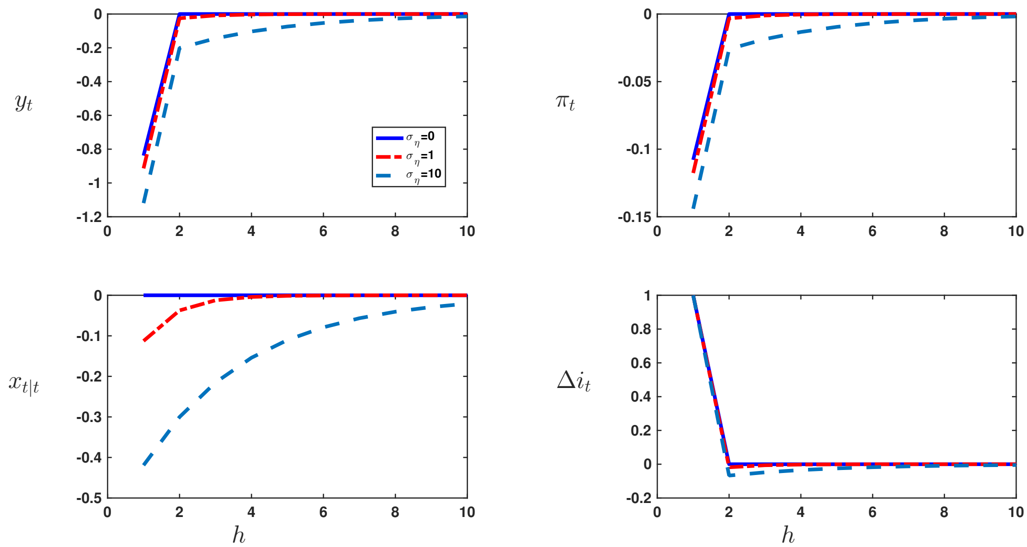
$$\frac{\partial y_{t+h}}{\partial m_t} = \frac{1}{1+\kappa\phi_\pi}[-(\rho\rho_{a,l,x})^h(1-\rho)(1-\delta)/(1-\rho_{a,l,x})] < 0$$
$$\frac{\partial \pi_{t+h}}{\partial m_t} = \frac{\kappa}{1+\kappa\phi_\pi}[-(\rho\rho_{a,l,x})^h(1-\rho)(1-\delta)/(1-\rho_{a,l,x})] < 0$$
$$\frac{\partial y_{t+h}}{\partial \eta_{a,l,t}} = \frac{1}{1+\kappa\phi_\pi}(\rho\rho_{a,l,x})^h(1-\rho)\delta > 0$$
$$\frac{\partial \pi_{t+h}}{\partial \eta_{a,l,t}} = \frac{\kappa}{1+\kappa\phi_\pi}(\rho\rho_{a,l,x})^h(1-\rho)\delta > 0$$

The monetary policy shock is independent across time, and the current monetary policy shock has no effect on either future productivity, $a_t$, or future monetary policy, $s_t$. The dynamic effects of a monetary policy shock on endogenous variables come from the fact it affects the perception of future persistent productivity. A similar effect is true for contemporary productivity shock. Both effects on output and inflation are negative for the monetary policy shock and both positive for the temporary productivity shock.

$$\frac{\partial y_{t+h}}{\partial \epsilon_{a,l,t}} = \frac{1}{1+\kappa\phi_\pi}[\kappa\phi_\pi(\rho_{a,l,x})^h + (1-\rho_{a,l,x})(\rho_{a,l,x})^h + (1-\rho^{h+1})\rho_{a,l,x}(\rho_{a,l,x})^h]$$
$$= \frac{1}{1+\kappa\phi_\pi}[\kappa\phi_\pi + 1 - \rho^{h+1}\rho_{a,l,x}](\rho_{a,l,x})^h > 0$$
$$\frac{\partial \pi_{t+\tau}}{\partial \epsilon_{a,l,t}} = \frac{\kappa}{1+\kappa\phi_\pi}[-(\rho_{a,l,x})^h + (1-\rho_{a,l,x})(\rho_{a,l,x})^h + (1-\rho^{h+1})\rho_{a,l,x}(\rho_{a,l,x})^h]$$
$$= -\frac{\kappa}{1+\kappa\phi_\pi}(\rho_{a,l,x}\rho)^{h+1} < 0$$

The effects of persistent productivity shocks on future output and inflation are different. The persistence is measured by $\rho_{a,l,x}$, thus unit current persistent productivity shock has $\rho_{a,l,x}^h$

Figure 1.1: Impulse Responses when the Fed Counters Only Productivity Level Shocks




Notes: $x_{t|t}$ *here is the perceived persistent productivity after observing both signals.* $\Delta i_t$ *is the interest rate surprise, not the monetary policy shock.* $\sigma_\epsilon$*,* $\sigma_\eta$*, and* $\sigma_m$ *are the standard deviation of the persistent productivity shock, the temporary shock and the monetary policy shock, respectively.* $\sigma_\epsilon$ *and* $\sigma_m$ *are set to be* 1*. The blue line corresponds to* $\sigma_\eta = 0$ *when the model collapses to a perfect information model, the red short-dash line corresponds to* $\sigma_\eta = 1$*, and the long-dash line corresponds to* $\sigma_\eta = 10$*.*

on $x_{t+h}$. $x_{t+h}$ enters both $a_{t+h}$ and $s_{t+h}$ term. Unit current persistent productivity shock also has an effect on $x_{t+h|t+h}$ measured by $\rho^{\tau}_{a,l,x} \sum_{t=0}^{h} [\rho^t (1-\rho)] = \rho^h_{a,l,x}(1-\rho^{h+1})$. It affects $x_{t+h|t+h}$ not only though $x_{t+h-1|t+h-1}$ but also $a_{t+h}$ and $s_{t+h}$ term.

To emphasize, the signaling role of monetary policy shocks is to decrease output and inflation both for the current period and future periods in the regime of productivity level shocks. A visualization of the analytical results is in Figure 1.1. Parameters choice and cross-regime comparison are discussed in Section 1.3. And the idea of interest rate surprises $\Delta i_t$ will be clear after the first part of Section 1.4.

### 1.2.3 Only Demand Shocks (Discount Factor)

Suppose there are only discount factor shocks, and no other fundamental shocks in the economy. The demand condition (discount factor), $z_t$, consists of a persistent part $x_{z,l,t}$ and a temporary part $\eta_{z,l,t}$.

$$z_t = x_{z,l,t} + \eta_{z,l,t}$$

The persistent component evolves as:

$$x_{z,l,t} = \rho_{z,l,x} x_{z,l,t-1} + \epsilon_{z,l,t}$$

while $\eta_{z,l,t}$ is i.i.d. across time, normal, with zero mean and variance $\sigma_\eta^2$.

The central bank observes perfectly $x_{z,l,t}$ and $\eta_{z,l,t}$. The central bank sets the interest rate tracking the persistent demand condition with inflation targeting:

$$i_t = (1 - \rho_{z,l,x}) x_{z,l,t} + m_t + \phi_\pi \tilde{\pi}_t$$

The central bank announces the nowcast of inflation $\tilde{\pi}_t$ it uses:

$$\tilde{\pi}_t = \pi_t + \xi_t$$

where $\xi_t$ is the nowcast error. $m_t$ is the monetary policy shock. Similar to the previous regime, households observe a noisy public signal about the persistent part of productivity shock with the monetary policy shock $m_t$ as the noise around it. Here the discount factor shock is just to capture a demand shock. I am not assuming the central bank has a better understanding of households' discount factor literally. This can also be thought of in a dispersed information model where households see their own discount factor but have no idea of the aggregate discount factor for all.

$$s_t = i_t - \phi_\pi \tilde{\pi}_t = (1 - \rho_{z,l,x}) x_{z,l,t} + m_t$$

The interest rate rule can be rewritten as:

$$i_t = s_t + \phi_\pi \tilde{\pi}_t$$

The inflation targeting term is introduced to avoid the indeterminacy problem. Plugging the interest rate rule into the Euler equation, the economy system ends up as two equations:

$$y_t = E_t y_{t+1} - E_t[(s_t + \phi_\pi \tilde{\pi}_t - \pi_{t+1} + z_{t+1} - z_t)]$$

$$\pi_t = \beta E_t \pi_{t+1} + \kappa y_t$$

Here $y_t$ is output, not the output gap. $y_t$ and $\tilde{y}_t$ coincide in the Phillips curve since no productivity shocks in this case.

The solution is (The derivation is similar as before, and is in the appendix):

$$y_t = \frac{1}{1+\kappa\phi_\pi}(z_t - s_t - \phi_\pi \xi_t - \rho_{z,l,x} x_{z,l,t|t}) \tag{1.12}$$

$$\pi_t = \frac{\kappa}{1+\kappa\phi_\pi}(z_t - s_t - \phi_\pi \xi_t - \rho_{z,l,x} x_{z,l,t|t}) \tag{1.13}$$

Again in my setting, the monetary policy shock is not only noise in the public signal $s_t$ but also serves its traditional function as a monetary shock.

$$\frac{\partial y_t}{\partial \eta_{z,l,t}} = \frac{1}{1+\kappa\phi_\pi}(1 - \rho_{z,l,x}\frac{\partial x_{z,l,t|t}}{\partial \eta_{z,l,t}})$$
$$\frac{\partial y_t}{\partial m_t} = \frac{1}{1+\kappa\phi_\pi}(-1 - \rho_{z,l,x}\frac{\partial x_{z,l,t|t}}{\partial m_t})$$
$$\frac{\partial y_t}{\partial \epsilon_{z,l,t}} = \frac{1}{1+\kappa\phi_\pi}(\rho_{z,l,x} - \rho_{z,l,x}\frac{\partial x_{z,l,t|t}}{\partial \epsilon_{z,l,t}})$$

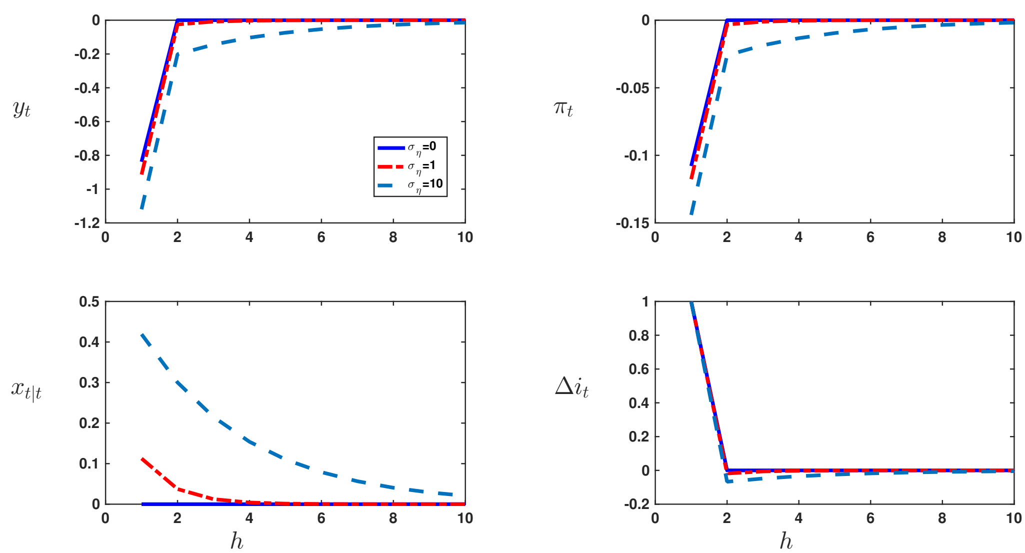
The first terms on the right-hand side of the equations are the direct effects of the three shocks respectively, and the second terms are the indirect effects on endogenous variables through the perception of persistent demand condition (discount factor).

Now we explicitly check the effects of the three shocks on output and inflation. Since the responses of inflation are just scaled down by a factor of $\kappa$ as compared to the responses of output, I omit the responses of inflation here. For the current period:

$$\frac{\partial y_t}{\partial \eta_{z,l,t}} = \frac{1}{1+\kappa\phi_\pi}(1-\rho_{z,l,x}(1-\rho)\delta) > 0$$
$$\frac{\partial y_t}{\partial m_t} = \frac{1}{1+\kappa\phi_\pi}[-1-\rho_{z,l,x}(1-\rho)(1-\delta)/(1-\rho_{z,l,x})] < 0$$
$$\frac{\partial y_t}{\partial \epsilon_{z,l,t}} = \frac{1}{1+\kappa\phi_\pi}\rho_{z,l,x}\rho > 0$$

For future periods as $\tau > 0$,

Figure 1.2: Impulse Responses when the Fed Counters Only Demand Shocks




Notes: $x_{t|t}$ *here is the perceived persistent demand condition after observing both signals.* $\Delta i_t$ *is the interest rate surprise, not the monetary policy shock.* $\sigma_\epsilon$*,* $\sigma_\eta$*, and* $\sigma_m$ *are the standard deviation of the persistent demand shock, the temporary shock and the monetary policy shock, respectively.* $\sigma_\epsilon$ *and* $\sigma_m$ *are set to be* 1*. The blue line corresponds to* $\sigma_\eta = 0$ *when the model collapses to a perfect information model, the red short-dash line corresponds to* $\sigma_\eta = 1$*, and the long-dash line corresponds to* $\sigma_\eta = 10$*.*

$$\frac{\partial y_{t+h}}{\partial \eta_{z,l,t}} = -\frac{1}{1+\kappa\phi_\pi}(1-\rho)\delta(\rho\rho_{z,l,x})^h < 0$$
$$\frac{\partial y_{t+h}}{\partial m_t} = -\frac{1}{1+\kappa\phi_\pi}[(1-\rho)(1-\delta)(\rho\rho_{z,l,x})^h/(1-\rho_{z,l,x})] < 0$$
$$\frac{\partial y_{t+h}}{\partial \epsilon_{z,l,t}} = \frac{1}{1+\kappa\phi_\pi}(\rho_{z,l,x}\rho)^{h+1} > 0$$

As in the previous case, the monetary policy shock, $m_t$, is independent across time. The dynamic effects on the endogenous variables are purely due to the signaling role for $h > 0$. This signaling role of monetary policy shocks leads to a further decrease in output. Similarly, an exogenous increase in $\eta_{z,l,t}$ will lead households to overestimate the persistent demand condition $x_{z,l,t|t}$ for both the current period and future periods. This leads to a decrease in output. However, since $\eta_{z,l,t}$ has a direct effect in the current period and it is larger than the signaling effect, its overall effect on current output is positive. The persistent demand shock has positive effects on output and inflation.

To emphasize, the signaling role of monetary policy shocks is to decrease output and inflation both for the current period and future periods in the regime of productivity level shock. A visualization of the analytical results is in Figure 1.2. Parameter choice and cross-regime comparison are discussed in Section 1.3. And the idea of interest rate surprises $\Delta i_t$ will be clear after the first part of Section 1.4.

### 1.2.4 Only Productivity Growth Rate Shocks

The first regime discussed above is when the interest rate is set to respond to a productivity level shock. However, monetary policy can also respond to productivity growth rate shocks instead of productivity level shocks. Assume the productivity growth consists of a permanent part and a temporary part, and households cannot distinguish them.

The change in productivity $\Delta a_t$ consists of a persistent part $x_{a,g,t}$ and a temporary part $\eta_{a,g,t}$.

$$\Delta a_t = x_{a,g,t-1} + \eta_{a,g,t}$$

$\Delta a_t = a_t - a_{t-1}$, $x_{a,g,t-1}$ is the persistent growth rate from $t-1$ to $t$. At time $t$, comparing $a_t$ and $a_{t-1}$ will deliver sensible growth rate is from $t-1$ to $t$. The persistent component evolves as:

$$x_{a,g,t} = \rho_{a,g,x} x_{a,g,t-1} + \epsilon_{a,g,t}$$

while $\eta_{a,g,t}$ is i.i.d. across time, normal, with zero mean and variance $\sigma_\eta^2$. The central bank sets the interest rate as:

$$i_t = x_{a,g,t} + m_t + \phi_\pi \tilde{\pi}_t$$

with

$$s_t = x_{a,g,t} + m_t$$

The central bank tracks $x_{a,g,t}$, which is the growth rate of $t$ to $t+1$. Now the two current period signals are $\Delta a_t$ and $s_t$, unlike the previous case in which both signals are about the current persistent productivity. $\Delta a_t$ is now about the growth rate from $t-1$ to $t$, while $s_t$ is about the growth rate from $t$ to $t+1$. This timing has important implications for the signaling role: even when $\sigma_\eta^2 = 0$, the monetary policy shock will still lead households to update their perceptions about the growth rate since observing last period growth rate perfectly does not imply observing the current period growth rate perfectly.

In order to fit the system into the solution method, I first use the output gap and inflation to solve the model and then adjust the output gap with productivity to get the output. The solutions are also easy to verify as done in the productivity level shock case. The Euler equation:

$$\tilde{y}_t = E_t \tilde{y}_{t+1} - E_t[s_t + \phi_\pi \tilde{\pi}_t - \pi_{t+1} - \Delta a_{t+1}]$$

The Phillips curve:

$$\pi_t = \beta E_t \pi_{t+1} + \kappa \tilde{y}_t$$

of which

$$\tilde{y}_t = y_t - a_t$$

Following the same solution method, I get:

$$\tilde{y}_t = \frac{1}{1+\kappa\phi_\pi}(-s_t - \phi_\pi \xi_t + x_{a,g,t|t})$$
$$\pi_t = \frac{\kappa}{1+\kappa\phi_\pi}(-s_t - \phi_\pi \xi_t + x_{a,g,t|t}))$$

Assume the economy starts from the steady state at time $t$, $a_{t-1} = 0$. Adjust output based on the solution:

$$y_{t+h} = \frac{1}{1+\kappa\phi_\pi}(-s_{t+h} - \phi_\pi \xi_{t+h} + x_{a,g,t+h|t+h}) + \sum_{h=0}^{H} \Delta a_{t+h}$$

The signal extraction problem in the current case is different from the level shock case, and $\rho_2$ and $\delta_2$ are different from $\rho$ and $\delta$ in the previous case (see the appendix for details). The perception of the persistent growth rate evolves as:

$$x_{a,g,t|t} = \rho_2 \rho_{a,g,x} x_{a,g,t-1|t-1} + \delta_1 \Delta a_t + \delta_2 s_t$$

Now we come to the effects of exogenous shocks. The monetary policy shock $m_t$ does not affect $\Delta a_t$. The effects on output and inflation are similar, and the inflation responses are scaled down by $\kappa$ as compared to output responses. For the current period:

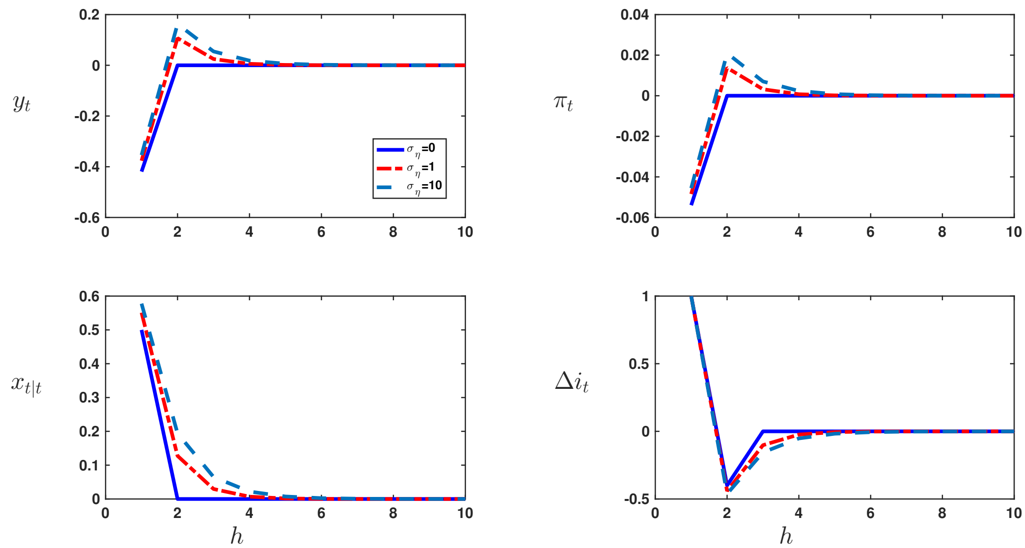
$$\frac{\partial y_t}{\partial m_t} = \frac{1}{1+\kappa\phi_\pi}[-1 + \delta_2] < 0$$

For future periods with $h > 0$,

$$\frac{\partial y_{t+h}}{\partial m_t} = \frac{1}{1+\kappa\phi_\pi}(\rho_2 \rho_{a,g,x})^h \delta_2 > 0$$

Effects of $\eta_{a,g,t}$ on output should now include its effect on $\Delta a_t$. This will lead to different

Figure 1.3: Impulse Responses when the Fed Counters Only Productivity Growth Rate Shocks




Notes: $x_{t|t}$ *here is the perceived persistent productivity growth rate after observing both signals.* $\Delta i_t$ *is the interest rate surprise, not the monetary policy shock.* $\sigma_\epsilon$, $\sigma_\eta$, *and* $\sigma_m$ *are the standard deviation of the persistent productivity growth rate shock, the temporary shock and the monetary policy shock, respectively.* $\sigma_\epsilon$ *and* $\sigma_m$ *are set to be* 1. *The blue line corresponds to* $\sigma_\eta = 0$, *the red short-dash line corresponds to* $\sigma_\eta = 1$, *and the long-dash line corresponds to* $\sigma_\eta = 10$.

responses of output and inflation to $\eta_{a,g,t}$ besides differences in scale. For the current period,

$$\frac{\partial y_t}{\partial \eta_{a,g,t}} = 1 + \frac{1}{1+\kappa\phi_\pi}\delta_1 > 0$$
$$\frac{\partial \pi_t}{\partial \eta_{a,l,t}} = \frac{\kappa}{1+\kappa\phi_\pi}\delta_1 > 0$$

For future periods with $h > 0$,

$$\frac{\partial y_{t+h}}{\partial \eta_{a,g,t}} = 1 + \frac{1}{1+\kappa\phi_\pi}(\rho_2\rho_{a,g,x})^h\delta_1 > 0$$
$$\frac{\partial \pi_{t+h}}{\partial \eta_{a,l,t}} = \frac{\kappa}{1+\kappa\phi_\pi}(\rho_2\rho_{a,g,x})^h\delta_1 > 0$$

The 1 appears in output responses because the temporary shock in the growth rate stays there for both current output and future output. Other terms capture effects through affecting the perception of the growth rate.

For the effects of $\epsilon_{a,g,t}$,

$$\frac{\partial y_t}{\partial \epsilon_{a,g,t}} = \frac{1}{1+\kappa\phi_\pi}[-1+\delta_2] > 0$$
$$\frac{\partial \pi_t}{\partial \epsilon_{a,g,t}} = \frac{\kappa}{1+\kappa\phi_\pi}[-1+\delta_2] < 0$$

$\epsilon_{a,g,t}$ affects $s_t$ and $\Delta a_{t+1}$. For the current period, it affects through $s_t$ and $x_{a,g,t|t}$. And its effect on $x_{a,g,t|t}$ is only through signal $s_t$. For future periods with $h > 0$,

$$\begin{aligned}\frac{\partial y_{t+h}}{\partial \epsilon_{a,g,t}} &= [1+\rho_{a,g,x}+...+\rho_{a,g,x}^{h-1}] \\ &+ \frac{1}{1+\kappa\phi_\pi}[-\rho_{a,g,x}^h + (\rho_2\rho_{a,g,x})^{h-1}\delta_1 + (\rho_2\rho_{a,g,x})^h\delta_2] > 0 \\ \frac{\partial \pi_{t+h}}{\partial \epsilon_{a,g,t}} &= \frac{\kappa}{1+\kappa\phi_\pi}[-\rho_{a,g,x}^h + (\rho_2\rho_{a,g,x})^{h-1}\delta_1 + (\rho_2\rho_{a,g,x})^h\delta_2] \\ &= \frac{\kappa}{1+\kappa\phi_\pi}\rho_{a,g,x}^{h-1}[-\rho_{a,g,x} + (\rho_2)^{h-1}\delta_1 + (\rho_2)^h\rho_{a,g,x}\delta_2]\end{aligned}$$

The sign of output responses are for sure positive and the responses grow with the horizon, for $\rho_{a,g,x}^{h-1}$ is larger in absolute value than the last term in the output response equation. The sign of the inflation response is not determined. The first term on the right-hand side is there because the central bank sets the interest rate tracking the productivity growth rate. The last two terms are there due to increased perceptions of persistent growth rate, which have positive effects on inflation. The overall effect depends on the relative strength of these forces.

To emphasize, the signaling role of monetary policy shocks in the productivity growth rate shock regime is to increase output and inflation. A visualization of the analytical results is in Figure 1.3. Parameter choice and cross-regime comparison are discussed in Section 1.3. And the idea of interest rate surprises $\Delta i_t$ will be clear after the first part of Section 1.4.

## 1.3 The Effects of Monetary Policy Shocks

In the first subsection, I compare the output and inflation responses across regimes using the analytical solutions above and visualized graphs. In the second subsection, I check the output expectations, inflation expectations, and term structure responses to monetary policy shocks. The question here is whether the effects of pure monetary policy shocks are similar to empirical findings using interest rate surprises.

### 1.3.1 Output and Inflation Responses

The monetary policy shock $m_t$ serves two roles in this model. The first role is the traditional role as its counterpart in a perfect information model to decrease output and inflation. The second role is a signaling role: it leads households to revise their perceptions about the fundamental and thus change their consumption decisions. When the signaling role leads to a further decrease, I refer to this as "the effects of the monetary policy shock are amplified." When the signaling role leads to an increase in output I refer to this as "the effects of the monetary policy shock are dampened". To summarize, the monetary policy shock $m_t$ has

Table 1.1: Parameters for Simulation

| Parameters | Description | Baseline | Low | High |
|---|---|---|---|---|
| $\beta$ | Discount Factor | 0.99 | | |
| $\theta$ | Calvo Pricing Parameter | 0.75 | | |
| $\sigma$ | Substitution Elasticity | 1 | | |
| $\varphi$ | Labor Elasticity | 0.5 | | |
| $\phi_\pi$ | Policy Coefficient | 1.5 | | |
| $\rho_x$ | Persistence of fundamental | 0.8 | | |
| $\sigma_\epsilon$ | SD. persitent shocks | 1 | | |
| $\sigma_\eta$ | SD. temporary shocks | 1 | 0 | 10 |
| $\sigma_m$ | SD. monetary policy shocks | 1 | | |
| $\kappa$ | Composite parameter | 0.129 | | |

amplified effects when there is a productivity level shock or a demand shock in the economy. However, it has dampened effects when there is a productivity growth rate shock in the economy. The comparison of different effects of monetary policy shock is clear comparing Figure 1.1, Figure 1.2, and Figure 1.3. The parameters are listed in Table 1.1. These parameters are all common in macro literature except the standard deviations which are picked at three different levels to show the results clearly. The parameters are shared for all three regimes. Two things need to be emphasized: first, the elasticity of intertemporal substitution $\sigma$ is set to 1 (I use log utility for simplicity); second, I fix the standard deviations of the persistent shock $\sigma_\epsilon^2 = 1$ and the monetary policy shock $\sigma_m^2 = 1$. By changing the standard deviation of the temporary shock $\sigma_\eta^2$ to different levels (0, 1, 10 respectively), I show the different significance of signaling role for monetary policy shocks.

Figure 1.1 is the visualization of the productivity level shock case but with the impulse responses only to the monetary policy shock $m_t$. When $\sigma_\eta^2 = 0$, the model collapses to a perfect information model. Households observe $a_t$ and $a_t = x_{a,l,t}$ when $\sigma_\eta^2 = 0$. Households also observe $s_t$, but now households do not need $s_t$ to update their perceptions about $x_{a,l,t}$. Instead, they use $s_t$ to figure out $m_t$. Comparing the responses of output to monetary policy shocks when $\sigma_\eta^2 = 0$ and $\sigma_\eta^2 = 10$ delivers clearly the message: the signaling role leads to a further reduction in output. And the responses at future periods are the results of only the signaling role. The signaling role of monetary policy shocks not only reduces the current output, it also reduces the future output. And the graph of $x_{t|t}$ shows clearly that households persistently underestimate $x_t$. There is no shock on productivity in Figure 1.1, and the updates on persistent productivity are caused by $m_t$. How long the effects will last depends on how quickly households learn the true state.

Figure 1.2 is almost the same as Figure 1.1 except the graph about the $x_{t|t}$. While in the productivity level shock case households persistently underestimate persistent productivity, they persistently overestimate persistent demand condition. The signaling role leads to a further decrease in output in both cases because underestimating future productivity and overestimating future demand both lead to a decrease in current output. Underestimating future productivity leads households to be more pessimistic about future and thus less consumption today. Overestimating future demand leads households to save more for tomorrow thus also less consumption today. Figure 1.3 shows the impulse responses for the productivity growth rate shock case. The sharp contrast with the previous cases is that now the output responses are dampened. It's much clearer for horizons larger than 2. There is a positive output response to monetary policy shocks. One key difference that needs to be emphasized here is that $\sigma_\eta^2 = 0$ does not correspond to the perfect information case as discussed above. The idea is that $\eta_t$ is the noise around growth rate from $t-1$ to $t$, while monetary policy shock is signaling information about the growth rate from $t$ to $t+1$. That is the reason for a change in $x_{t|t}$ even at period one even when $\sigma_\eta^2 = 0$.

The exact same magnitude of results for the productivity level shock case and the demand shock case is because I set elasticity of intertemporal substitution $\sigma = 1$. $\sigma$ matters not only for the sensitivity of output to real interest rate but also for the interest rate rule when the central bank is tracking the natural real rate. So it can affect the signal extraction problem in the productivity level shock case. When $\sigma \neq 1$, the magnitudes of the amplified responses are different, but the sign is still the same between the productivity level shock and demand shock case.

### 1.3.2 Output, Inflation Expectations and Natural Term Structure Responses

This part investigates the output and inflation expectations responses, and also the natural real term structure to monetary policy shocks. The natural real term structure is defined as the term structure for the real rate the central bank is trying to track. There is literature claiming that output expectations and the long end of real term structure respond positively to interest rate surprises (Nakamura & Steinsson (2018)) and/or monetary policy shocks (Zhang (2017)). Here I am trying to investigate how expected output, inflation and the term structure are responding to monetary policy shocks in all these regimes. The results are visualized in Figure 1.5, Figure 1.7, and Figure 1.9.

The natural real rate moves as the monetary policy shock moves households' perceptions about the fundamentals. For the case of only productivity level shocks,

$$\tilde{r}_t^n = -(1-\rho_{a,l,x})x_{a,l,t}$$

$$\tilde{r}_{t+\tau}^n = -(1-\rho_{a,l,x})x_{a,l,t+\tau}$$

$$\tilde{r}_{t+\tau|t}^n = -(1-\rho_{a,l,x})\rho_{a,l,x}^{\tau}x_{a,l,t|t}$$

Thus the natural real term structure responds to monetary policy shocks:

$$\begin{aligned}\frac{\partial \tilde{r}_{t+\tau}^n}{\partial m_t} &= -(1-\rho_{a,l,x})\rho_{a,l,x}^{\tau}(1-\rho)(1-\delta)\frac{1}{\rho_{a,l,x}-1} \\ &= \rho_{a,l,x}^{\tau}(1-\rho)(1-\delta)\end{aligned}$$

If the central bank moves the nominal interest rate, the short end of real term structure moves because of two reasons: the movement due to the natural real rate and the movement due to nominal rigidity. The first movement reflects changes in households' perceptions of the fundamental. The second movement is because the nominal interest rate is changed by the central bank but the inflation response is less than one-for-one. However, the second movement should die out $\tau$ periods ahead for $\tau$ big enough since price adjusts fully several quarters out under reasonable assumptions. So the long end of term structure can move only due to revisions in the perception about the fundamentals in the setting of this paper. For the case of only demand shocks:

$$\begin{aligned}\frac{\partial \tilde{r}_{t+\tau}^n}{\partial m_t} &= -(1-\rho_{z,l,x})\rho_{z,l,x}^{\tau}(1-\rho)(1-\delta)\frac{1}{\rho_{z,l,x}-1} \\ &= \rho_{z,l,x}^{\tau}(1-\rho)(1-\delta)\end{aligned}$$

For the productivity growth rate shock case:

$$\frac{\partial r^*_{t+\tau|t}}{\partial m_t} = \rho^\tau_{a,g,x}\delta_2$$

In all the three regimes, the natural real rate is moved by the monetary policy shock following the same pattern. Positive monetary policy shock moves the natural real rate positively. The size of the natural interest rate movement is affected by two factors. The first factor is the persistence of the fundamental shock, and the second factor is the size of revisions on the perception about the fundamental caused by an exogenous monetary policy shock.

Table 1.2: Signaling Role of Monetary Policy Shocks on Output Expectations

| Experiments | $\frac{\partial y_{t+\tau\|t}}{\partial m_t}$ |
|---|---|
| $a_t$ | $-\rho^\tau_{a,l,x}(1-\rho)(1-\delta)\frac{1}{1-\rho_{a,l,x}} < 0$ |
| $z_t$ | $0$ |
| $\Delta a_t$ | $\frac{\rho_{a,g,x}-\rho^\tau_{a,g,x}}{1-\rho_{a,g,x}}\rho^\tau_{a,g,x}s_2 > 0$ |

What is the effect of monetary policy shocks on output and inflation expectations? To check this, I first get expected output and inflation, and then take the derivative of the expectation term with respect to monetary policy shocks. Table 1.2 shows the results for different cases. In the productivity growth rate shock case, expected output responds positively to monetary policy shocks. Expected output responds to monetary policy shocks negatively in the productivity level case, and there is no response for the demand shock case. There are no expected inflation responses in all cases.

## 1.4 Discussion

It is notoriously difficult to identify monetary policy shocks empirically. In the first subsection, I discuss the relation between interest rate surprises (Nakamura & Steinsson (2018)), monetary policy shocks, and information shocks (Jarociński & Karadi (2020)) in my setting.

In the second subsection, I emphasize the noise role of monetary policy shocks in this setting by directly rewrite my results using Lorenzoni (2009) terminology.

### 1.4.1 Monetary Policy Shocks and Interest Rate Surprises

The interest rate surprise is a concept closely related to the monetary policy shock. This part discusses the link between these two concepts. The key message is that interest rate surprises do not coincide with monetary policy shocks in the imperfect information models. Suppose the central bank sets interest rate according to:

$$i_t = f(I_t^{cb}) + m_t$$

of which $I_t^{cb}$ is the central bank's information set at time $t$. $m_t$ is the monetary policy shock. The agents expect the interest rate to be:

$$i_t^e = f(I_t^a)$$

of which $I_t^a$ is the agents' information set at time $t$. The monetary policy shock in agents' expectation is zero. In a model with rational expectation and perfect information, the function $f$ is the same to the central bank and the private agents by the rational expectation assumption, and $I_t^{cb}$ equals $I_t^a$ due to perfect information assumption. Thus

$$\Delta i_t = m_t$$

That is the logic implicitly or explicitly used in Romer-Romer shocks and the shocks identified through the high-frequency approach. The latter tries to narrow the time window of policy announcements to make $I_t^{cb}$ and $I_t^a$ approximately the same.

However, when there is asymmetric information between the central bank and the private agents, the interest rate surprises no longer correspond to $m_t$. Instead,

$$\Delta i_t = f(I_t^{cb}) - f(I_t^a) + m_t = f(I_t^{cb} - I_t^a) + m_t$$

the second equation holds if the function $f$ is linear in the information set. The interest rates surprises $\Delta i_t$ now consist of the $m_t$ and an additional part due to information gap $f(I_t^{cb} - I_t^a)$.

Specifically in my model, when there is only a discount factor shock, the interest rate surprise is $(1-\rho_x)(x_t^{cb} - x_t^a) + m_t$. I assume that the Fed observes $x_t$ perfectly, so $x_t^{cb} = x_t$. And $x_t^a$ should be approximated by $x_{t|t-1}$. Output and inflation responses to interest rate surprises depend on whether the surprise is caused by movements in the fundamental or monetary policy shocks. This can be seen by comparing left columns with right columns using information about $\Delta i_t$ from Figure 1.4, Figure 1.6, and Figure 1.8. The key message here is that impulse responses of output and inflation to monetary policy shocks can be quite different from responses to interest rate surprises.

### 1.4.2 Signaling Role or Noise Role

The signaling role of monetary policy shocks is to generate households' perception revisions. As shown above, monetary policy shocks actually lead to either overestimates or underestimates of the true fundamental. It is in this sense the signaling role of monetary policy shocks is similar to the role of noise.

Here I rephrase the main results about the additional role of monetary policy shocks as noise and try to connect the results with noise shocks literature.

**(i)** *When the central bank is countering a certain persistent shock, the interest rates serves as a signal about the persistent fundamental. $m_t$ is noise around the true fundamental.*

**(ii)** *Noise around the persistent productivity level generates effects as a demand shock: it increases output and inflation.*

**(iii)** *Noise around the persistent discount factor generates effects as a negative demand shock: it decreases output and inflation.*

**(iv)** *Noise around the persistent productivity growth rate generates effects as a demand shock: it increases output and inflation.*

**(v)** *The interest rate set by the central bank tracks negatively the persistent productivity, positively the persistent discount factor, and positively the persistent productivity growth rate.*

**(vi)** *Thus $m_t$ is noise around the persistent discount factor, and the persistent productivity growth rate, but $m_t$ is noise around the NEGATIVE persistent productivity. So it generates effects as a negative demand shock independent of whether the fundamental is a demand shock or a productivity level shock. It generates positive responses of output for the productivity growth rate shock case.*

**(ii)** restates the result from Lorenzoni (2009), in which the noise shock about the productivity shock generates a demand shock. Here $m_t$ as noise generates negative effects on output and inflation (a negative demand shock) which seems to contradict Lorenzoni's results. The reason is in the interest rate rule: the $m_t$ is noise around the negative persistent productivity shock. Thus an increase in $m_t$ leads to a negative updating on persistent productivity shock. **(iii)** suggests the noise around the persistent demand condition generates effects similar to a negative demand shock, which is proved in the appendix.

## 1.5 Conclusion

I show that monetary policy shocks can have different effects depending on the macro shocks in the economy using multiple regimes building on a unified framework. The main channel is through the households' consumption decision. When the macro shock is about productivity, the monetary policy shock leads households to downward revise beliefs about future productivity level in the productivity level shock case, but it leads households to upward revise beliefs about the productivity growth rate in the productivity growth rate shock case. The difference between a level and a growth rate leads to quite different outcomes. Interestingly, signaling information about productivity level or a demand level does not lead to different outcomes. The reason is that the monetary policy shock leads households to believe either a lower future productivity or a stronger future demand, but both depress current consumption. In my setting where the interest rate signals the central bank's private information, the signaling role does not generate effects like a productivity level shock when monetary policy signals information about productivity level. This is different from Jarociński & Karadi (2020) in a different setting about the Fed information effect.

This new regime-dependence of monetary policy adds new justifications to time-varying monetary policy effects. First, the type of fundamental macro shocks can matter for the effects of monetary policy. Second, the variance of the temporary shock can also have a role: when the variance is large, the signaling role is more prominent. Different historical periods can have different types of fundamental macro shocks and a different composition of persistent shocks and temporary shocks. This can lead to substantial time-varying effects of monetary policy shocks.

The model has empirical implications to be explored: especially the different responses of output between the case of productivity level shock and productivity growth rate shock. The dynamic effects caused by the signaling role of monetary policy shocks dies out quite fast in the current setting. Existing literature shows dispersed information can help to slow down the learning process while strategic complementarity can lend the public signal a more prominent role. These are all interesting questions for future research.

# Appendix

## Demand Noise Generates Effects Similar to a Negative Demand Shock

This part is to check what will be the effect of demand noise in a similar setting as in Lorenzoni (2009). And it shows the noise around demand condition (discount factor) generate effects similar as a negative demand shock.

The discount factor $z_t$ consists of a permanent part $x_t$ and a temporary part $\eta_t$.

$$z_t = x_t + \eta_t$$

where $\eta_t$ is an i.i.d. shock, normal, with zero mean and variance of $\sigma_\eta^2$. $x_t$ is a random walk that evolves as:

$$x_t = x_{t-1} + \epsilon_t$$

where $\epsilon_t$ is an i.i.d. shock, normal, with zero mean and variance of $\sigma_\epsilon^2$. Agents observe current demand condition and a noisy signal $s_t$ regarding the permanent component of the discount factor process, given by

$$s_t = x_t + e_t$$

where $e_t$ is an i.i.d shock, normal, with zero mean and variance of $\sigma_e^2$. Monetary policy responds only to the current inflation:

$$i_t = i^* + \phi_\pi \pi_t$$

where $i^* = -log(\beta)$ and $\phi_\pi$ is a constant coefficient by the monetary authority.

Following standard steps, the Euler equation goes as:

$$y_t = E_t y_{t+1} - E_t[(i_t^* + \phi_\pi \pi_t - \pi_{t+1} + z_{t+1} - z_t)]$$

The Phillips curve:

$$\pi_t = \beta E_t \pi_{t+1} + \kappa y_t$$

$\kappa$ is similarly defined capturing the nominal rigidity. Here $y_t$ is output, not the output gap. $y_t$ and $\tilde{y}_t$ coincide in the PC curve since there is no productivity shock in this case.

Let $x_{t|t}$ denote the agents' expectation regarding $x_t$ based on their information at date $t$, that is,

$$x_{t|t} \equiv E_t x_t$$

Conjecture the expecting terms as:

$$E_t y_{t+1} = 0$$

$$E_t \pi_{t+1} = 0$$

and solve the equilibrium:

$$\begin{aligned} y_t &= \frac{1}{1+\kappa\phi_\pi} E_t(z_t - z_{t+1}) \\ \pi_t &= \frac{\kappa}{1+\kappa\phi_\pi} E_t(z_t - z_{t+1}) \end{aligned}$$

in which

$$\begin{aligned} E_t z_{t+1} &= E_t(x_t + \epsilon_{t+1} + \eta_{t+1}) \\ &= x_{t|t} \end{aligned}$$

and $E_t z_t = z_t$, we have:

$$y_t = \frac{1}{1+\kappa\phi_\pi}(z_t - x_{t|t})$$
$$\pi_t = \frac{\kappa}{1+\kappa\phi_\pi}(z_t - x_{t|t})$$

It's easy to confirm the conjectures $E_t y_{t+1} = 0$, $E_t \pi_{t+1} = 0$ are right. The permanent discount factor shock updates as:

$$x_{t|t} = \rho x_{t-1|t-1} + (1-\rho)[\delta s_t + (1-\delta) z_t]$$

where $\rho$ is increasing in $\sigma_e^2$ and $\sigma_\eta^2$, $\delta$ depends on the ratio $\sigma_e^2/\sigma_\eta^2$. $\delta$ increases with the precision of the signal $s_t$.

Since in this setting $y_t$ and $\pi_t$ move the same direction with different scale, I just show the output response to the three exogenous shocks.

For the current and future periods $\tau \geq 0$,

$$\frac{\partial y_{t+\tau}}{\partial e_t} = -\frac{1}{1+\kappa\phi_\pi}[\rho^\tau(1-\rho)\delta] < 0$$
$$\frac{\partial y_{t+\tau}}{\partial \epsilon_t} = \frac{1}{1+\kappa\phi_\pi}\rho^{\tau+1} > 0$$

For the current period,

$$\frac{\partial y_t}{\partial \eta_t} = \frac{1}{1+\kappa\phi_\pi}[1-(1-\rho)(1-\delta)] > 0$$

For future periods $\tau > 0$,

$$\frac{\partial y_t}{\partial \eta_t} = -\frac{1}{1+\kappa\phi_\pi}[\rho^\tau(1-\rho)(1-\delta)] < 0$$

Lorenzoni (2009) concludes that the noise around permanent productivity generates results similar as a demand shock. Here the key conclusion here is the noise shock for the demand condition generates a negative demand shock (the demand noise decreases output, inflation, and employment. Without productivity shocks, the employment coincides with output). A recent paper, Benhima & Poilly (2020), suggests a demand noise will generate a negative effect on output, and under certain monetary policy rule, it will generate effects like an adverse productivity shock. Here the noise shock also generates both negative responses of inflation and output. The first glance of the conclusion *a demand noise shock generates a negative demand shock* seems counterintuitive. The reason is that agents use the observed $z_t$ as the current discount factor. Furthermore, they do not know what is the size of the permanent part relative to the temporary part. An increase in the noise will lead the agents to upward update the permanent part of the discount factor. And the best guess of future discount factor totally depends on the perceived permanent part $x_{t|t}$. An update of $x_{t|t}$ can lead households to reallocate more of their consumption to the future, thus decreasing output today.

## Solution to the Endogenous Variables

The solution to the system is suggested in the appendix of Blanchard et al. (2013). The logic for the solutions to the matrix equation system is as follows:

$$
\begin{aligned}
Y_t &= PY_{t-1} + QS_t + RX_{t|t} \\
FE_t[y_{t+1}] &= FE_t[PY_t + QS_{t+1} + RX_{t+1|t+1}] \\
&= FE_t\{P[PY_{t-1} + QS_t + RX_{t|t}] + QS_{t+1} + RX_{t+1|t+1}\} \\
&= FP^2Y_{t-1} + FPQS_t + FPRX_{t|t} + FQE_tS_{t+1} + FRE_t[X_{t+1|t+1}] \\
&= FP^2Y_{t-1} + FPQS_t + FPRX_{t|t} + FQE_tS_{t+1} + FRE_tX_{t+1|t+1} \\
GY_t &= GPY_{t-1} + GQS_t + GRX_{t|t}
\end{aligned}
$$

Plug the last two equations into the system equation:

$$
\begin{aligned}
(FP^2 + GP + H)Y_{t-1} + (FPQ + GQ + M)S_t + (FPR + GR)X_{t|t} \\
+ FQE_tS_{t+1} + FRE_tX_{t+1|t} = 0 \\
S_t &= CX_t + Du_t \\
E_tS_{t+1} &= E_t(CX_{t+1} + Du_{t+1}) \\
&= E_t[C(AX_t + Bv_{t+1}) + Du_{t+1}] \\
&= CAX_{t|t} \\
E_tX_{t+1|t+1} &= X_{t+1|t} = E_t(Ax_t + Bv_{t+1}) = AX_{t|t}
\end{aligned}
$$

Plug the equations for $E_tS_{t+1}$ and $E_tX_{t+1|t+1}$ into the endogenous variables:

$$
\begin{aligned}
&(FP^2 + GP + H)Y_{t-1} + (FPQ + GQ + M)S_t \\
&\qquad + \{(FP + G)R + [F(QC + R) + NC]A\}X_{t|t} = 0
\end{aligned}
$$

For the equation to hold:

$$
\begin{aligned}
FP^2 + GP + H = 0 \\
FPQ + GQ + M = 0 \\
(FP + G)R + [F(QC + R) + NC]A = 0
\end{aligned}
$$

One thing that needs to be emphasized here is $v_t$ in the state equation and $u_t$ in the observation equation do not have to be the same. The solution only requires that the future exogenous shocks are not expected in the current period.

To solve the system of equations as in Section 1.2.2. We first start from

$$FP^2 + GP + H = 0$$

and we have $H = 0$, thus

$$FP^2 + GP = 0$$

In a forward-looking model the endogenous variables should depend on no past observations, so $P = 0$. This is the shortcut for this specific model setting. And then we can solve the system of equations manually. The solutions to all the cases are presented in the main text.

## State Evolving for the Productivity Level Shock and the Demand Shock Cases

In a Kalman filter setting, $P_{t-1|t-1}$ is the conditional variance and co-variance matrix for the states $(x_{t-1}, x_{t-2})'$. The matrix $P$ and $Q$ are just for this section. Suppose

$$P_{t-1|t-1} = \begin{bmatrix} \sigma_{11}^2 & \sigma_{12}^2 \\ \sigma_{12}^2 & \sigma_{22}^2 \end{bmatrix},$$

Update the variance and covariance matrix for the states:

$$P_{t|t-1} = AP_{t|t}A' + Q = \begin{bmatrix} \rho_x & 0 \\ 1 & 0 \end{bmatrix} * \begin{bmatrix} \sigma_{11}^2 & \sigma_{12}^2 \\ \sigma_{12}^2 & \sigma_{22}^2 \end{bmatrix} * \begin{bmatrix} \rho_x & 0 \\ 1 & 0 \end{bmatrix}' + \begin{bmatrix} \sigma_\epsilon^2 & 0 \\ 0 & 0 \end{bmatrix}$$
$$= \begin{bmatrix} \rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2 & \rho_x\sigma_{11}^2 \\ \rho_x\sigma_{11}^2 & \sigma_{11}^2 \end{bmatrix}$$

Update the variance and covariance matrix for the observations (here I show the solution for only demand shocks. When it comes to the case of only productivity shocks, $(1-\rho_x)$ needs to be replaced by $-(1-\rho_x)$ in the C matrix):

$$G_{t|t-1} = CP_{t|t-1}C' + R$$
$$= \begin{bmatrix} 1 & 0 \\ (1-\rho_x) & 0 \end{bmatrix} * \begin{bmatrix} \rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2 & \rho_x\sigma_{11}^2 \\ \rho_x\sigma_{11}^2 & \sigma_{11}^2 \end{bmatrix} * \begin{bmatrix} 1 & 0 \\ (1-\rho_x) & 0 \end{bmatrix}' + \begin{bmatrix} \sigma_\eta^2 & 0 \\ 0 & \sigma_m^2 \end{bmatrix}$$
$$= \begin{bmatrix} \rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2 + \sigma_\eta^2 & (1-\rho_x)(\rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2) \\ (1-\rho_x)(\rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2) & (1-\rho_x)^2(\rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2) + \sigma_m^2 \end{bmatrix}$$

$$G_{t|t-1}^{-1} = \frac{1}{\gamma} * \begin{bmatrix} (1-\rho_x)^2(\rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2) + \sigma_m^2 & -(1-\rho_x)(\rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2) \\ -(1-\rho_x)(\rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2) & \rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2 + \sigma_\eta^2 \end{bmatrix}$$

of which

$$\gamma = (1-\rho_x)^2(\rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2)\sigma_\eta^2 + \sigma_\eta^2\sigma_m^2 + (\rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2)\sigma_m^2$$

The Kalman gain matrix:

$$
\begin{aligned}
KG = P_{t|t-1}C'G_{t|t-1}^{-1} &= \frac{1}{\gamma} * kg \\
&= \frac{1}{\gamma}\begin{bmatrix} \rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2 & \rho_x\sigma_{11}^2 \\ \rho_x\sigma_{11}^2 & \sigma_{11}^2 \end{bmatrix} * \begin{bmatrix} 1 & 0 \\ (1-\rho_x) & 0 \end{bmatrix}' \\
&* \begin{bmatrix} (1-\rho_x)^2(\rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2) + \sigma_m^2 & -(1-\rho_x)(\rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2) \\ -(1-\rho_x)(\rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2) & \rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2 + \sigma_\eta^2 \end{bmatrix}
\end{aligned}
$$

Suppose $kg_{11}$,$kg_{12}$,$kg_{21}$ and $kg_{22}$ are the four elements in the scaled Kalman gain matrix.

$$
\begin{aligned}
kg_{11} &= (\rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2)\sigma_m^2 \\
kg_{12} &= (1-\rho_x)(\rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2)\sigma_\eta^2 \\
kg_{21} &= \rho_x\sigma_{11}^2\sigma_m^2 \\
kg_{22} &= \rho_x(1-\rho_x)\sigma_{11}^2\sigma_\eta^2
\end{aligned}
$$

Now

$$
KG = \frac{1}{\gamma}\begin{bmatrix} kg_{11} & kg_{12} \\ kg_{21} & kg_{22} \end{bmatrix}
$$

Using the following equation and focusing on the evolving of the first state,

$$
\begin{aligned}
X_{t|t} &= AX_{t-1|t-1} + KG(S_t - S_{t|t-1}) \\
&= (I - KG * C)AX_{t-1|t-1} + KGS_t
\end{aligned}
$$

we get,

$$x_{t|t} = \rho\rho_x x_{t-1|t-1} + (1-\rho)[\delta z_t + (1-\delta)\frac{i_t^*}{1-\rho_x}]$$

with $\rho = \frac{\frac{1}{\sigma_x^2}}{(1-\rho_x)^2\frac{1}{\sigma_m^2}+\frac{1}{\sigma_x^2}+\frac{1}{\sigma_\eta^2}}$ and $\delta = \frac{\frac{1}{\sigma_\eta^2}}{(1-\rho_x)^2\frac{1}{\sigma_m^2}+\frac{1}{\sigma_\eta^2}}$. Of which $\sigma_x^2$ is the conditional variance for the persistent part of the discount factor. The value is determined by the Riccati equation.

## State Evolving for the Productivity Growth Rate Shock Case

In a Kalman filter setting, $P_{t-1|t-1}$ is the conditional variance and covariance matrix for the states $(x_{t-1}, x_{t-2})'$. The matrix $P$ and $Q$ are just for this section. Suppose

$$P_{t-1|t-1} = \begin{bmatrix} \sigma_{11}^2 & \sigma_{12}^2 \\ \sigma_{12}^2 & \sigma_{22}^2 \end{bmatrix},$$

Update the variance and co-variance matrix for the states:

$$\begin{aligned} P_{t|t-1} = AP_{t|t}A' + Q &= \begin{bmatrix} \rho_x & 0 \\ 1 & 0 \end{bmatrix} * \begin{bmatrix} \sigma_{11}^2 & \sigma_{12}^2 \\ \sigma_{12}^2 & \sigma_{22}^2 \end{bmatrix} * \begin{bmatrix} \rho_x & 0 \\ 1 & 0 \end{bmatrix}' + \begin{bmatrix} \sigma_\epsilon^2 & 0 \\ 0 & 0 \end{bmatrix} \\ &= \begin{bmatrix} \rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2 & \rho_x\sigma_{11}^2 \\ \rho_x\sigma_{11}^2 & \sigma_{11}^2 \end{bmatrix} \end{aligned}$$

$$\begin{aligned} G_{t|t-1} &= CP_{t|t-1}C' + R \\ &= \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} * \begin{bmatrix} \rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2 & \rho_x\sigma_{11}^2 \\ \rho_x\sigma_{11}^2 & \sigma_{11}^2 \end{bmatrix} * \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}' + \begin{bmatrix} \sigma_\eta^2 & 0 \\ 0 & \sigma_m^2 \end{bmatrix} \\ &= \begin{bmatrix} \sigma_{11}^2 + \sigma_\eta^2 & \rho_x\sigma_{11}^2 \\ \rho_x\sigma_{11}^2 & \rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2 + \sigma_m^2 \end{bmatrix} \end{aligned}$$

$$G_{t|t-1}^{-1} = \frac{1}{\gamma} * \begin{bmatrix} \rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2 + \sigma_m^2 & -\rho_x^2\sigma_{11}^2 \\ -\rho_x^2\sigma_{11}^2 & \sigma_{11}^2 + \sigma_\eta^2 \end{bmatrix}$$

of which

$$\gamma = \sigma_{11}^2(\sigma_\epsilon^2 + \sigma_m^2) + \sigma_\eta^2(\rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2 + \sigma_m^2)$$

The Kalman gain matrix:

$$\begin{aligned} KG = P_{t|t-1}C'G_{t|t-1}^{-1} &= \frac{1}{\gamma} * kg \\ &= \frac{1}{\gamma} \begin{bmatrix} \rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2 & \rho_x\sigma_{11}^2 \\ \rho_x\sigma_{11}^2 & \sigma_{11}^2 \end{bmatrix} * \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}' \\ &* \begin{bmatrix} \rho_x^2\sigma_{11}^2 + \sigma_\epsilon^2 + \sigma_m^2 & -\rho_x^2\sigma_{11}^2 \\ -\rho_x^2\sigma_{11}^2 & \sigma_{11}^2 + \sigma_\eta^2 \end{bmatrix} \end{aligned}$$

Suppose $kg_{11}$,$kg_{12}$,$kg_{21}$ and $kg_{22}$ are the four elements in the scaled Kalman gain matrix.

$$\begin{aligned} kg_{11} &= \rho_x\sigma_{11}^2\sigma_m^2 \\ kg_{12} &= \rho_x^2\sigma_{11}^2\sigma_\eta^2 + \sigma_\epsilon^2\sigma_{11}^2 + \sigma_\epsilon^2\sigma_\eta^2 \\ kg_{21} &= \sigma_{11}^2(\sigma_\epsilon^2 + \sigma_m^2) \\ kg_{22} &= \rho_x\sigma_{11}^2\sigma_\eta^2 \end{aligned}$$

Now

$$KG = \frac{1}{\gamma} \begin{bmatrix} kg_{11} & kg_{12} \\ kg_{21} & kg_{22} \end{bmatrix}$$

Using the following equation and focusing on the evolving of the first state,

$$
\begin{aligned}
X_{t|t} &= AX_{t-1|t-1} + KG(S_t - S_{t|t-1}) \\
&= (I - KG * C)AX_{t-1|t-1} + KGS_t
\end{aligned}
$$

We get,

$$x_{t|t} = \rho_2 \rho_x x_{t-1|t-1} + \delta_1 \Delta a_t + \delta_2 s_t$$

with $\rho = \frac{\sigma_\eta^2 \sigma_m^2}{\gamma}$, $\delta_1 = \frac{\rho_x \sigma_{11}^2 \sigma_m^2}{\gamma}$ and $\delta_2 = \frac{\rho_x^2 \sigma_{11}^2 \sigma_\eta^2 + \sigma_{11}^2 \sigma_\epsilon^2}{\gamma}$.

## Solution to Only Demand Shocks

The solution method is the same as the appendix from Blanchard et al. (2013). The exogeneous state evolves according to:

$$X_t = AX_{t-1} + Bv_t$$

The private sector observes:

$$S_t = CX_t + Du_t$$

where $X_t = (x_t, x_{t-1})'$, $v_t = (\epsilon_t, 0)'$, $S_t = (z_t, i_t^*)'$ and $u_t = (\eta_t, m_t)'$. So the matrices A, B, C, and D are:

$$A = \begin{bmatrix} \rho_x & 0 \\ 1 & 0 \end{bmatrix}, B = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} C = \begin{bmatrix} 1 & 0 \\ 1 - \rho_x & 0 \end{bmatrix}, D = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Let $Y_t = (y_t, \pi_t)'$ is the vector of endogenous variables. Suppose the economic model can be described in terms of the stochastic difference equation:

$$FE_t[Y_{t+1}] + GY_t + HY_{t-1} + MS_t + NE_t[S_{t+1}] = 0$$

where F, G, H, M, and N are matrices of parameters as follows:

$$F = \begin{bmatrix} 1 & 1 \\ 0 & \beta \end{bmatrix}, G = \begin{bmatrix} -1 & -\phi_\pi \\ \kappa & -1 \end{bmatrix}, H = 0, M = \begin{bmatrix} 1 & -1 \\ 0 & 0 \end{bmatrix}, N = \begin{bmatrix} -1 & 0 \\ 0 & 0 \end{bmatrix}.$$

Suppose there is a unique stable solution of the model:

$$Y_t = PY_{t-1} + QS_t + RX_{t|t}$$

The matrices P, Q, and R can be found by solving the following equations:

$$FP^2 + GP + H = 0; (FP + G)Q + M = 0; (FP + G)R + [F(QC + R) + NC]A = 0$$

Solving the matrix equation system, I get

$$P = 0; Q = \begin{bmatrix} \frac{1}{1+\kappa\phi_\pi} & -\frac{1}{1+\kappa\phi_\pi} \\ \frac{\kappa}{1+\kappa\phi_\pi} & -\frac{\kappa}{1+\kappa\phi_\pi} \end{bmatrix}; R = \begin{bmatrix} -\rho_x \frac{1}{1+\kappa\phi_\pi} & 0 \\ -\rho_x \frac{\kappa}{1+\kappa\phi_\pi} & 0 \end{bmatrix}.$$

## Solution to Only Productivity Growth Rate Shocks

The exogenous state evolves according to:

$$X_t = AX_{t-1} + Bv_t$$

The private sector observes:

$$S_t = CX_t + Du_t$$

where $X_t = (x_t, x_{t-1})'$, $v_t = (\epsilon_t, 0)'$, $S_t = (\Delta a_t, s_t)'$ and $u_t = (\eta_t, m_t)'$. So the matrices A, B, C, and D are:

$$A = \begin{bmatrix} \rho_x & 0 \\ 1 & 0 \end{bmatrix}, B = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} C = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, D = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Let $Y_t = (y_t, \pi_t)'$ is the vector of endogenous variables. Suppose the economic model can be described in terms of the stochastic difference equation:

$$FE_t[Y_{t+1}] + GY_t + HY_{t-1} + MS_t + NE_t[S_{t+1}] = 0$$

where F, G, H, M, and N are matrices of parameters as follows:

$$F = \begin{bmatrix} 1 & 1 \\ 0 & \beta \end{bmatrix}, G = \begin{bmatrix} -1 & -\phi_\pi \\ \kappa & -1 \end{bmatrix}, H = 0, M = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix}, N = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}.$$

Suppose there is a unique stable solution of the model:

$$Y_t = PY_{t-1} + QS_t + RX_{t|t}$$

The matrices P, Q, and R can be found by solving the following equations:

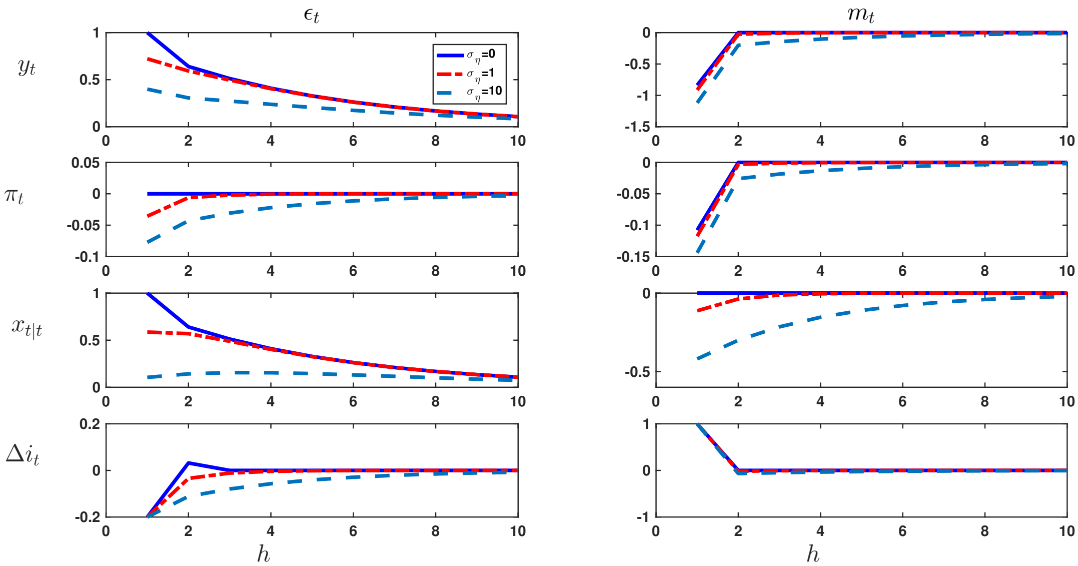
$$FP^2 + GP + H = 0; (FP + G)Q + M = 0; (FP + G)R + [F(QC + R) + NC]A = 0$$

Solving the matrix equation system, I get

$$P = 0; Q = \begin{bmatrix} 0 & -\frac{1}{1+\kappa\phi_\pi} \\ 0 & -\frac{\kappa}{1+\kappa\phi_\pi} \end{bmatrix}; R = \begin{bmatrix} -\frac{1}{1+\kappa\phi_\pi} & 0 \\ -\frac{\kappa}{1+\kappa\phi_\pi} & 0 \end{bmatrix}.$$

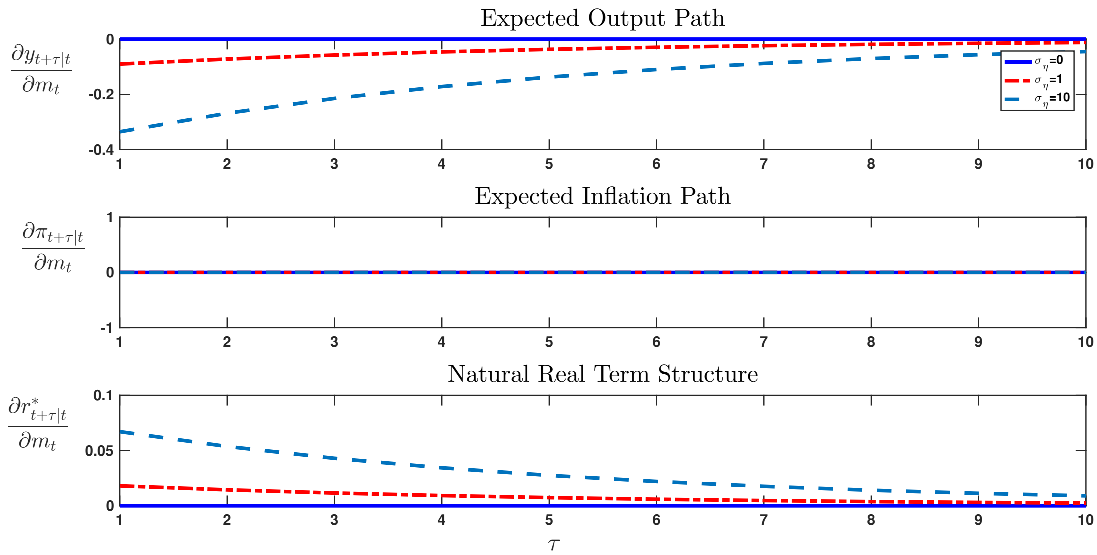
# Figures

Figure 1.4: Impulse Responses: Only Productivity Level Shocks



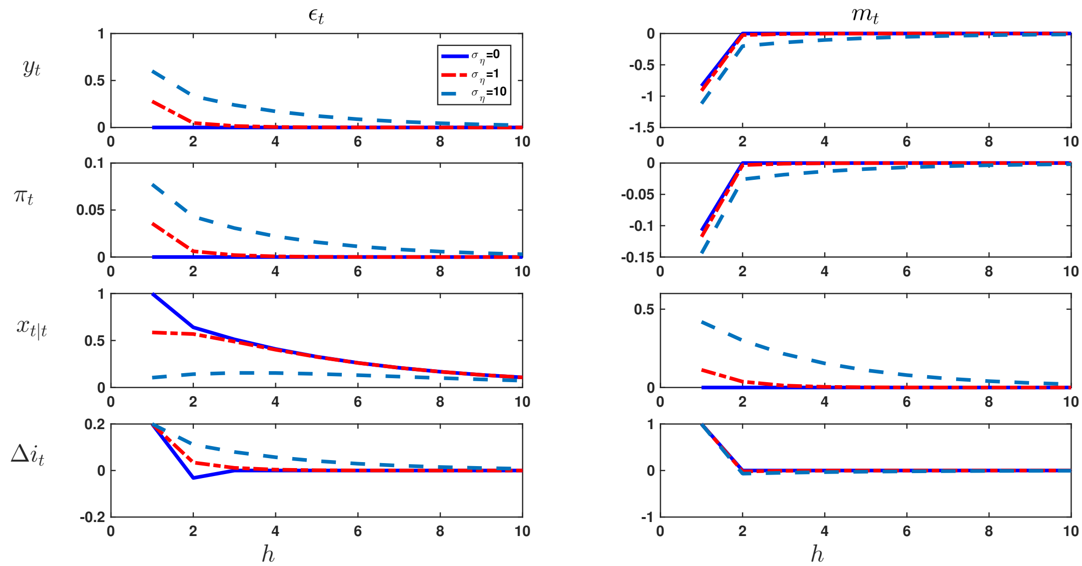

Notes: *Only productivity level shock case.* $x_{t|t}$ *here is the perceived persistent demand condition after observing both signals.* $\Delta i_t$ *is the interest rate surprise, not the monetary policy shock.* $\sigma_\epsilon$*,* $\sigma_\eta$*, and* $\sigma_m$ *are the standard deviation of the persistent productivity shock, the temporary shock and the monetary policy shock, respectively.* $\sigma_\epsilon$ *and* $\sigma_m$ *are set to be* 1*. The blue line corresponds to* $\sigma_\eta = 0$ *when the model collapses to a perfect information model, the red short-dash line corresponds to* $\sigma_\eta = 1$*, and the long-dash line corresponds to* $\sigma_\eta = 10$*.*

Figure 1.5: Expectations Responses: Only Productivity Level Shocks



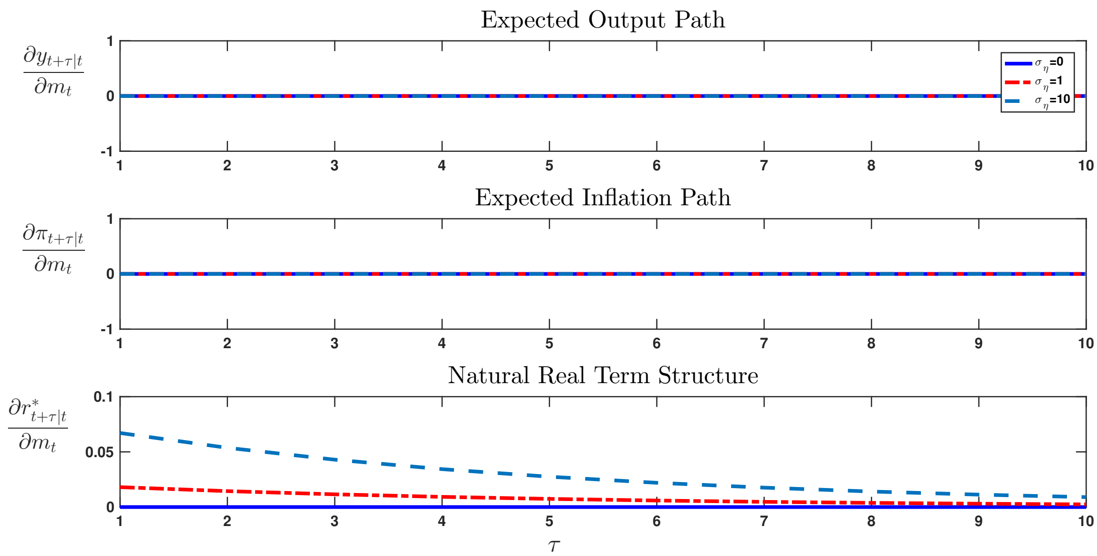

Notes: *$\sigma_\epsilon$, $\sigma_\eta$, and $\sigma_m$ are the standard deviation of the persistent productivity shock, the temporary shock and the monetary policy shock, respectively. $\sigma_\epsilon$ and $\sigma_m$ are set to be* 1*. The blue line corresponds to $\sigma_\eta = 0$ when the model collapses to a perfect information model, the red short-dash line corresponds to $\sigma_\eta = 1$, and the long-dash line corresponds to $\sigma_\eta = 10$.*

Figure 1.6: Impulse Responses: Only Demand Shocks



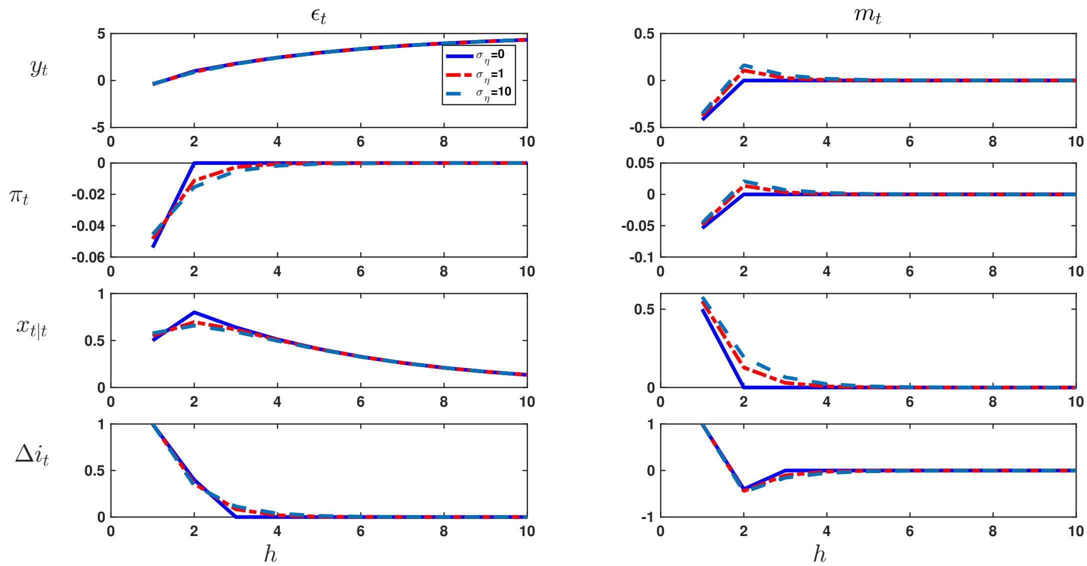

Notes: $x_{t|t}$ *here is the perceived persistent demand condition after observing both signals.* $\Delta i_t$ *is the interest rate surprise, not the monetary policy shock.* $\sigma_\epsilon$*,* $\sigma_\eta$*, and* $\sigma_m$ *are the standard deviation of the persistent demand shock, the temporary shock and the monetary policy shock, respectively.* $\sigma_\epsilon$ *and* $\sigma_m$ *are set to be* 1*. The blue line corresponds to* $\sigma_\eta = 0$ *when the model collapses to a perfect information model, the red short-dash line corresponds to* $\sigma_\eta = 1$*, and the long-dash line corresponds to* $\sigma_\eta = 10$*.*

Figure 1.7: Expectations Responses: Only Demand Shocks



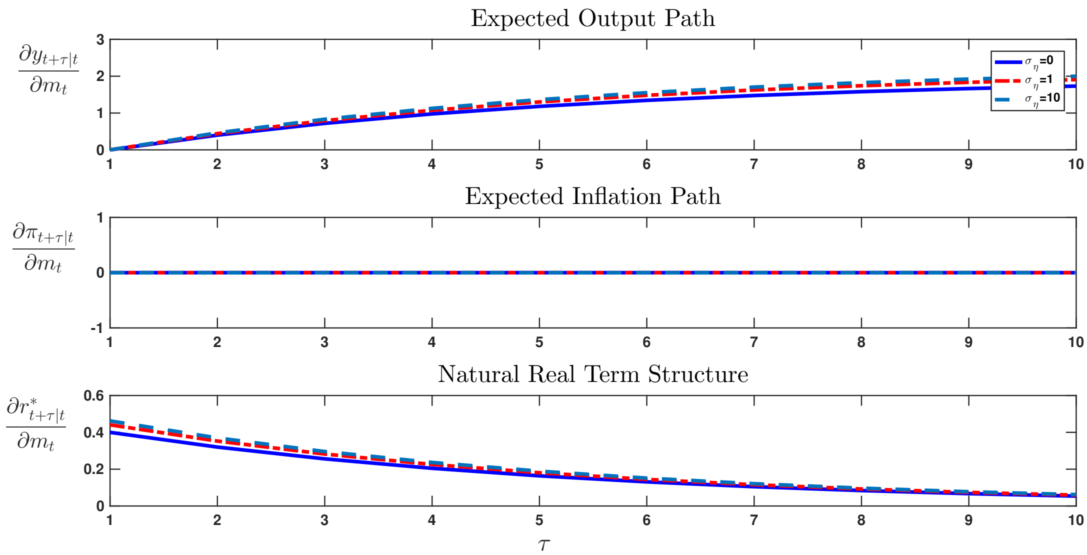

Notes: *$\sigma_\epsilon$, $\sigma_\eta$, and $\sigma_m$ are the standard deviation of the persistent productivity shock, the temporary shock and the monetary policy shock, respectively. $\sigma_\epsilon$ and $\sigma_m$ are set to be* 1*. The blue line corresponds to $\sigma_\eta = 0$ when the model collapses to a perfect information model, the red short-dash line corresponds to $\sigma_\eta = 1$, and the long-dash line corresponds to $\sigma_\eta = 10$.*

Figure 1.8: Impulse Responses: Only Productivity Growth Rate Shocks




Notes: $x_{t|t}$ *here is the perceived persistent demand condition after observing both signals.* $\Delta i_t$ *is the interest rate surprise, not the monetary policy shock.* $\sigma_\epsilon$*,* $\sigma_\eta$*, and* $\sigma_m$ *are the standard deviation of the persistent productivity growth rate shock, the temporary shock and the monetary policy shock, respectively.* $\sigma_\epsilon$ *and* $\sigma_m$ *are set to be* 1*. The blue line corresponds to* $\sigma_\eta = 0$*, the red short-dash line corresponds to* $\sigma_\eta = 1$*, and the long-dash line corresponds to* $\sigma_\eta = 10$*.*

Figure 1.9: Expectations Responses: Only Productivity Growth Rate Shocks




Notes: *$\sigma_\epsilon$, $\sigma_\eta$, and $\sigma_m$ are the standard deviation of the persistent productivity shock, the temporary shock and the monetary policy shock, respectively. $\sigma_\epsilon$ and $\sigma_m$ are set to be 1. The blue line corresponds to $\sigma_\eta = 0$, the red short-dash line corresponds to $\sigma_\eta = 1$, and the long-dash line corresponds to $\sigma_\eta = 10$.*

# Chapter 2

# The Position Effect: A New State-dependent Monetary Policy

*Once the Fed starts raising rates, multiple rate hikes are par for the course.*[1]

The New York Times.

*For weeks now, the financial question of the day has been this: How fast and how far will the Federal Reserve raise short-term interest rates?*[2]

The New York Times.

## 2.1 Introduction

Will the effects of monetary policy shocks, when people know there are multiple monetary policy actions in quarters ahead, differ from when people believe there is a slim chance of further actions? Exploring the heterogeneous effects of monetary policy shocks conditional on people's expectations about future monetary policy actions critically depends on the

[1]This comment is quoted from the New York Times following an increase in the federal funds rate by the Federal Reserve on March 25, 1997. See Sack (2000).

[2]By Jonathan Fuerbringer, on July 11, 2004, this New York Times article was about to introduce Piazzesi & Swanson (2008)

measurement for this expectation. Measuring expectations is a challenging task, if not impossible. I, instead, find a simple proxy to capture the differences of people's expectations about future monetary policy: the relative position of a time point in a monetary policy sequence.

I first define a monetary policy sequence as consecutive monetary policy actions in the same direction. Then I cut into two halves, in an ex-post way, the timeline from the beginning of a monetary policy sequence to the end[3]. The length of the monetary policy sequence can be measured either in days or months. Any day or month can be classified as in the first half of a monetary policy sequence or not. Then all shocks happening in the first half of monetary policy sequences can be identified. This relative position in a monetary policy sequence gives people a sense of future monetary policy actions. Suppose every monetary policy sequence from the past consists of ten policy actions, each 25 basis points, within three years in the same direction. People conjecture this pattern will also hold for the current monetary policy sequence. They can then guess there are probably five more actions in the coming two years if they have observed five actions within the past year since the start of the current monetary policy sequence. The first quote from the New York Times is a vivid example of how people conjecture future monetary policy actions standing at the starting point of a monetary policy sequence. The question of interest is converted to how the effects of the monetary policy vary depending on the shock's relative position in a monetary policy sequence.

I investigate this question using both an event study approach and local projections(Jordà (2005)). First, I explore the asset price responses to monetary policy shocks using high frequency identification approach pioneered by Kuttner (2001), Cochrane & Piazzesi (2002)[4]. To get the monetary policy shocks, following Gürkaynak et al. (2005), I first measure rate changes over a set of future contracts around a 30-minute time window of FOMC announcements (10 minutes before the announcements to 20 minutes after the announcements). The

[3] The end of a monetary policy sequence is defined as $t-1$ if the next monetary policy sequences start at $t$.

[4] Rigobon & Sack (2004),Bernanke & Kuttner (2005),Gürkaynak et al. (2005) and Nakamura & Steinsson (2018) also use high frequency identification approach.

set of future contracts include the current month federal funds future, the federal funds future covering the next FOMC meeting, the Eurodollar futures at around two, three, four quarters ahead. I then extract the principal components from the futures rates changes, rotate the first two principal components to get new principal components. The new first principal component captures the change purely on the level of the federal fund rates, and the new second principal component contains information other than the level change[5]. I use the rotated new first principal component (the target factor as in Gürkaynak et al. (2005)) as the monetary policy shocks[6].

Financial data from January 1990 to June 2008 shows that treasury yields respond significantly less in the first half of monetary policy sequences across maturities from two years to 30 years. Moreover, the magnitude of the difference is large. For example, the five-year Treasury yields increase by 0.339 basis points to 1-basis-point monetary policy shocks which are not in the first half of a monetary policy sequence. In contrast, for those shocks in the first half of a monetary policy sequence, the five-year Treasury yields increase only by 0.149 basis points (0.19 basis points less, 56 percent less). In a baseline New Keynesian model, output is determined not only by the current real rate gap but also the expected future real rate gaps. After observing the different term structure responses to monetary policy shocks depending on the relative position in a monetary policy sequence, a natural question follows: Does a less response in interest rate imply a weaker monetary policy effect on output and inflation? To answer this question, I then employ the state-dependent local projections to study the heterogeneous monetary policy effects similar to Tenreyro & Thwaites (2016)[7]. I collapse the monetary policy shocks to a monthly series by a simple summation of shocks

[5]The data shared by Refet Gurkaynak. The details about the construction of monetary policy shocks are in appendix

[6]This is different from Nakamura & Steinsson (2018) and Barakchian & Crowe (2013), they both use the first principal as the monetary policy shocks. I do not want to include any information from the path factor into the monetary policy level shock. The path factor can be affected by the forward guidance, and it is also possibly affected by the relative position of the monetary policy sequence. The idea is that agents get a sense of what might happen in the future by conjecture from the relative position of the monetary policy.

[7]Auerbach & Gorodnichenko (2012b) and Ramey & Zubairy (2018) use state-dependent local projections to study heterogeneous effect of fiscal policy

happening within that certain month as similar in Barakchian & Crowe (2013). Local projections results confirm that there are significantly weaker output responses to monetary policy shocks in the first half of a monetary policy sequence.

What theory might explain the above empirical results? Different implicit forward guidances, different information effects, and the Fed's different interest rate smoothing behavior at different positions of monetary policy sequences can all be consistent with the empirical findings. People conjecture future monetary policy actions from the relative position in a monetary policy sequence. Agents get the information about the future monetary policy actions not from the central bank communication (the traditional forward guidance) but the relative position in monetary policy sequences. I refer to this as implicit forward guidance, forward guidance without the Fed communicating it explicitly to the public. Campbell et al. (2012) distinguish between Odyssean forward guidance, which publicly commits the FOMC to a future action, and Delphic forward guidance, which merely forecasts macroeconomic performance and likely monetary policy actions. Both Odyssean and Delphic forward guidance are explicit forward guidance, different from implicit forward guidance. However, the implicit forward guidance may share some of Delphic's characteristics in the sense that the conjectured future monetary policy actions are not the Fed's commitment but likely actions based on the macroeconomic situation at the time. This implicit forward guidance can attenuate the effects of monetary policy shocks. If the implicit forward guidance happens more in the first half of monetary policy sequences, it can be consistent with the empirical results here.

A second possible explanation is about whether there is a stronger or weaker Fed information effect at different positions of monetary policy sequences. Nakamura & Steinsson (2018) shows that the long-end of the real term structure responds significantly to the monetary policy shock. And this is consistent with the Fed information effect. The monetary policy shock affects not only the real rate but also expectations about the natural real rate for it contains information about the natural real rate. Agents will change their beliefs about the natural real rate after they update the information contained in the monetary shocks. The Fed information effect should be more prominent in the first half of monetary policy sequences if there is more uncertainty about the natural real rate. The gap between the real rate and the natural real rate (which matters for the output in a New Keynesian model) is moved less compared to a standard New Keynesian model where monetary policy shock only moves the real rate but not expectations of the natural real rate. So monetary policy will have a weaker effect on output.

A third possible explanation is about different Fed's interest rate smoothing behavior at different position of monetary policy sequences. I provide empirical evidence consistent with this explanation[8]. The effects of macroeconomic shocks depend not only on their size but also their persistence. The Fed acts less gradually in the first half of monetary policy sequences, which is equivalent to a smaller interest rate smoothing parameter in a monetary policy rule with interest rate smoothing. This subsequently implies less persistence of the monetary policy shocks in the first half, thus weaker effects. Empirical estimation of the interest rate smoothing parameter similar to Rudebusch (2002) is consistent with this explanation. In a simple setting where people conjecture future monetary policy by observing past monetary policy sequences, people have more uncertainty about future monetary policy direction as they move toward the end of a monetary policy sequence. While monetary policy effectiveness heavily depends on peoples' beliefs about future monetary policy actions, uncertainty about monetary policy effectiveness increases with the agents' uncertainty about future monetary policy actions as time approaches the end of monetary policy sequences. As in Brainard (1967), the Fed will hold off from its optimal action as uncertainty about policy effectiveness shows up. In a multiple period setting, the Fed allocates more actions toward periods with less uncertainty around the policy effectiveness, thus moving faster (less gradually) in the first half of monetary policy sequences.

**Related literature.** This paper relates to three strands of literature: macro-finance

[8] I do not provide empirical evidence supporting or against these two explanations due to volume and data availability constraints. I leave this for future research.

literature on asset price responses to monetary policy shocks; state-dependent monetary policy effects; and the Fed's interest rate smoothing behavior.

A strand of macro-finance literature studies the asset price (term structure) responses to monetary policy using event study methods. Examples include Kuttner (2001), Cochrane & Piazzesi (2002), Gürkaynak et al. (2005) and Nakamura & Steinsson (2018). They differ from each other slightly on the event window length and the monetary policy shock construction. Kuttner (2001) and Cochrane & Piazzesi (2002) use a daily time window, and they measure monetary policy shocks as the daily change on the federal funds rate. Gürkaynak et al. (2005) and Nakamura & Steinsson (2018) use an intra-day (30 minutes around FOMC announcement) time window and measure monetary policy shocks as extracted principal components from a set of future rates. Nakamura & Steinsson (2018) uses the first principal component from a set of future rates as the monetary policy news shock while Gürkaynak et al. (2005) uses the first two principal components from the same set of future rates but rotate them to get the *target factor* and the *path factor*. I investigate the asset price responses to monetary policy shocks closely following Gürkaynak et al. (2005). I take the target factor as the monetary policy shock in the local projections, and I also include the path factor as a control in a robustness check. I differ with all of these papers in exploring the heterogeneous effects of monetary policy shocks on asset price, output and inflation depending on the relative position of monetary policy sequences.

There is a large volume of literature studying monetary policy effects. This paper belongs to this strand but is closely related to two papers: Barakchian & Crowe (2013) and Tenreyro & Thwaites (2016). Barakchian & Crowe (2013) extracted the first principal component from daily changes of federal funds futures one to six months ahead on FOMC dates as the monetary policy shocks and converted them into a monthly series, and then use that series as a Romer-Romer (Romer & Romer (2004)) shock in a VAR. I also construct monetary policy shocks from the rate changes for the same set of futures. However, I use a shorter time window for the futures' rate change as in Gürkaynak et al. (2005), and I use local projections instead of VAR. In addition, I investigate a new type of state-dependent monetary policy rather than the effects of monetary policy in general. Angrist et al. (2018) investigate whether contractionary or expansionary monetary policy have a larger impact. Tenreyro & Thwaites (2016) studies the different effects of monetary policy across business cycles and concludes monetary policy is less potent during a recession. I use state-dependent local projections as their paper building on local projections (Jordà (2005)). We differ in topics of interest. I am interested in how the monetary policy effects are affected by the relative position of shocks in monetary policy sequences rather than the state of the economy.

As for topics of interest, mine is closest in spirit to Berger et al. (2018) and Eichenbaum et al. (2018) in which they claim the monetary policy effect depends on the history of monetary policy actions. My results also suggest the monetary policy effect depends on the monetary policy history (a measurement of the relative position depends on the monetary policy action history). However, the mechanism is quite different. These papers mainly study the different mortgage decisions conditional on different monetary policy action history, while my paper suggests that what matters for monetary policy effect is the expectation of future monetary policy actions. History matters in my paper because history provides information for agents to conjecture future monetary policy actions.

Another related area of research is about interest rate smoothing behavior. Rudebusch (2002) and Rudebusch (2006) provide estimates and discussions about reasons for interest smoothing behavior. On the theoretical side, Brainard (1967) is a seminal paper that provides uncertainty about policy effectiveness as a reason for policymakers to hold off from the optimal policy action if no uncertainty were presenting. Sack (1998) travels down this road and suggests a learning process for the central bank as a reason for the Fed's interest rate smoothing behavior. However, in Sack (1998) as the Fed learns more and more about the policy effectiveness, the Fed should act more aggressively (a smaller interest rate smoothing parameter) in the later part of monetary policy sequences. While in my model, monetary policy effectiveness heavily depends on agents' expectations about future monetary policy actions. In my setting, the Fed is less uncertain about the policy effectiveness in the early period of a monetary policy sequence (except the initial action). The Fed acts faster in the first half of the monetary policy sequences.

**The structure of the paper.** Section 2.2 presents the construction of the First-Half dummy, the monetary policy shocks, and the empirical results. In section 2.3, I elaborate a plausible theoretical explanation for the empirical results. In section 2.4, I conclude and discuss some related issues.

## 2.2 Empirical Results

### 2.2.1 Data

The high-frequency identification data is generously shared by Refet Gurkaynak. The asset price responses are based on this data set, and the monthly monetary policy shock series is also constructed based on this data set. Industrial Production, the Consumer Price Index, the Federal Funds Rate are from FRED St.Louis data.

I focus on a sample period from 1990m2 to 2008m6 for several reasons. First, the monetary policy shock and its monthly series are based on certain future contract rates. The data availability determines the starting point[9]. Secondly, the set of future contracts includes some federal funds rate futures. However, the federal funds future rates will no longer be a proper measure of the monetary policy ahead entering the Zero Lower Bound period[10]. Thirdly, this sample period lies in a period where the monetary policy displays a more predictable pattern. Actions are in 25, 50, or 75 basis points compared to multiples of 6.25 basis points between 1984 and 1988. Moreover, monetary policy sequences last longer and have fewer reverses of directions as compared to 1984-1988. Some literature also suggest a

[9] The market for these contracts started in October 1988.See Angrist et al. (2018)

[10] Gertler & Karadi (2015) use a shorter sample high frequency identified rate movements for certain future contracts to instrument a longer sample policy rates in a VAR. I do not employ this approach in order to make comparable the samples for the asset price responses and the local projections results for output and inflation.

structural break around 1990 for US monetary policy.

### Monetary Policy Sequences and the First-Half Dummy Variable

Monetary policy sequence is defined as consecutive monetary policy actions in the same direction, either tightening or easing. I download the federal funds rate target data from Fred Economic Data. The first difference will show the changes in the federal funds rate target and corresponding dates. I double-check these dates with data from the Fed website about FOMC meetings and an early sample with Hamilton & Jorda (2002). Table 2.1 lists all federal funds rate target changes from June 1989 to December 2017.

Table 2.2 lists the 22 monetary policy sequences from March 1984 to December 2015. It also contains basic information about the 22 monetary policy sequences, such as the duration, the total basis points change for a sequence, and whether it is a tightening sequence or easing sequences. The longest monetary policy sequence[11] lasts for more than three years, from June 6, 1989, to February 3, 1994, with 25 easing actions and a cumulative 681.25 basis points. On March 25, 1997, the Fed raised the federal fund rate target by 25 basis points after three consecutive interest rate easing actions. On September 29, 1998, the Fed lowered the federal funds rate target again (probably the Fed was responding to the Asian Financial Crisis). The 17th sequence is a single-action sequence, so is the 10th sequence.

The reason to introduce monetary policy sequences is to explore different effects of monetary policy shocks at a different position in the monetary policy sequence. I then calculate the duration for each sequence in days. Those days within half of the duration from the starting of monetary policy sequences are classified as in the first half of monetary policy sequences. And the rest days till the end of the monetary policy sequence are classified as the second half of the monetary sequence. Similarly, I cut the monetary policy sequences into halves in months. If the duration divided by two is not an integer, I take the floor of the number as half of the duration. The *First-Half* dummy equals one if the month is in

[11] Ignore the last one with three rounds of Quantitative Easings

Table 2.1: The Federal Funds Rate Target Changes from 1989m6 to 2017m12

| Date | FFR target | Tightening | Easing | Date | FFR target | Tightening | Easing |
|---|---|---|---|---|---|---|---|
| 6-Jun-1989 | 9.5625 | | -25 | 3-Jan-2001 | 6 | | -50 |
| 7-Jul-1989 | 9.3125 | | -25 | 31-Jan-2001 | 5.5 | | -50 |
| 27-Jul-1989 | 9.0625 | | -25 | 20-Mar-2001 | 5 | | -50 |
| 10-Aug-1989 | 9 | | -6.25 | 18-Apr-2001 | 4.5 | | -50 |
| 18-Oct-1989 | 8.75 | | -25 | 15-May-2001 | 4 | | -50 |
| 6-Nov-1989 | 8.5 | | -25 | 27-Jun-2001 | 3.75 | | -25 |
| 20-Dec-1989 | 8.25 | | -25 | 21-Aug-2001 | 3.5 | | -25 |
| 13-Jul-1990 | 8 | | -25 | 17-Sep-2001 | 3 | | -50 |
| 29-Oct-1990 | 7.75 | | -25 | 2-Oct-2001 | 2.5 | | -50 |
| 14-Nov-1990 | 7.5 | | -25 | 6-Nov-2001 | 2 | | -50 |
| 7-Dec-1990 | 7.25 | | -25 | 11-Dec-2001 | 1.75 | | -25 |
| 19-Dec-1990 | 7 | | -25 | 6-Nov-2002 | 1.25 | | -50 |
| 9-Jan-1991 | 6.75 | | -25 | 25-Jun-2003 | 1 | | -25 |
| 1-Feb-1991 | 6.25 | | -50 | 30-Jun-2004 | 1.25 | 25 | |
| 8-Mar-1991 | 6 | | -25 | 10-Aug-2004 | 1.5 | 25 | |
| 30-Apr-1991 | 5.75 | | -25 | 21-Sep-2004 | 1.75 | 25 | |
| 6-Aug-1991 | 5.5 | | -25 | 10-Nov-2004 | 2 | 25 | |
| 13-Sep-1991 | 5.25 | | -25 | 14-Dec-2004 | 2.25 | 25 | |
| 31-Oct-1991 | 5 | | -25 | 2-Feb-2005 | 2.5 | 25 | |
| 6-Nov-1991 | 4.75 | | -25 | 22-Mar-2005 | 2.75 | 25 | |
| 6-Dec-1991 | 4.5 | | -25 | 3-May-2005 | 3 | 25 | |
| 20-Dec-1991 | 4 | | -50 | 30-Jun-2005 | 3.25 | 25 | |
| 9-Apr-1992 | 3.75 | | -25 | 9-Aug-2005 | 3.5 | 25 | |
| 2-Jul-1992 | 3.25 | | -50 | 20-Sep-2005 | 3.75 | 25 | |
| 4-Sep-1992 | 3 | | -25 | 1-Nov-2005 | 4 | 25 | |
| 4-Feb-1994 | 3.25 | 25 | | 13-Dec-2005 | 4.25 | 25 | |
| 22-Mar-1994 | 3.5 | 25 | | 31-Jan-2006 | 4.5 | 25 | |
| 18-Apr-1994 | 3.75 | 25 | | 28-Mar-2006 | 4.75 | 25 | |
| 17-May-1994 | 4.25 | 50 | | 10-May-2006 | 5 | 25 | |
| 16-Aug-1994 | 4.75 | 50 | | 29-Jun-2006 | 5.25 | 25 | |
| 15-Nov-1994 | 5.5 | 75 | | 18-Sep-2007 | 4.75 | | -50 |
| 1-Feb-1995 | 6 | 50 | | 31-Oct-2007 | 4.5 | | -25 |
| 6-Jul-1995 | 5.75 | | -25 | 11-Dec-2007 | 4.25 | | -25 |
| 19-Dec-1995 | 5.5 | | -25 | 22-Jan-2008 | 3.5 | | -75 |
| 31-Jan-1996 | 5.25 | | -25 | 30-Jan-2008 | 3 | | -50 |
| 25-Mar-1997 | 5.5 | 25 | | 18-Mar-2008 | 2.25 | | -75 |
| 29-Sep-1998 | 5.25 | | -25 | 30-Apr-2008 | 2 | | -25 |
| 15-Oct-1998 | 5 | | -25 | 8-Oct-2008 | 1.5 | | -50 |
| 17-Nov-1998 | 4.75 | | -25 | 29-Oct-2008 | 1 | | -50 |
| 30-Jun-1999 | 5 | 25 | | 16-Dec-2008 | 0-0.25 | | -87.5 |
| 24-Aug-1999 | 5.25 | 25 | | 17-Dec-2015 | 0.25-0.50 | 25 | |
| 16-Nov-1999 | 5.5 | 25 | | 15-Dec-2016 | 0.50-0.75 | 25 | |
| 2-Feb-2000 | 5.75 | 25 | | 16-Mar-2017 | 0.75-1.00 | 25 | |
| 21-Mar-2000 | 6 | 25 | | 15-Jun-2017 | 1.00-1.25 | 25 | |
| 16-May-2000 | 6.5 | 50 | | 14-Dec-2017 | 1.25-1.50 | 25 | |

Notes: *The federal funds rate target changes in basis points and their dates. On December 16, 2008, the target change is 75-100 basis points, I put the average in the table.*

Table 2.2: Monetary Policy Sequences 1984-2008

| Number | Start Date | End Date | Direction | NO. action | Total BPs | Duration in Days | Duration in Months |
|---|---|---|---|---|---|---|---|
| 1 | 01Mar1984 | 29Aug1984 | Hike | 9 | 206.3 | 182 | 6 |
| 2 | 30Aug1984 | 23Jan1985 | Ease | 11 | -343.8 | 147 | 4 |
| 3 | 24Jan1985 | 27Mar1985 | Hike | 4 | 50 | 63 | 3 |
| 4 | 28Mar1985 | 24Jul1985 | Ease | 6 | -93.75 | 119 | 4 |
| 5 | 25Jul1985 | 27Dec1985 | Hike | 4 | 31.25 | 156 | 4 |
| 6 | 28Dec1985 | 21May1986 | Ease | 5 | -125 | 145 | 5 |
| 7 | 22May1986 | 10Jul1986 | Hike | 2 | 12.50 | 50 | 2 |
| 8 | 11Jul1986 | 03Dec1986 | Ease | 3 | -100 | 146 | 5 |
| 9 | 04Dec1986 | 01Jul1987 | Hike | 3 | 87.50 | 210 | 7 |
| 10 | 02Jul1987 | 26Aug1987 | Ease | 1 | -12.50 | 56 | 1 |
| 11 | 27Aug1987 | 21Oct1987 | Hike | 4 | 68.75 | 56 | 2 |
| 12 | 22Oct1987 | 29Mar1988 | Ease | 5 | -81.25 | 160 | 5 |
| 13 | 30Mar1988 | 05Jun1989 | Hike | 18 | 331.3 | 433 | 15 |
| 14 | 06Jun1989 | 03Feb1994 | Ease | 25 | -681.3 | 1704 | 56 |
| 15 | 04Feb1994 | 05Jul1995 | Hike | 7 | 300 | 517 | 17 |
| 16 | 06Jul1995 | 24Mar1997 | Ease | 3 | -75 | 628 | 20 |
| 17 | 25Mar1997 | 28Sep1998 | Hike | 1 | 25 | 553 | 18 |
| 18 | 29Sep1998 | 29Jun1999 | Ease | 3 | -75 | 274 | 9 |
| 19 | 30Jun1999 | 02Jan2001 | Hike | 6 | 175 | 553 | 19 |
| 20 | 03Jan2001 | 29Jun2004 | Ease | 13 | -550 | 1274 | 41 |
| 21 | 30Jun2004 | 17Sep2007 | Hike | 17 | 425 | 1175 | 39 |
| 22 | 18Sep2007 | 16Dec2015 | Ease | 10 | -512.5 | 3012 | 99 |

Notes: *"Direction" indicates whether a sequence is in hiking or easing. "Hike" indicates increasing the policy rate, and "Ease" indicates decreasing the policy rate. Duration for the sequence is both measured in days and months. "NO.action" is the total number of monetary policy actions within the sequence, and "Total BPs" is the total basis points changed within certain sequences.*

between the starting month of the sequence and the starting month plus half the duration.

### Monetary Policy Shocks and its Monthly Series

The identification of monetary policy shocks is notoriously difficult for the endogeneity problem and the simultaneity problem. In short, the endogeneity problem arises because output and inflation respond to monetary policy actions and monetary policy decisions are based on output and inflation. The simultaneity problem is likely to appear when a third macroeconomic shock affects both output and the interest rates simultaneously. The high-frequency identification approach avoids the above problems under a mild assumption: the only relevant information during the 30 minutes time window around the FOMC announcements is about the monetary policy shock; the financial markets absorb all relevant information up to 10 minutes before the FOMC announcements. Nakamura & Steinsson (2018) argues this measurement avoids the problem of endogeneity and simultaneity for it uses data from future contracts and measures the change in a relatively short time window.

I use the high-frequency data about the future contracts rates to construct the monetary policy shock and its monthly series. The data set consists of a tight window of asset price movements around the FOMC announcements. I use the following five futures to construct monetary policy shocks:the federal funds rate over the remainder of the month (FF1), the federal funds rate at the time of the next scheduled FOMC meeting (FF2), three Eurodollar rates[12]. Since the change in the federal funds futures reflect the average change over the whole month due to characteristics in the federal funds futures market, thus the change needs to be adjusted to reflect the jump the announcements cause at the time point. I adjust the changes on FF1 and FF2 to get MP1 and MP2 as Kuttner (2001)[13]. MP1 is a measure of the monetary policy shock on the federal funds rate after the announcement, and MP2 is a measure of the monetary policy shock on the federal funds rate after the next FOMC meeting. I extract the principal components from changes on MP1, MP2, ED2, ED3 and ED4, rotate the first two principal components to get the *target factor* and *path factor* as in Gürkaynak et al. (2005). The target factor captures shocks in the federal funds rate level, and the path factor captures most of the remaining information in the set of futures rate movements other than the level change. The path factor captures the information from the Fed's forward guidance.

I use only the target factor as the monetary policy shock instead of any other measurement

[12] Ed2, ED3, and ED4, measuring Eurodollar rates around 1.5, 2.5, 3.5 quarters ahead.

[13] Details of the adjustment are in the appendix.

containing information about the future monetary policy. Nakamura & Steinsson (2018) uses the first principal component of changes on the same set of future contracts as monetary policy shocks. This measurement contains not only information about the level change but also information about the future monetary policy actions. Thus Nakamura & Steinsson (2018) shock already contains information signaled through the relative position of the shock besides the information the Fed conveys through explicit communication. Barakchian & Crowe (2013) also uses the first principal component as monetary policy shocks, but they use the daily change over a different set of futures (the federal funds futures 1-6 months ahead). I also use Nakamura & Steinsson (2018) and Barakchian & Crowe (2013) as robustness checks, and I also include the path factor as a control variable in the local projections as a robustness check. Different measures of shocks do not change the general results: effects of monetary policy are weaker in the first half of monetary policy sequences. Summing up the shocks within a particular month delivers the monthly series of shocks. Figure 2.1 shows shocks by observations, and those red spikes are shocks in the first half of monetary policy sequences.

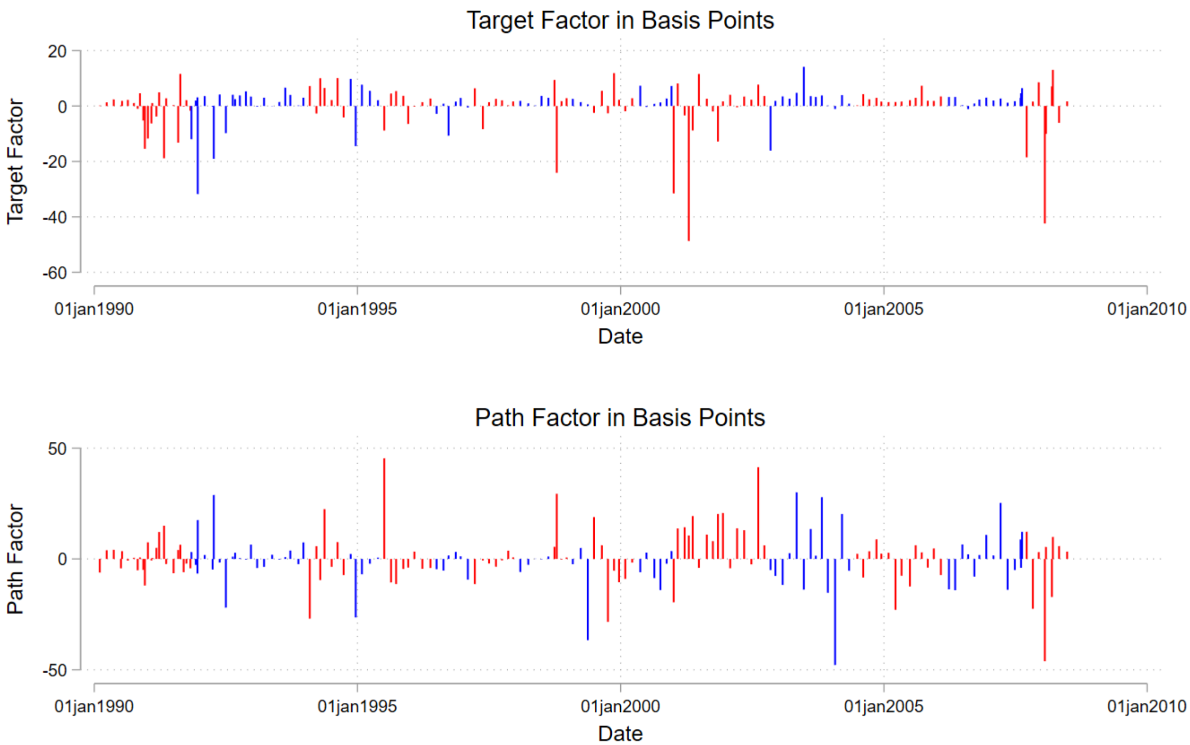
### 2.2.2 Asset Price Responses

The main goal of this section is to explore the asset price responses to monetary policy shocks, and more importantly, how the responses are different depending on the relative position in monetary policy sequences. I begin my study using the commonly employed event study approach following Kuttner (2001), Cochrane & Piazzesi (2002) and Gürkaynak et al. (2005). To identify the effects of monetary policy shocks on asset price, the standard approach is to estimate:

$$\Delta\ S_t = \alpha\ + \gamma \Delta i_t + \epsilon_t$$

where $\Delta\ S_t$ is the change in an outcome variable of interest, e.g., the yield on a 2-year Treasury bond. $\Delta i_t$ is a measure of the monetary policy shocks revealed around the FOMC

Figure 2.1: The Target and Path Factor across Observations




Notes: *The red spikes are those in the first half of monetary policy sequences, while the blue spikes are those in the second half of monetary policy sequences.*

announcement, $\epsilon_t$ is an error term, and $\alpha$ and $\gamma$ are parameters. The parameter of interest is $\gamma$, which measures the effect of the FOMC announcement on $\Delta\ S_t$ relative to its effect on the policy indicator $\Delta i_t$.

If $\Delta S_t$ and $\Delta i_t$ are both measured in monthly data or quarterly data, then there may be an endogeneity problem or a simultaneity problem. The first problem happens when monetary policy responds to a change in term structure earlier than the monetary policy action in that month or quarter. The simultaneity problem arises when both the monetary policy action and the term structure are responding to macroeconomic news releases other than monetary policy news itself. In both cases, the error term $\epsilon_t$ is not orthogonal to $\Delta i_t$, which leads to a biased estimate of $\gamma$. While using intraday data, especially a 30-minute time window around the FOMC announcements, can avoid the endogeneity problem under mild assumptions. First, monetary policy decisions take into account all information before the time window start. Second, there is no other important macroeconomic news released within the 30-minute time window; the monetary policy action and the term structure are not responding to any future macroeconomic news release.

Gürkaynak et al. (2005) think $\Delta i_t$ is due to not only a level change in the short end interest rate but also information in the Fed announcements about future monetary policy path. These two different components can have different effects on asset price. In order to disentangle the different effects, Gürkaynak et al. (2005) estimates:

$$\Delta S_t = \alpha + \gamma_1 \Delta F_1 + \gamma_2 \Delta F_2 + \epsilon_t$$

where $F_1$ and $F_2$ are two rotated orthogonal principal components extracted from rate changes for a set of the federal funds rate and Eurodollar futures. The unexpected change in the current target for the federal funds rate is driven exclusively by $\Delta F1$, plus a small amount of white noise. And $\Delta F2$ is all other aspects of the FOMC announcement that move near-term interest rates without changing the current federal funds rate level. They name the first factor the *target factor* and the second factor the *path factor*, and they show that the path factor helps to explain the asset price responses by a large margin.

The used set of federal funds futures rates and eurodollar futures rates includes MP1, MP2, ED2, ED3, and ED4. The rate changes in the first two federal funds futures are adjusted to reflect the jump at the monetary policy action. Following Kuttner (2001) and Gürkaynak et al. (2005), I adjust the federal funds rate to get the monetary policy shock as follows:

$$MP1 = (ff1_t - ff1_{t-\Delta t}) \frac{D1}{D1 - d1}$$

The federal funds future rate is an average across the month. $D1$ is the total number of days in the month, while $d1$ is the day when the FOMC announcement happens. $(ff1_t - ff1_{t-\Delta t})$

measures the jump of federal funds rate within a 30-minute window for the whole month, scaling by $\frac{D1}{D1-d1}$ delivers a proper measure of the monetary policy shock measured on the federal funds rate for the remaining days in that month instead of a shock to the average on that particular month. However, when the FOMC announcement happens within the last seven days of the month, they use the unscaled change in federal funds futures contracts in the next month to avoid scaling it by a very large factor. They get $MP2$ in a similar manner for the month that containes the next FOMC meeting. ED2, ED3, and ED4 are Eurodollar futures at around 1.5, 2.5, and 3.5 quarters ahead[14]. The details of the construction of the two factors are in the appendix.

As shown in Table 2.3, treasury yields changes around the FOMC announcement are small in general. Moreover, they are not significantly different between those in the first half of monetary policy sequences and those not. For example, the 2-year treasury yields on average drop by 0.78 basis points for all the observations with 6.48 basis points as the standard error. The average is -1.14 for 96 observations within the first half of monetary policy sequences and -0.40 for the rest 74 observations. The difference between the two means is 0.74, but not significant as indicated by the t-statistics (0.7). Factor 1 and 2 are the first two principal components from the changes over the GSS set of futures[15]. The target and path factors are constructed as in Gürkaynak et al. (2005). It is interesting to notice that the target factor within the first half of monetary policy sequences is negative on average and positive for the remaining. However, the difference is not significant.

I confirm Gürkaynak et al. (2005) results using a slightly longer sample period with treasury yields data (Table 2.10 and Table 2.11 in Appendix). The target factor itself can only explain a limited amount of variation in asset price, the term structure to be specific. A second factor, the path factor, can help to explain the asset price variation by a large margin. Moreover, this is more prominent at the long end of the term structure. For example, the target factor explains 11.3 percent of the variation in 5-year treasury yields,

[14] Eurodollar futures have expiration dates lie about two weeks before the end of each quarter

[15] MP1, MP2, ED2, ED3, and ED4 as in Gürkaynak et al. (2005)

Table 2.3: Descriptive Statistics for Yields and Factors Movements

| | Full sample | | Second-half | | First-half | | Difference | |
|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD | Gap | T-statistics |
| 3MthT | -1.24 | 5.23 | -1.27 | 4.24 | -1.21 | 6.06 | -0.06 | (-0.07) |
| 6MthT | -1.16 | 5.80 | -0.77 | 4.68 | -1.53 | 6.71 | 0.77 | (0.82) |
| 2yrT | -0.78 | 6.48 | -0.40 | 5.87 | -1.14 | 7.04 | 0.74 | (0.70) |
| 5yrT | -0.22 | 5.58 | -0.02 | 5.23 | -0.40 | 5.92 | 0.38 | (0.42) |
| 10yrT | -0.07 | 4.08 | 0.10 | 3.73 | -0.22 | 4.40 | 0.32 | (0.48) |
| 30yrT | 0.10 | 3.27 | 0.05 | 2.87 | 0.15 | 3.62 | -0.10 | (-0.20) |
| Factor 1 | 0.00 | 19.43 | 2.76 | 16.44 | -2.13 | 21.29 | 4.89 | (1.69) |
| Factor 2 | 0.00 | 7.88 | -0.11 | 7.13 | 0.08 | 8.45 | -0.20 | (-0.16) |
| Target Factor | -0.00 | 8.62 | 0.95 | 6.53 | -0.74 | 9.91 | 1.69 | (1.34) |
| Path Factor | -0.00 | 12.76 | -1.15 | 12.49 | 0.89 | 12.95 | -2.04 | (-1.04) |
| Observations | 170 | | 74 | | 96 | | 170 | |

Notes: *Sample period: 1990m2-2008m6, the observation on September 17, 2001 is dropped. The first column is the name for the different yields and factors. Factor 1 and 2 are the first two principal components from a Gürkaynak et al. (2005) set of futures. The Target factor and path factor are constructed as Gürkaynak et al. (2005). All numbers except those in last column are in basis points. Column 2 and 3 are for the full sample, Column 4 and 5 are for observations in the second half of a monetary policy sequence, Column 6 and 7 are for observations in the first half of a monetary policy sequence, and Column 8 and 9 are the difference between sub-samples and the t-statistics for the difference.*

and the path factor explains an additional 58.7 percent. The first principal component contains information about the forward guidance. The first principal component can explain more variation in asset price variation across term structure than the target factor alone. However, there is still quite a large part of asset price variations left unexplained. Adding the second principal component greatly reduces the unexplained part, especially at the long end (Table 2.11 in Appendix). Again, take the 5-year treasury yields as an example, two principal components in total explain 79.0 percent of the variation while the first principal component alone explains 55.6 percent.

To explore different effects depending on the relative position of the monetary policy shock, I add one dummy variable indicating the position interacted with the two factors into their estimation equation:

$$\Delta S_t = \alpha + \gamma_1 \Delta F_1 + \gamma_2 \Delta F_2 + \phi_1 D * \Delta F_1 + \phi_2 D * \Delta F_2 + \epsilon_t$$

$D = 1$ if the monetary policy shock happens in the first half of a monetary policy sequence. $\gamma_1, \gamma_2, \phi_1, \phi_2$ are parameters of interest. $\gamma_1$ captures the asset price responses to monetary target factor shock if the shock does not happen in the first half of the monetary policy sequence. $\gamma_2$ is the counterpart for a path factor shock. $\phi_1$ captures the difference of asset price responses to monetary policy target factor shock between those in the first half and those not in the first half of monetary policy sequences. Similarly, $\phi_2$ is the counterpart for the path factor.

**Baseline Results**

As in Gürkaynak et al. (2005), I re-scale the target factor such that its effect on current federal funds rate change (MP1) is one basis point, and re-scale the path factor such that the effect on ED4 futures is the same as the effect of target factor on ED4 futures. Table 2.4 presents estimates of monetary factor shocks on asset prices. The first row is the estimate of $\gamma_1$, the response of the asset price to the target factor is monotonically decreasing as maturity increases. The response of asset price to the path factor displays a hump shape: a larger response on 2-year and 5-year treasury yields and less response on both the short and long end. Estimates of $\gamma_1$ and $\gamma_2$ are all positive which indicates that all treasury yields move in the same direction to the target and path factors[16].

The row of most interest is the third row, which shows that the estimate of $\phi_1$. All the negative estimates suggest less response of asset price to target factor shock if the shock happens in the first half of monetary policy sequences. Moreover, the differences are significant at the 95 percent level for 5-year, 10-year, and 30-year treasury bonds. As for the responses

[16] When comes to scaling the path factor to have the same effect on the ED4 future, I scale it by a negative number of similar magnitude as the scale for the target factor. Thus the response to the un-scaled path factor should be negative

Table 2.4: Heterogeneous Responses of Asset Price to the Target and Path Factors

| | 3MthT | 6MthT | 2yrT | 5yrT | 10yrT | 30yrT |
|---|---|---|---|---|---|---|
| Target Factor | 0.551*** | 0.539*** | 0.479*** | 0.325*** | 0.162*** | 0.0716* |
| | (0.0639) | (0.0601) | (0.0373) | (0.0481) | (0.0523) | (0.0394) |
| Path Factor | -0.0845*** | -0.167*** | -0.366*** | -0.340*** | -0.234*** | -0.155*** |
| | (0.0132) | (0.0345) | (0.0277) | (0.0375) | (0.0312) | (0.0258) |
| TF*firsthalf | -0.132 | -0.0856 | -0.0897* | -0.141** | -0.124** | -0.136** |
| | (0.0877) | (0.0747) | (0.0483) | (0.0590) | (0.0609) | (0.0596) |
| PF*firsthalf | -0.118** | -0.128*** | -0.00643 | -0.00420 | -0.0278 | -0.00876 |
| | (0.0462) | (0.0451) | (0.0351) | (0.0489) | (0.0410) | (0.0387) |
| Constant | -1.368*** | -1.279*** | -0.958*** | -0.367* | -0.149 | 0.0401 |
| | (0.228) | (0.200) | (0.177) | (0.206) | (0.182) | (0.193) |
| Observations | 152 | 152 | 152 | 152 | 152 | 152 |
| Adjusted $R^2$ | 0.749 | 0.833 | 0.888 | 0.797 | 0.705 | 0.453 |

Notes: *Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Sample is all monetary policy announcements from Feb 1991 to Jun 2008. The Target and Path Factors are defined in the main text following Gürkaynak et al. (2005). The target factor captures the shocks in the federal funds rate level, and the path factor captures most of the remaining information in the set of futures rate movements other than the level change. Firsthalf is a dummy that indicates a certain monetary policy shock in the first half of monetary policy sequences.*

to the path factor, there are significant differences at the short end, no significant difference for maturity longer than two years. We should not care much about the significant difference at the short end[17]. Let us take the 10-year treasury yield as an example, the response to the target factor is 0.162 for those shocks happening in the second half of monetary policy sequences, while those shocks that happen in the first half of monetary policy sequences have a 0.124 less response to the target factor. i.e., there is a very small response (0.038=0.162-0.124) to the target factor for shocks in the first half of monetary policy sequences. The above results have important implications on both asset price and monetary policy. First, the financial market responds to monetary target shocks differently depending on the relative

[17]Since the principal components are extracted from the set MP1, MP2, ED2-4, which covers a time span of around one year ahead. So the response of the short end treasury reflects different factor loading for the two factors. If we believe the target and path factors depict the monetary policy stance, we should look at the different responses at maturity longer than one year

position in the monetary policy sequences. Secondly, monetary policy can generate different effects on output and inflation since agents care about not only the change at the short end but also the change along with the whole term structure of interest rates.

### 2.2.3 Robustness Checks

Are these results caused by those inter-meeting actions? Those inter-meeting monetary policy announcements are more likely related to some exogenous shocks and other macroeconomic releases on that day. For example, two unexpected 50-basis-point cuts happened on January 3 and April 18, 2001, respectively, as inter-meeting actions. On October 15, 1998, the Fed cut the federal fund target by 25 basis points in response to conditions in Asia and Russia. To rule out the possibility that the above results are driven more by those inter-meeting actions, I redo the exercise, dropping those inter-meeting observations[18]. Table 2.12 in the Appendix shows the results are even more prominent after dropping inter-meeting actions. The responses of asset price to the target factor are less in the first half of monetary policy sequences. The differences are significant at the long end at 5-year, 10-year, and 30-year treasury yields. There are no significant different responses to the path factor.

Are these results caused by the early sample in which the Fed announcements are implicitly through open market operations the day after the FOMC meeting? The policy of announcing target rate changes explicitly began in February 1994. Moreover, there tends to be more macroeconomic news releases on the same day of FOMC announcements in the early sample. I redo the exercise using observations between February 1994 and June 2008, dropping those early sample observations and the inter-meeting announcements. The results are similar to the above results with only FOMC meeting date announcements (Table 2.13 in Appendix). Are these results caused by the reversal points of the monetary policy? As Demiralp & Jorda (2004) points out (also in Bernanke & Kuttner (2005)), those monetary

[18] Dropping certain observations affect the principal components extracted, thus the construction of target factor and path factor. Thus instead of dropping the observations after the target and path factors are constructed. I drop certain observations and then extract the principal component again and construct the target and path factor accordingly.

policy shocks at the reversal point, which indicates the reverse of the monetary policy direction have a larger effect. I redo the exercise, further dropping those observations at reversal points. Similar results remains (Table 2.14 in Appendix). Nakamura & Steinsson (2018) and Barakchian & Crowe (2013) both use the first principal component as monetary policy shock (Nakamura & Steinsson (2018) paper refers as monetary policy news shock). Is there a different response to the first principal component depending on whether the shock is in the first half of monetary policy sequences? I redo the exercise using the first and second principal components. The results of asset price responses are difficult to explain due to a lack of meaning for the principal components. However, the results suggest significantly different responses between those shocks happening in the first half of monetary policy sequences and those not. And there are less responses in all maturity to the first principal component and significant at the long end.

### 2.2.4 Local Projections Results

After observing different term structure responses to monetary policy shocks depending on the relative position in monetary policy sequences, I want to explore how monetary policy effects depend on the relative position of shock in monetary policy sequences. I use local projections to explore the heterogeneous effects. As proved in Jordà (2005), the local projections method is equivalent to vector autoregression (VAR) when the true data generating process is a VAR process. Furthermore, the local projections method is much easier to implement to explore the nonlinear effects.

I first use local projections method to estimate the impulse responses in the baseline setting. The linear model looks as follows:

$$y_{t+h} = \alpha_h + \beta_b^h \epsilon_t + \phi_b' x_t + u_{t+h}$$

And then I use a state dependent local projections to explore the position effect similar to

Tenreyro & Thwaites (2016). Specifically, I estimate:

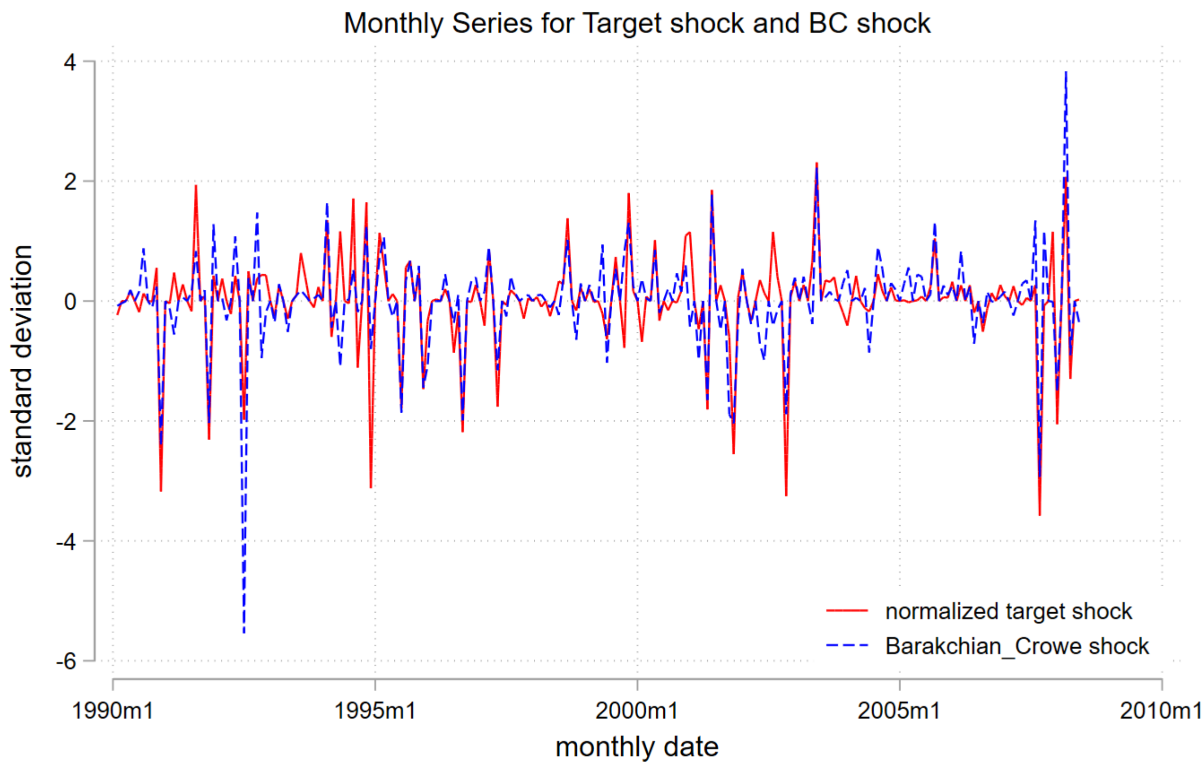
$$y_{t+h} = I(z_t)(\alpha_{f,h} + \beta_f^h \epsilon_t + \phi_f' x_t) + (1 - I(z_t))(\alpha_{r,h} + \beta_r^h \epsilon_t + \phi_r' x_t) + u_{t+h}$$

$I(z_t)$ can takes value from 0 to 1 in general for each month. Here, $I(z_t) = 1$ if the shock happens in the first half of a monetary policy sequence. And 0 for the second half. $y$ is the dependent variable, it can be Industrial Production or the Consumer Price Index (CPI). $x$ include lags of the variables in $y$, and sometimes a price index of commodity as a control [19]. Following Tenreyro & Thwaites (2016) and Ramey & Zubairy (2018), I use Driscoll-Kraay standard errors. I include 12 lags as suggested by Coibion (2012) using monthly data.

$\epsilon_t$ is the monetary policy shock. Barakchian & Crowe (2013) use the first principal component as the monetary policy shocks, and they argue the first principal component avoids the problem of endogeneity. The first principal component contains also information about the forward guidance, so it is a proper measure of the monetary policy shock for their purpose. My main interest is to explore how monetary policy effects depend on the relative position of shocks. Thus I rotate and orthogonalize the components as Gürkaynak et al. (2005) and focus on the impulse response to only the target factor. The reason to avoid including information from the path factor in the monetary policy shock is that it potentially contains some of the information conveyed by the relative position. Figure 2.2 shows the Barakchian & Crowe (2013) shock and the monetary policy shock (the target factor) in this paper. The correlation between the two shock series is 0.7315. As a robustness check, I also use the first principal component as well as Romer-Romer shock as the monetary policy shock for comparison purposes.

[19] Whether including the current level of variables depends on the employment of the recursiveness assumption

Figure 2.2: Monthly Barakchian-Crowe shocks and the Target Factor




Rewrite the above estimation equation:

$$
\begin{aligned}
y_{t+h} &= I(z_t)(\alpha_{f,h} + \beta_f^h \epsilon_t + \phi'_f x_t) + (1 - I(z_t))(\alpha_{r,h} + \beta_r^h \epsilon_t + \phi'_r x_t) + u_{t+h} \\
&= \alpha_{r,h} + I(z_t)(\alpha_{f,h} - \alpha_{r,h}) + \beta_r^h \epsilon_t + (\beta_f^h - \beta_r^h) I(z_t) \epsilon_t \\
&+ \phi'_r x_t + (\phi'_f - \phi'_r) I(z_t) x_t + u_{t+h}
\end{aligned}
$$

The state-dependent local projections can be implemented as the dependent variable on a constant, the dummy, the monetary policy shock, the interaction term of monetary policy shock with the dummy, the controls, and their interaction with the dummy. The coefficient of interest is $\beta_f^h - \beta_r^h$, the coefficient on the interaction of monetary policy shock and the dummy. It measures the different responses of $y_t$ to monetary policy shocks between states at horizon $h$[20]. Now the coefficient on the monetary policy shocks $\beta_r^h$ measures the response of $y_t$ to monetary policy shocks at horizon $h$ when the dummy equals zero. The estimates of $\beta_f^h - \beta_r^h$ across horizon $h$ delivers a direct measure of the difference across states. Adding up estimates $\beta_r^h$ and $\beta_f^h - \beta_r^h$ will result impulse responses for the state of interest.

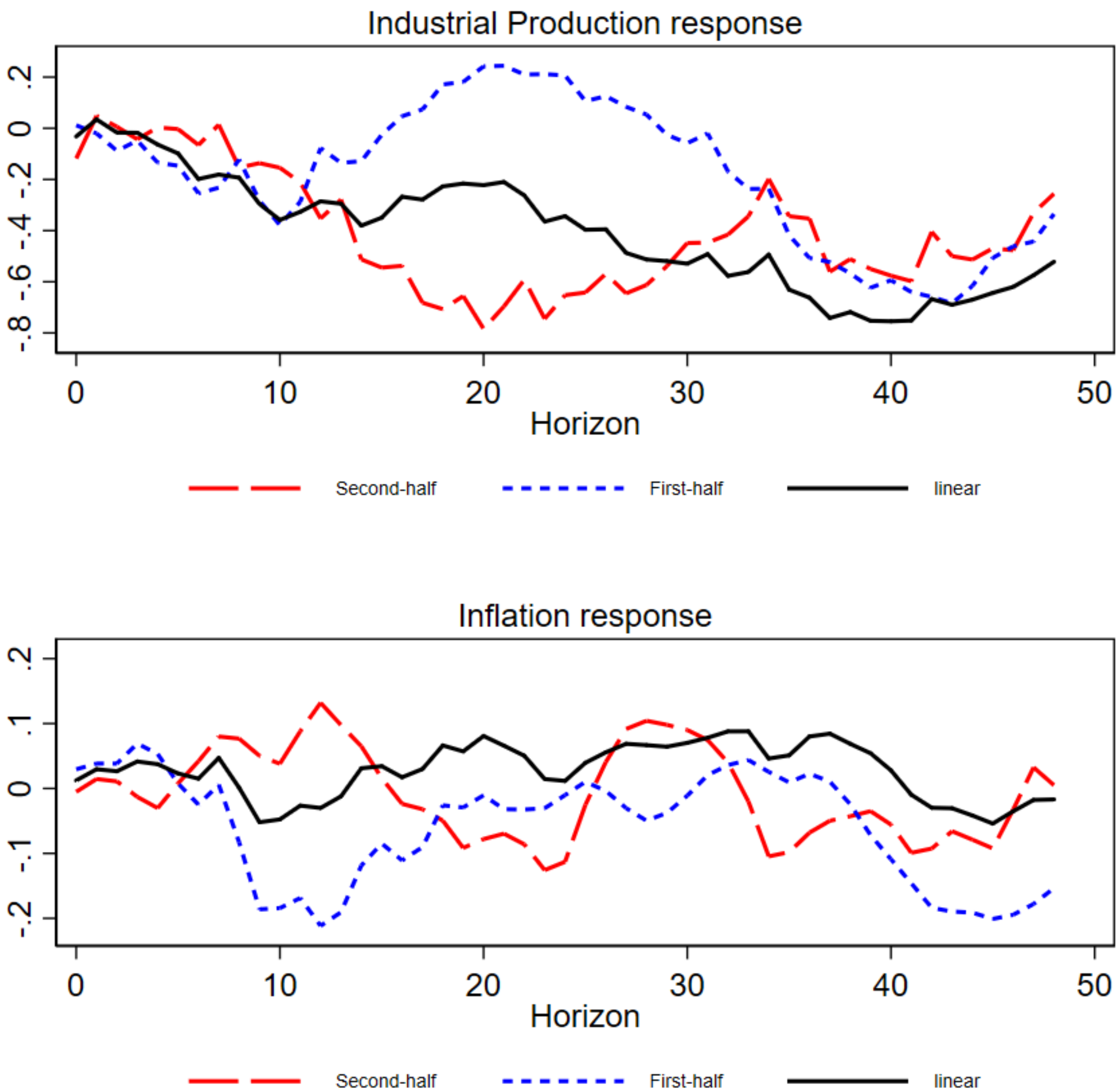
Figure 2.3 shows the impulse responses of Industrial Production, the CPI to an identified monetary policy shock that generates an initial one standard deviation rise in the target factor. The short-dash blue line is the impulse response for monetary policy shocks happening in the first half of monetary policy sequences, while the long-dash red line is the impulse response of the monetary policy shocks happening in the second half of monetary policy sequences. The black line is the overall response in a linear model. First, the full sample responses of output and inflation to the monetary policy shock are similar to the results from Barakchian & Crowe (2013). There is no positive response of output to monetary policy shocks in the 1990m2-2008m6 sample, unlike the results using Romer-Romer shock for this period. Second, and more importantly for this paper, there are different responses depending on the relative position. The first half shocks have a weaker effect in the sense that the output is not reduced as much as by shocks in the second half. Output is reduced by 0.8 percent in the second half 20 months after the shock, while the output response is positive 0.2 percent for the first half at the same horizon.

In Figure 2.4, the estimate of $\gamma_1 = \beta_f^h - \beta_r^h$ (the graphs in the second column) measures the difference in responses of dependent variables to shocks in the first half of monetary policy sequences as compared to those shocks in the second half. The estimate of $\gamma_1$ suggests there is less response in industrial production in the first half. There seems to be more response in the CPI inflation for the first few horizons in the first half of monetary policy sequences[21].

[20] If $I(z_t) = 1$ is a continuous measure of probability for a particular state, then $\beta_f^h - \beta_r^h$ measures the difference of $y_t$'s response if the recession probability increases by a 100 percent. The economic meaning is slightly different from the dummy case, and the results depend on the probability function form for a particular state.

[21] This may be a first-difference form of the price puzzle.

Figure 2.3: Heterogeneous Effects of Monetary Policy Shocks: Relative Position

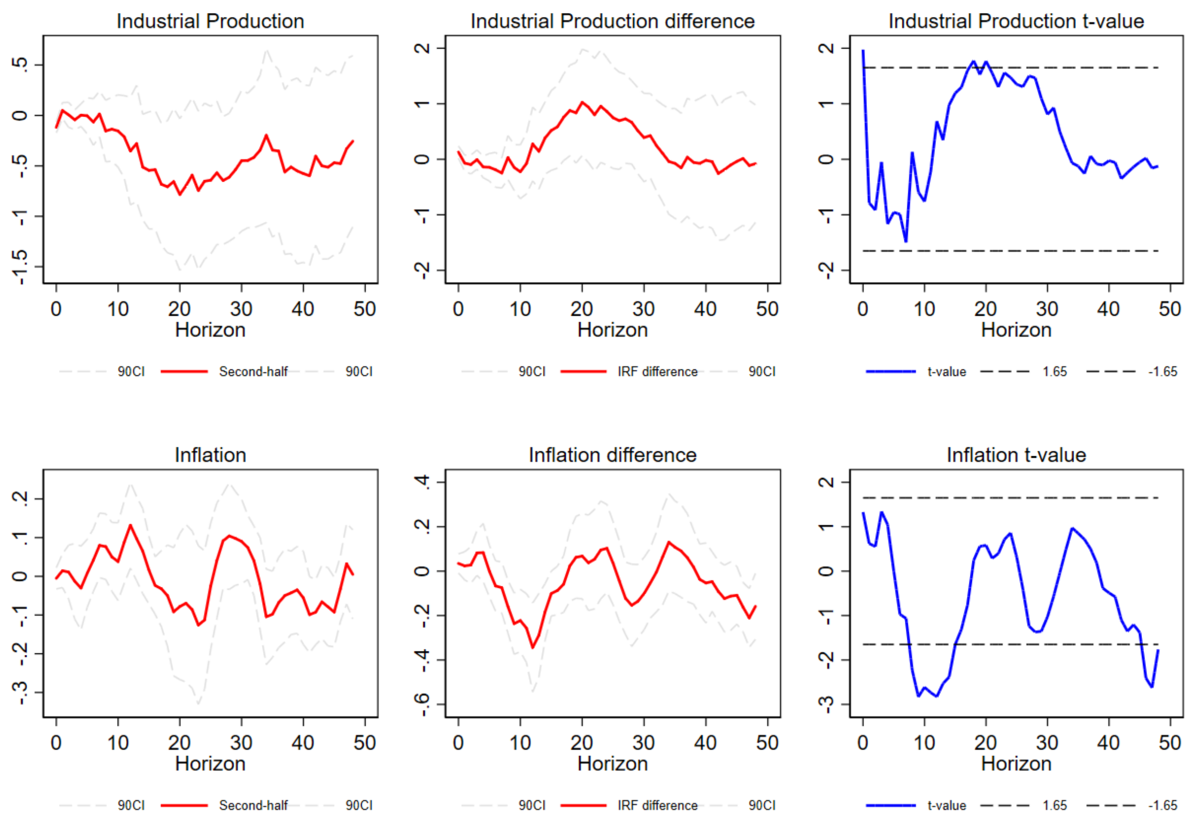



Notes: *The shortdash blue line is the impulse response for monetary policy shocks happening in the first half of monetary policy sequences, while the longdash red line is the impulse response of the monetary policy shocks happening in the second half of monetary policy sequences. The black line is the overall response in a linear model.*

### 2.2.5 Robustness Checks

Several previous papers have identified different types of state-dependent effects of monetary policy. Tenreyro & Thwaites (2016) show that monetary policy has weaker effect during

Figure 2.4: Estimates of $\gamma$s and t-values: Relative Position




Notes: *The red lines are the estimates for $\gamma$s across horizons, with the dashed gray lines indicating 90 percent confidence intervals. The graphs in the first column is $\gamma_0 = \beta_r^h$: the impulse response for the second half of monetary policy sequences. The graphs in the second column is $\gamma_1 = \beta_f^h - \beta_r^h$: the difference between impulse response of the first half to the second half. The last column are the t-value for $\gamma_1$ at certain horizons.*

recessions using 1969q1-2002q4 quarterly data. Angrist et al. (2018) shows less effects for expansionary shocks using the semiparametric method. Jordà et al. (2019) shows that the effects of monetary policy shocks are weaker during slumps and low inflation periods in which they use cross country panel data at an annual frequency. Before concluding that there are weaker effects of monetary policy shocks in the first half of monetary sequences, I need to check whether these state-dependent effects confound my results.

I define the low growth rate state as a dummy with the seven-month average industrial production below the sample average. This low growth state correlates to the recession state.

The low inflation rate state is similarly defined using the CPI inflation. Expansionary shocks are negative monetary policy shocks. Output slack is defined as negative real output gap. As shown in the Appendix, monetary policy has weaker effects during the low growth period (Graph 2.10 in the Appendix). This finding confirms the Tenreyro & Thwaites (2016) results using monthly data with a high-frequency identification shock.

Also, evidence suggests expansionary shocks tend to have a weaker effect (Graph 2.11 in the Appendix). This is consistent with Angrist et al. (2018). However, at the monthly frequency, with the high frequency identified monetary policy shocks, and for the specific sample period, I cannot replicate convincing results suggesting weaker effect for low inflation state and output slack periods.

I check whether those confounding factors are significantly imbalanced between sub-samples cut by the first half dummy. The results are in Table 2.5. The sub-samples cut by the first-half dummy is balanced for low growth rate and expansionary shocks. So we should not worry too much about these two confounding states cause weaker effects in the first half of the monetary sequence. As for the low inflation state, in fact, the second half is loaded with more low inflation observations. So if low inflation is going to cause weaker effects, the second half should have weaker effects instead of the first half[22]. A similar observation is true for the output slack state. So the only state that may concern us is the low growth state, but it should not concern us by a large margin since the low growth state is also relatively balanced across sub-samples.

Further evidence in favor of an additional role for the relative position is the term structure response. In the following Table 2.6, I explore the term structure response conditional on two states: first-half and low growth. As can been see in the table, after conditioning on the low growth state, there is still a weaker response of treasury yields to the monetary policy shock in the first half. It is statistically significant for the 2-year treasury yields at a five percent level. There are also less responses for 5-year, 10-year, and 30-year treasury

[22] Higher level of inflation in the second half may help explain why there are more inflation responses to monetary policy shocks in the second half.

Table 2.5: Descriptive Statistics for Different States

| | Full sample | | Second-half | | First-half | | Difference | |
|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD | Gap | T-statistics |
| Low growth | 0.42 | 0.49 | 0.40 | 0.49 | 0.43 | 0.50 | -0.02 | (-0.35) |
| Low inflation | 0.52 | 0.50 | 0.56 | 0.50 | 0.49 | 0.50 | 0.07 | (1.05) |
| Expansionary shock | 0.26 | 0.44 | 0.26 | 0.44 | 0.26 | 0.44 | -0.01 | (-0.09) |
| Output slack | 0.52 | 0.50 | 0.61 | 0.49 | 0.44 | 0.50 | 0.16* | (2.42) |
| Observations | 221 | | 104 | | 117 | | 221 | |

Notes: *Sample: 1990m2-2008m6 monthly observation. "Low growth","Low inflation" are defined as industrial production growth rate and CPI inflation rate below the mean. "Expansionary shock" is a dummy for negative shocks. "Output slack" is defined as negative detrended industrial production.*

yields, although not individually significant. The general pattern remains even after controlling for the low growth state. The term structure response also provides evidence confirming Tenreyro & Thwaites (2016) results suggesting less responses during recession (low growth state here).

Other robustness checks: as pointed by Gürkaynak et al. (2005), the path factor has an important role in explaining the asset price variations. Thus, it is like an omitted variable in the local projections setting if the path factor is not included in the regression. The omitted variable will generate efficiency loss but not bias when the omitted variable is orthogonal to the explanatory variables. Thus including the path factor shock in the local projections should deliver a tighter error band. Suppose we have already identified two independent shocks[23], local projections will deliver estimates of their effects on dependent variables, respectively. Thus I include the path factor in the local projections as a robustness check. Graph 2.9 in the Appendix shows the results. The general pattern is not changed. Graph 2.8 in the Appendix shows the results using Romer-Romer shock, and the results are robust using Romer-Romer shock. Graph 2.7 in the Appendix shows results using

[23]The path factor and target factor are constructed to be orthogonal to each other for the current period. However, the current path factor might affect the target factor of the next period.

Table 2.6: Heterogeneous Responses of Asset Price to the Target and Path Factors

| | 3MthT | 6MthT | 2yrT | 5yrT | 10yrT | 30yrT |
|---|---|---|---|---|---|---|
| Target Factor | 0.458*** | 0.337* | 0.422*** | 0.286*** | 0.150** | 0.0395 |
| | (0.153) | (0.179) | (0.0341) | (0.0689) | (0.0591) | (0.0600) |
| Path Factor | -0.0512*** | -0.104*** | -0.183*** | -0.180*** | -0.139*** | -0.0949*** |
| | (0.0177) | (0.0203) | (0.0118) | (0.0137) | (0.0144) | (0.0113) |
| TF*firsthalf | 0.101 | 0.0901 | -0.129** | -0.113 | -0.118 | -0.0370 |
| | (0.184) | (0.207) | (0.0608) | (0.0888) | (0.0892) | (0.0895) |
| PF*firsthalf | -0.000714 | -0.0188 | 0.00852 | 0.0130 | -0.0137 | -0.0166 |
| | (0.0231) | (0.0264) | (0.0149) | (0.0307) | (0.0326) | (0.0282) |
| TF*lowgrowth | 0.270 | 0.257 | -0.266*** | -0.153 | -0.0339 | -0.0409 |
| | (0.172) | (0.192) | (0.0869) | (0.137) | (0.134) | (0.119) |
| PF*lowgrowth | -0.000548 | 0.0401 | -0.0359 | -0.0294 | -0.00650 | 0.000744 |
| | (0.0182) | (0.0244) | (0.0240) | (0.0336) | (0.0282) | (0.0261) |
| TF*lowgrowth | -0.523** | -0.338 | 0.0802 | -0.176 | -0.242 | -0.335** |
| *FirstH | (0.239) | (0.249) | (0.205) | (0.201) | (0.174) | (0.150) |
| PF*lowgrowth | -0.0347 | -0.00785 | 0.0539 | 0.0631 | 0.0817* | 0.0603 |
| *FirstH | (0.0423) | (0.0375) | (0.0364) | (0.0492) | (0.0446) | (0.0403) |
| Constant | -0.778*** | -0.520*** | -0.334** | -0.132 | -0.164 | -0.164 |
| | (0.176) | (0.178) | (0.157) | (0.165) | (0.152) | (0.159) |
| Observations | 129 | 129 | 129 | 129 | 129 | 129 |
| Adjusted $R^2$ | 0.709 | 0.693 | 0.832 | 0.800 | 0.749 | 0.592 |

Notes: *Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Sample is all monetary policy announcements from Feb 1991 to Jun 2008. The Target and Path Factors are defined in the main text following Gürkaynak et al. (2005). The target factor captures the shocks in the federal funds rate level, and the path factor captures most of the remaining information in the set of futures rate movements other than the level change. Firsthalf is a dummy that indicates a certain monetary policy shock in the first half of monetary policy sequences. "Low growth" is defined as industrial production growth rate below the mean.*

Barakchian-Crowe shocks are similar to the baseline but smaller in magnitude. This might be because the first principal component already contains at least partially the information in the relative position of monetary policy sequences.

## 2.3 Theoretical Explanations

Different theories may explain the empirical results. First, people may conjecture information about the future monetary policy actions from the relative position in monetary policy sequences. This relative position serves a similar function as implicit forward guidance. The effects of monetary policy shocks interacted with the effects of forward guidance may help to explain weaker effects in the first half of monetary policy sequences.

Nakamura & Steinsson (2018) use the Fed information effect to explain long-end real term structure response to monetary policy shocks. Monetary policy shocks move not only the real rate but also expectations of the natural real rate. And output is determined by the current and expected future gaps between the real rate and the natural real rate. Monetary shocks move the real rate and expectations of the natural real rate in the same direction. Suppose the same monetary policy shock moves expectations of the natural real rate more in the first half of monetary policy sequences. Then output should respond less to monetary policy shocks in the first half of monetary policy sequences where the expected real rate gap is moved by less.

Another possible explanation is about different Fed's interest rate smoothing behavior at different position of monetary policy sequences. I elaborate this idea with some empirical support as follows.

### 2.3.1 Equivalence of Interest Rate Smoothing and Persistence of the Monetary Policy Shock

Blinder (1998,p.80) notes *that central banks generally control only the overnight interest rate, an interest rate is relevant to virtually no economically interesting transactions. Monetary policy has important macroeconomic effects only to the extent that it moves financial market prices that really matter–like long-term interest rates, stock market value, and exchange rate.*

It has long been known that the persistence of the monetary policy shock will affect the monetary policy effect. In a model with interest rate smoothing, the smoothing parameter is equivalent to the persistence measure of the monetary policy shock even if the shock itself is not persistent at all.

A New Keynesian model boils down to three equations: the IS curve, the Phillips curve, and the monetary policy equation. Let us ignore the Phillips curve for this moment to think about an experiment where the central bank controls the real interest rate directly (or an experiment with fixed prices). And we will come back to the case with the nominal interest rate and a model with determinacy.

$$\tilde{y}_t = E_t\tilde{y}_{t+1} - \frac{1}{\sigma}(r_t - r_t^*)$$
$$\tilde{y}_t = -\frac{1}{\sigma}\sum_{j=0}^{\infty} E_t(r_{t+j} - r_{t+j}^*)$$

Of which $\tilde{y}_t$ is the output gap, $r_t$ is the real interest rate, and $r_t^*$ is the natural real rate. Now set $\sigma = 1$ for simplicity (assume log utility for agents).

Monetary policy rule 1: real rate tracks the natural real rate with monetary policy shock $\epsilon_t$. $\epsilon_t$ is i.i.d across time.

$$r_t = r_t^* + \epsilon_t$$

Agents' expectation formation for future periods ($j > 0$):

$$E_t(r_{t+j} - r_{t+j}^*) = 0$$

The effect of monetary policy on the output gap:

$$\frac{\partial \tilde{y}_t}{\partial \epsilon_t} = -1 \tag{2.1}$$

Monetary policy rule 2: real rate tracks the natural real rate with monetary policy shock

$\epsilon_t$, but also with real interest rate smoothing.

$$r_t = \rho r_{t-1} + (1-\rho) r_t^* + \epsilon_t$$

Assume no changes in natural real rate across time $\Delta r_t^* = r_t^* - r_{t-1}^* = 0$. The output gap then can be written as:

$$\tilde{y}_t = -\frac{\rho}{1-\rho}\tilde{r}_{t-1} - \frac{1}{1-\rho}\epsilon_t \tag{2.2}$$

in which $\tilde{r}_{t-1} = r_{t-1} - r_{t-1}^*$, the real rate gap of last period.

From equation 2.2, we can see that the current output gap is determined by two factors. (i) The first term is related to the pre-existing real rate gap. If the pre-existing gap is zero, the first term is zero. (ii) The second term is related to the monetary policy shock, and it is of interest here. $\rho$ is the interest rate smoothing parameter, and it can also be thought of as the persistence of the monetary policy shock. And the $\frac{1}{1-\rho}$ is the duration of the shock. The effect of monetary policy shock can be decomposed into two parts:

$$\frac{\partial \tilde{y}_t}{\partial \epsilon_t} = -\frac{1}{1-\rho} = -1 - \frac{\rho}{1-\rho}$$

The first part is the direct effect of monetary policy shock on the output gap, while the second term the effect of current shock on future real rate gaps. So if $\rho$ is time-varying, and generally, $\rho$ is smaller in the first half of monetary policy sequences. Then the shock's effect is weaker in the first half of monetary policy sequences.

The above part uses real interest rates directly in the monetary policy rule, and the above monetary policy rule will lead to indeterminacy. We can easily change to a policy rule with a nominal interest rate, inflation, and a policy rule that will lead to determinacy:

$$i_t = (1-\rho)(g_\pi \bar{\pi}_t + r_t^*) + \rho i_{t-1} + \epsilon_t$$

Suppose inflation is a function of the current monetary policy shock: $\pi(\epsilon_t)$, then the change in real interest rate is $\epsilon_t - \pi(\epsilon_t)$, $\rho\epsilon_t - \pi(\rho\epsilon_t)$ for $t$ and $t+1$ respectively, and analogously for $t+h$ with $h$ as the horizon from $t$. Again, assume the inflation response to monetary policy shock is linear in its size: $\rho\epsilon_t - \pi(\rho\epsilon_t) = \rho(\epsilon_t - \pi(\epsilon_t))$. Above conclusion that a weaker monetary policy effect for smaller $\rho$ still holds with nominal interest rate and a policy rule with determinacy. Besides this, I simulate a simple NK model with different interest rate smoothing parameters in the monetary policy rule. The output responds less when the interest rate smoothing parameter is smaller. Levin et al. (1999) also has a comparison of different levels of interest rate smoothing parameter. It is consistent with the above claim.

We now move to estimating the interest rate smoothing parameter. Rudebusch (2002) estimates the following equation using quarterly data:

$$i_t = (1-\rho)(g_\pi \bar{\pi}_t + g_y y_t) + \rho i_{t-1} + \xi_t$$

of which $\bar{\pi}_t$ is the 4-quarter average inflation, $y_t$ is the output gap. Rudebusch got 0.73 using 1987q4-1999q4 data.

I estimate a similar equation using monthly data:

$$i_t = (1-\rho)(g_\pi \bar{\pi}_t + g_u u_t) + \rho i_{t-1} + \xi_t \tag{2.3}$$

of which $\bar{\pi}_t$ is the 3-month average inflation, $u_t$ is the unemployment gap since the monthly output is not available. And then I check whether there are significant different interest rate smoothing behavior in the first half of monetary policy sequences.

$$i_t = (1-\rho D)(\phi_\pi \bar{\pi}_t + \phi_u u_t) + \rho D i_{t-1} + \xi_t \tag{2.4}$$

$D = 1$ indicates months in the first half of monetary policy sequences.

Table 2.7 shows the estimates. For the 1990m2-2008m6 sample, $\rho$ equals 0.964 on average for monthly data. 0.956 for the first half of monetary sequences, and 0.974 for the

Table 2.7: Estimates of the Interest Rate Smoothing Parameter

| | (1) | (2) | (3) |
|---|---|---|---|
| L.Effective FFR | 0.964*** | 0.974*** | 0.976*** |
| | (0.00911) | (0.00936) | (0.00889) |
| PCE Core Inflation | 0.0451* | 0.0588** | 0.0639** |
| | (0.0200) | (0.0200) | (0.0202) |
| Unemployment Rate Gap | -0.0773*** | -0.0837*** | -0.0941*** |
| | (0.0207) | (0.0204) | (0.0221) |
| Firsthalf*L.FFR | | -0.0181** | -0.0164** |
| | | (0.00549) | (0.00568) |
| Natural real rate | | | -0.0699 |
| | | | (0.0469) |
| Constant | 0.0460 | 0.0191 | 0.187 |
| | (0.0388) | (0.0406) | (0.124) |
| Observations | 221 | 221 | 221 |
| Adjusted $R^2$ | 0.989 | 0.989 | 0.989 |
| Caculated $\phi_\pi$ | 1.25 | 2.26 | 2.66 |
| Caculated $\phi_u$ | -2.15 | -3.22 | -3.92 |

Notes: *Standard errors in parentheses; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Dependent variable is the effective federal funds rate (FFR) for current month, $\pi$ is the quarterly average PCE core inflation, unemployment rate gap is monthly measurement. Regression equation is $i_t = (1-\rho D)(\phi_\pi \bar{\pi}_t + \phi_u u_t) + \rho D i_{t-1} + \xi_t$ for the first two columns. Regression equation for the last columns is $i_t = (1-\rho D)(\phi_\pi \bar{\pi}_t + \phi_u u_t + \phi_r r^*) + \rho D i_{t-1} + \xi_t$. $r^*$ is the natural real rate. Estimates of $r^*$ are from Holston et al. (2017). I assign the quarterly value of $r^*$ to each month within the quarter. D is the dummy variable indicating a first half of monetary policy sequences. Sample periods are 1990m2-2008m6. The last two row are calculated coefficients on the inflation and unemployment gap in a Taylor rule.*

remaining. The difference is significant at a 99 percent confidence interval. How large is that difference? $0.974^{12} = 0.73$, and $0.956^{12} = 0.58$, one unit shock will have 0.73 remained after 12 months if the persistence is 0.974 while 0.58 if the persistence is 0.956. The last column in Table 2.7 shows the results with the r-star included in the regression. The general pattern still holds. However, the coefficient on the natural real rate is of the opposite sign but not significant. This might be caused by the co-movement of a general declining natural real rate with inflation and the unemployment gap. As can been see from the table, the calculated coefficient on inflation increase from 2.26 to 2.66. The size of the coefficient on the unemployment rate gap increase from 3.22 to 3.92.

### 2.3.2 Rationale for Time-varying Interest Rate Smoothing Behavior of the Fed

The evidence above shows that interest rate smoothing behavior is time-varying. Rudebusch (2006) shows both policy inertia and persistence of macroeconomics shock can lead to interest rate smoothing behavior[24]. I focus on an explanation where the time-varying interest rate smoothing behavior is derived from the Fed optimal decision. I argue that people's uncertainty about the direction of future monetary policy is of great importance and may be the reason for the time-varying interest rate smoothing behavior[25]. I illustrate that there is more uncertainty about the direction of future monetary policy as we approach the end of a sequence. Then I provide a straightforward explanation for the time-varying interest rate smoothing behavior.

My approach introduces a double uncertainty setting where the policy effectiveness uncertainty depends on uncertainty people have about future monetary policy direction. There is less uncertainty about policy effectiveness when there is less uncertainty about future policy direction. The Fed will move more aggressively when there is less policy effectiveness uncertainty as in Brainard (1967). In this model, the first action in a monetary policy sequence will have a larger effect since it reduces the uncertainty about future monetary policy actions, thus reducing policy effectiveness itself, which further leads the Fed to act more aggressively after that. However, the Fed's monetary policy direction uncertainty is not reduced uniformly across time ahead. It reduces more uncertainty around the near end but

[24] Other research (English et al. (2003) and Gerlach-Kristen (2004)) finds that both an intrinsically gradualist approach to policy and gradual changes in the underlying economic environment are needed to explain the historical patterns of U.S. monetary policy.

[25] I discuss the possible reasons for interest rate smoothing behavior in the literature in the appendix.

less for periods far ahead. This leads to faster movements in the first half of the monetary policy sequence and slower actions later.

Are my assumptions too crazy? I quote here Bernanke's 2004 speech about central bank talk and monetary policy. "*Without guidance from the central bank, market participants can do no better than* ***form expectations based on the average past behavior of monetary policymakers****, a strategy that may be adequate under some or even most circumstances but may be seriously misguided in others.*" Expectation formation based on the average past behavior is precisely what this paper aims to capture[26]. In the empirical part, the relative position indicates significantly different effects even after using the path factor as a control. Given that the path factor contains all information about the Fed forward guidance (and the path factor also contains information from relative position), the additional information from the relative position suggests the simple statistical average approach may be at work.

Suppose people experienced three monetary policy sequences in the past ten years, and there were 4, 6, 9 actions in these sequences, respectively, with 25 basis-points change for each action. People are naive in a sense that they conjecture the future by simple statistical learning of past 10-year history (they just count the number of actions in past monetary policy sequences). The effects of monetary policy depend on the current monetary action and three future actions (people are myopic who condition their decisions only on the current monetary policy action and three future actions.). Now people see the Fed raises interest rate, which marks the start of a monetary sequence. People guess a probability for the three future actions as (1,1,1) since the shortest sequence lasts four actions based on the past 10-year history. Later, the Fed does raise the interest rate again. People form a simple guess about the future actions probability as (1,1,2/3) after observing a second hike. People will guess the probability (1,2/3,2/3) after another hike is realized. After eight hikes in a row,

[26]Suppose people have a fixed cost on collecting information from the Fed communication and no cost of knowing the historical average behavior of monetary policy. Then the share of people who choose to be inattentional to the Fed communication depends on the size of the fixed cost comparing to the benefit of listening carefully to the Fed communication.

people will guess a probability of (1/3,0,0). Please see Table 2.8.

Table 2.8: Probability for Future Three Monetary Policy Actions

| Time T | T+1 | T+2 | T+3 |
|---|---|---|---|
| 1st Hike | 1.00 | 1.00 | 1.00 |
| 2nd Hike | 1.00 | 1.00 | 0.67 |
| 3rd Hike | 1.00 | 0.67 | 0.67 |
| 4th Hike | 0.67 | 0.67 | 0.33 |
| 5th Hike | 0.67 | 0.33 | 0.33 |
| 6th Hike | 0.33 | 0.33 | 0.33 |
| 7th Hike | 0.33 | 0.33 | 0.00 |
| 8th Hike | 0.33 | 0.00 | 0.00 |
| 9th Hike | 0.00 | 0.00 | 0.00 |

Notes: *The probability is calculated using simple statistical learning from the monetary policy history for the past 10 years. We assume there were 3 monetary policy sequences with 4, 6 and 9 actions, respectively. Probabilities in the table cell are probability there is an action in the same direction. For example, after the 5th hike, agents think there are 0.67 probability one more hike in next period, 0.33 probability for two and three periods from now.*

The uncertainty around future monetary policy action depends on the relative position in a monetary policy sequence. As you move toward the end of a monetary policy sequence, there is more uncertainty about future monetary policy direction[27]. And this uncertainty about future monetary policy action has important implications since people's decisions are based on the current monetary policy action and future monetary policy actions. The private sector's uncertainty about future monetary policy actions will translate into the Fed's uncertainty about monetary policy effectiveness since the effects of the current monetary policy action depends not only on the current move but also on the possible future moves. As I quote from Sack & Wieland (2000) "*Once the policymaker has established a reputation of conducting a policy of small steps in the same direction with infrequent reversals, a changed path of future rates can be communicated effectively by means of a small initial move*[28]." The quote restates the importance of future monetary policy actions on the outcome and

[27]0 indicates people are not sure about the direction of monetary policy.

[28]also see Goodfriend (1991)

emphasizes the critical role of a possible reversal. As people move along the monetary policy sequences, the probability of a reversal increases. At the same time, the reversal itself has a disproportionally larger effects (Demiralp & Jorda (2004)). A 25 basis points decrease in the federal funds rate target creates less effects after a few decreases than after a few hikes.

The existence of "naive" people in the economy will justify the uncertainty around the policy effectiveness if the Fed knows there exist "naive" people in the economy. The Fed now has to consider its monetary policy action history when making monetary policy decisions. Historical actions help people to form their expectations. Uncertainty about the future monetary policy direction arises as we move toward the end of monetary policy sequences. This dramatically affects people's economic decisions, thus the monetary policy effectiveness. The Fed understands agents' expectation formation process and sees the increasing policy effectiveness uncertainty as moving toward the end of monetary policy sequences. So the Fed tends to move aggressively at the early stage of monetary policy sequences as it did in history. The Fed has a tendency to follow its historical pattern. *History does not repeat itself, but it often rhymes.*

Is there some evidence supporting more uncertainty about the monetary policy direction at the late period of a monetary policy sequence? Evidence from the Fed plot and the SPF tells part of the story . The slope of the Fed dot plot (Figure 2.5) gives us some sense of the uncertainty about monetary policy direction. After the first monetary policy action, it is always easy to see an upward slope Fed dot plot. Nobody believes there might be an easing following a hike. As we approach the end of a monetary policy sequence, you are more likely to see a flat Fed dot plot. Figure 2.5 shows the Fed's forecasts of future policy rates at two time-points in the most recent hiking sequence. In December 2015, which is the starting point of the hiking sequence, you see a positive steep Fed dot plot with the central bankers believe the policy rate will be higher in the future. As we move to the end of this monetary policy sequence, we see a relatively flat Fed dot plot in September 2018. The central bankers in September 2018 believe the policy rate should be kept at the same level or with a modest increase[29]. Since there is little chance that the Fed shifts a positive 45-degree Fed dot plot at $t$ to a negative 45-degree Fed dot plot at $t+1$, the slope of yield curve delivers information about the probability of reversal for monetary policy. In reality, the uncertainty about direction matters, and the speed of the action matters. Some people, not as "naive" as assumed above, will care about how fast the Fed closes certain interest rate gaps. The complexity does not preclude my story if there do exist a non-negligible amount of "naive" people.

The Fed dot plot might contain insider information about the expectation for future monetary policy. The SPF forecasts may better reflect the private sector's expectations. Thus, I use the SPF forecasts data to show my point. I pick some quarters with all three months in the quarter classified as the first half, and then I calculate the forecast slope using the 6-quarter ahead 3-month treasury bill yield minus the current quarter 3-month treasury bill. Table 2.9 shows that in hiking sequences, the first half has a steeper forecast slope. Similar is true for the easing sequence. Slightly different is that the slope turns positive in the second half of easing sequences.

Table 2.9: SPF 3-month Treasury Bill Forecast Slope

| Type | Slope | Observations |
|---|---|---|
| Hike+First | 1.2943 | 7 |
| Hike+Second | 0.8763 | 8 |
| Ease+First | -0.4029 | 14 |
| Ease+Second | 0.4386 | 14 |

Notes: *Slope is defined as the 6 quarter ahead forecast yields minus the current yields for the 3-month treasury bill. Observations are quarters, I count the quarter as in the first half only when all three months are in the first half of monetary policy sequences. "Hike" and "Ease" are the direction of monetary policy sequences. "first", "second" indicates a certain quarter is in the first half, second half of monetary policy sequences.*

Figure 2.6 also shows similar results as the Table 2.9. The long time series is the 3-month treasury bill yield. The red line with circle in it is the forecast at the start of a hiking

[29] Ignore the last point in the plot since it reflects the central banker's belief about long-run neutral rate.

sequence, the solid red line is at the end of a hiking sequence. The dash blue line with the plus signs in it is the forecast at the start of a easing sequence, and the dash blue line is at the end of an easing sequence. Since I use quarterly data here, I only classify a particular quarter as in the first half when all three months in that quarter can be classified as first half. I do not draw all the forecast series for all the quarters that are classified appropriately. I pick the first and last quarters in the monetary policy sequence [30]. Generally, those forecasts in the first half of monetary policy sequences tend to show less uncertainty for monetary policy direction. In the second half a monetary policy sequence, there are expectations about reversal of monetary policy[31].

Can the Fed talk away the uncertainty about the direction of monetary policy? Not all. First, even the Fed holds press conferences after the FOMC meeting, not everyone will and can understand what the Fed tries to convey, not to mention to dig deep into their statements to look for more information. Second, the Fed talks are subject to the time-inconsistent problem. It is not wise for the Fed to make firm promises about future monetary policy actions. The assumption that uncertainty increases as we approach the end of monetary policy sequences does not preclude the power of forward guidance on reducing uncertainty about future monetary policy. What is needed here is that the Fed has no incentive or ability to offset all the uncertainty.

[30] I do not pick certain sequences to draw. I do not want to draw more than two quarters in one sequence, making the picture hard to read.

[31] In the picture, there seems one data point at odds with what I claim. There is a blue dash line with a negative slope and forecast no reverse of direction. That time point is the fourth quarter of 1995 in a short easing sequence with three actions (see Table 2.1). This sequence starts in July 1995, followed by another easing in December 1995 with the last easing in Jan 1996, and then interrupted by a hike in March 1997. I classify the fourth quarter as the last quarter in the second half because this is the quarter with all three months being classified as in the second half. The sequence started just five months ago, and people expect more easing action according to past experience. However, one month later, this sequence ended, resulting the fourth quarter of 1995 is classified as in the second half of monetary policy sequences. So the seemingly odd observation is not odd at all.

**Brainard model in multiple periods.**

Agents' uncertainty about the direction of monetary policy has implications on the Fed's behavior. It has long been known that the Fed moves the interest rate gradually (empirically Rudebusch (1995), theoretically Clarida et al. (2000)). There is literature that explains interest rate smoothing behavior ad-hoc by introducing the variance of interest rates in the Fed's objects. Brainard (1967) is the first to introduce uncertainty of effectiveness as the reason for gradualism. As argued by Sack (1998), the uncertainty in the Brainard model is exogenous. Sack then endogenizes the policy effectiveness uncertainty by introducing the learning process of the Fed. So in his model, the policy action affects the current output and has a dynamic effect on future output. In my model, I start with a simple one-period model like Brainard's paper. Later, I introduce a multiple-period model as in Sack's paper. Unlike the Sack model, the Fed cannot learn about the policy effectiveness for it roots in agents' understanding of future monetary policy actions.

Moreover, the initial action in a monetary policy sequence reduces the uncertainty around the future monetary policy actions[32]. And the uncertainty about the monetary policy actions increases with time. So there is less uncertainty in the near future and more far ahead. Thus there is less uncertainty about the policy effectiveness in the near future and more far ahead. This can be easily seen from Table 2.8 about the simple statistical learning approach. If we allow people in the model to see as far as ten actions ahead. And people are now at a time point where they see no probability for hiking at all. Once they see the initial hike, the uncertainty for the first three actions ahead disappears immediately. However, the uncertainty nine actions ahead remains the same. No past sequence lasts longer than nine actions, so no information is transmitted about nine actions ahead after the initial hike in a sequence. In this simplest statistical learning setting, only the initial hike reduces uncertainty. Since not all monetary policy action reduces the uncertainty about the future monetary policy action, the Fed is not moving faster and faster as we move toward the end

[32]The Fed communication can also help to reduce uncertainty about future monetary policy

of a monetary policy sequence.

Suppose that the policy-maker is concerned with one target variable $y$. Assume that change in the independent variable $\Delta y$ depends linearly on a policy instrument change $\Delta r$, for example, real interest rate[33].

$$\Delta y_t = a_t \Delta r_t$$

If the Fed does not care about uncertainty, and suppose that the Fed wants to change the output by $\Delta y^*$, so the optimal change in policy instrument is given by equation 2.5 in which $\bar{a}_t$ is the average policy effectivenss:

$$\Delta y_t^* = E a_t \Delta r_t^*$$

$$\Delta r_t^* = \Delta y_t^* / \bar{a}_t \tag{2.5}$$

With uncertainty about the policy effectiveness as in Brainard (1967), and the Fed has disutility if the outcome is far from the target:

$$U = -(\Delta y_t - \Delta y_t^*)^2$$

Then the optimal action for the Fed is:

$$\Delta r_t^* = \frac{\bar{a}_t \Delta y_t^*}{(\bar{a}_t)^2 + \sigma_{at}^2} \tag{2.6}$$

The more uncertainty around the policy effectiveness, the more the Fed is deviating from its optimal action comparing to when there is no uncertainty.

Now in a multiple periods setting. With the Fed's utility depends on the uncertainty

[33] I ignore other random term, such as other macroeconomic shocks as in Brainard (1967), and the random intercept term as in Sack (1998).

every period.

$$U = -\sum_{i=0}^{N-1} (\Delta y_{t+i} - \Delta y^*_{t+i})^2$$

A few simplifying assumptions about the Fed's utility are needed here: First, there is no discount between today's and tomorrow's deviation from the optimal target. The result will not change if the discount factor is close to 1. If the discount factor is far from 1, it will make the multiple-period result look like the one-period situation. In an extreme example, when the discount factor is zero, it is exactly the one-period setting. Second, the Fed only cares about the uncertainty around every period, and does not care about the size of the change in policy instrument every period. This will not make any difference in a setting where the uncertainty about the monetary policy effectiveness is time-invariant since the change in the policy rate will also be equalized across periods. However, it does make a difference when the Fed also cares about the size of interest change in every period in a time-varying policy effectiveness uncertainty setting. The first term in the utility tends to load more change to those periods with less uncertainty in policy effectiveness.

$$U = -\sum_{i=0}^{N-1} [(\Delta y_{t+i} - \Delta y^*_{t+i})^2 + (\Delta r_{t+i})^2] \tag{2.7}$$

The second term in equation 2.7 provides incentives for the Fed to equalize the policy instrument changes across periods. The reason I assume away the second term is as follows. Suppose the Fed has to raise 25 basis points every time. If the optimal action is above 25 basis points, the Fed will take action. If not, the Fed waits. So every time the change can be of the same size, the second term can be ignored. The difference in fastness in action now lies in the duration, i.e. the time interval between the two actions.

Now we compare two cases where the policy effectiveness is time-variant and time-invariant. The Fed wants to make a total one unit change in two periods. Let us assume the Fed assign a $s$ to the first period and $1 - s$ to the second period. I normalize $\bar{at} = 1, \sigma_a^2 = 1$, assume $\sigma^2_{a_{t=0}} = \alpha\sigma^2_a = \alpha; \sigma^2_{a_{t=1}} = \gamma\sigma^2_a = \gamma$. By applying the previous results we know $\Delta r^*_{t=0} = \frac{s}{1+\alpha}$ and $\Delta r^*_{t=1} = \frac{s}{1+\gamma}$.

$$EU = -[(\frac{s}{1+\alpha} - s)^2 + \alpha(\frac{s}{1+\alpha})^2 + (\frac{1-s}{1+\gamma} - (1-s))^2 + \gamma(\frac{1-s}{1+\gamma})^2] \tag{2.8}$$

The first order condition delivers the results:

$$S = \frac{\frac{\gamma^2+\gamma}{(1+\gamma)^2}}{\frac{\gamma^2+\gamma}{(1+\gamma)^2} + \frac{\alpha^2+\alpha}{(1+\alpha)^2}} \tag{2.9}$$

When $\alpha = \gamma$, $s = 0.5$. The uncertainty about policy effectiveness is the same across periods, then, the task is evenly distributed. This corresponds to the time-invariant case. When $\alpha = 1, \gamma = 2$, $s = \frac{4}{7}$. In fact, $s$ is an increasing function of $\gamma$ and decreasing function of $\alpha$. When $\alpha$ is relatively small to $\gamma$, there is less uncertainty in the first period, more action is loaded into the first period. The Fed tends to move aggressively in the first period.

Now suppose in a multiple-period model where policy effectiveness uncertainty is $\alpha$ in the first period, and uncertainty is a function $\gamma(N) = N - 1$ for the following periods. N is the number of the monetary policy actions in the monetary policy sequences. This function form captures the relative position of the monetary policy sequence. This function indicates that the uncertainty of policy effectiveness is larger when it comes to the later period of monetary policy sequences[34]. The results should be similar to the two-period case. If the Fed wants to close a certain output gap in N action, it will load more interest rate movements at periods with less uncertainty and less movements at periods with more uncertainty.

[34]The function form about uncertainty can be anything conditional on it is an increasing function of monetary policy action

## 2.4 Conclusion and Discussions

My paper finds weaker responses of asset price to monetary policy shocks in the first half of monetary policy sequences. Monetary policy shocks of the same size move the 10-year treasury yield by 3.8 basis points if they happen in the first half of monetary policy sequences, compared to 16.2 basis points if they happen in the second half of monetary policy sequences. Also, there are weaker effects of monetary policy shocks on output using the state-dependent local projections. Monetary policy shocks of the same size increase output by 0.2 percent after 20 months if they happen in the first half of monetary policy sequences, while they decreases output by 0.8 percent after 20 months if they happen in the second half of monetary policy sequences. A plausible explanation is to connect interest rate smoothing with the persistence of the monetary policy shock. Empirical results suggest less interest rate smoothing during the first half of monetary policy sequences, thus weaker effects. A simple model with policy effectiveness uncertainty depending on people's perceived uncertainty around future policy will lead the Fed to act more aggressively in the early period of monetary policy sequences where there is less uncertainty in a simple statistical learning setting. This model can explain a smaller interest rate smoothing parameter in the first half of the monetary policy sequences. Although people get information about future monetary policy through the Fed's explicit communication, they also get information by observing the relative position in a monetary policy sequence.

Interest rate rule with interest rate smoothing can generate a response in the long end of the term structure, but not as long as empirical evidence suggests. With $\rho = 0.95$ as the interest rate smoothing parameter for monthly data, equivalent to put, the monetary policy shock persistence is 0.95. 0.54 of a unit shock will remain after one year, 0.046 remains after five years, and 0.002 after ten years. These numbers are much smaller than empirically estimated term structure responses. This suggests that interest rate smoothing alone can not fully explain the long-end term structure responses. Other explanations, such as the time-varying information effect and implicit forward guidance, need to be investigated empirically.

And these are for future research.

# Appendix

## The Monetary Policy Shock Construction

I have no innovation on constructing the monetary policy shocks using high frequency data. This part uses information from Kuttner (2001), Gürkaynak et al. (2005), Barakchian & Crowe (2013) and Nakamura & Steinsson (2018).

**Gürkaynak et al. (2005) the target and path factors construction:** The part about the construction of the factors are from their appendix. Let X denote the matrix of changes in MP1, MP2, ED2, ED3 and ED4 across observations. The Fed funds futures have a payout that is based on the average effective federal funds rate that prevails over the calendar month specified in the contract. Thus, immediately before an FOMC meeting, at time $t - \Delta t$, the implied rate from the current-month federal funds future contract,$ff1$, is largely a weighted average of the federal funds rate that has prevailed so far in the month, $r_0$, and the rate that is expected to prevail for the reminder of the month, $r_1$:

$$ff1_{t-\Delta t} = \frac{d1}{D1} r_0 + \frac{D1 - d1}{D1} E_{t-\Delta t}(r_1) + \rho 1_{t-\Delta t}$$

where $d1$ denotes the day of the FOMC meeting, $D1$ is the number of days in the month, and $\rho 1$ denotes any term or risk premium that may be present in the contract. Set $\Delta t = -10, 20$ minutes around the FOMC timing $t$, difference the two equations and get the instant monetary policy shock under the assumption that change in $\rho$ during this narrow window is small relative to the change in the federal funds rate expectations[35]:

$$MP1 = (ff1_t - ff1_{t-\Delta t}) \frac{D1}{D1 - d1}$$

[35] Piazzesi & Swanson (2008) provides evidence this assumption is not inconsistent with the data.

Similarly,

$$MP2 = [(ff2_t - ff2_{t-\Delta t}) - \frac{d2}{D2}MP1]\frac{D2}{D2-d2}$$

Let $ff2$ denote the federal funds futures rate for the month containing the second FOMC meeting (typically the three-month-ahead contract). Then where $d2$ and $D2$ are the day of that FOMC meeting and the number of days in the month containing that FOMC meeting, respectively.

They decompose X into its principal components after normalizing each column to have zero mean and unit variance. We let $\Delta Z1$ and $\Delta Z2$ denote the first two principal components of X, and normalize each of them to have unit variance. To allow for a more structural interpretation of these unobserved factors, we rotate them so that the first factor corresponds to surprise changes in the current federal funds rate target and the second factor corresponds to moves in interest rate expectations over the coming year that are not driven by changes in the current funds rate. They define a matrix $\Delta F$ by

$$\Delta F = \Delta Z U$$

and where

$$U = \begin{bmatrix} \alpha_1 & \beta_1 \\ \alpha_2 & \beta_2 \end{bmatrix}$$

$U$ is identified by four restrictions. First, the columns of $U$ are normalized to have unit length (which normalizes $\Delta F1$ and $\Delta F2$ to have unit variance). Second, the new factors $\Delta F1$ and $\Delta F2$ should remain orthogonal to each other:

$$E(\Delta F1 \Delta F2) = \alpha_1\beta_1 + \alpha_2\beta_2 = 0$$

Lastly, we impose the restriction that $\Delta F2$ does not influence the current policy surprise, MP1, as follows. Let $\gamma 1$ and $\gamma 2$ denote the (known) loadings of MP1 on $\Delta Z1$ and $\Delta Z2$, respectively. Since

$$\Delta Z_1 = \frac{1}{\alpha_1\beta_2 - \alpha_2\beta_1}[\beta_2\Delta F_1 - \alpha_2\Delta F_2]$$
$$\Delta Z_2 = \frac{1}{\alpha_1\beta_2 - \alpha_2\beta_1}[\beta_2\Delta F_2 - \alpha_2\Delta F_1]$$

which is the final restriction. It is then easy to solve for the unique matrix U satisfying these restrictions. Finally, they rescale $\Delta F1$ and $\Delta F2$ so that $\Delta F1$ moves the current policy surprise MP1 one-for-one and $\Delta F2$ has the same magnitude effect on the year-ahead eurodollar futures rate as $\Delta F1$ has on that rate.

**Nakamura & Steinsson (2018) monetary policy news shock:** They extract the principal components from changes with 30-minute FOMC announcement in MP1, MP2, ED2, ED3 and ED4 (same as Gürkaynak et al. (2005)) across observations. They use the first principal component as the monetary policy news shock and argue that contains information about forward guidance.

**Barakchian & Crowe (2013) monetary policy shock monthly series:** They measure daily changes on FOMC dates in FF1, FF2, FF4, FF4, FF5 and FF6 which are the federal funds futures contracts in 1-6 months ahead as the monthly observation. They put a zero in months where there are no FOMC meeting in that month. Then they extract the principal components from these daily changes. They also use the first principal component as the monetary policy shock (same as Nakamura & Steinsson (2018)) and argue that contains information about forward guidance.

## Alternative Reasons for Interest Rate Smoothing

A Bernanke 2004 speech about gradualism (interest rate smoothing)[36] summarizes reasons for gradualism as follows: (1) policymakers' uncertainty about the economy; (2) gradualism gives policymakers greater influence over the long-term interest rates that most affect the economy[37], and (3) gradualism reduces risks to financial stability."[38]

The discussion about the first type of reason is in the main text. There is no good reason for the second reason and third reason for explaining the time-varying characteristic for interest rate smoothing, even it might be a true reason for gradualism in general. The interest-rate smoothing can lend the Fed leveraged effects of monetary policy. This can not explain why the Fed smooths interest rates to different extents at different times. Similarly, if stabilizing the financial market is one of the objects the Fed cares about, there is no good reasons to conjecture why the Fed acts more aggressively at some time relative to others, except that the financial market is more resilient in some periods as to others. As for policymaker's uncertainty, Sack & Wieland (2000) discuss in details about data uncertainty about the economy, parameter uncertainty, and model uncertainty[40]. These different types of uncertainties can be summarized as policy effectiveness uncertainty in Brainard (1967) [41].

Data uncertainty is less likely to be smaller in the first half of the monetary policy. I conjecture that it may be the opposite[42]: there is more data uncertainty in the first half.

[36] There are different terminology for the same Fed behavior in the literature. Bernanke defines gradualism (Bernanke 2004) *"As a general rule, the Federal Reserve tends to adjust interest rates incrementally, in a series of small or moderate steps in the same direction "."This relatively slow adjustment of the policy rate has been referred to variously as interest-rate smoothing, partial adjustment, and monetary policy inertia."*

[37] Woodford (1999) and Levin et al. (1999) use models a forward-looking expectation and conclude interest rate smoothing as optimal monetary policy.

[38] Sack & Wieland (2000) summarize and experiment on data uncertainty[39], parameter uncertainty, and model uncertainty, which belongs to the first category in Bernanke's speech, what they refer to as "forward-looking expectation" is same as the second reason in Bernanke speech. more details on this.

[40] Sack & Wieland (2000) is the first paper, as I know, to discuss the possibility of the time-varying interest rate smoothing. As I quote here, "because the degree of uncertainty about relevant parameters varies over time, the incentive for cautious policy-making is not constant."

[41] The uncertainty has to be smaller in the first half of the monetary policy sequence and larger at the later part of monetary policy sequences to be consistent with the empirical evidence on the time-varying interest rate smoothing parameter.

[42] Orphanides (2001) has some data on data revision. The data revision can be extracted from the Greenbook data set. A regression of data revision on the first half dummy will show whether the data

There may be larger macro shocks in the early period of monetary policy sequence, which causes fluctuation in the data, and it is likely to get more measurement error then. While in the second half of monetary policy sequences, there are little macro shocks causing limited variation in the data, thus more minor measurement error. The Fed should respond to larger macroeconomic shocks more aggressively and less aggressively when there is more data uncertainty. These two factors work in the opposite direction as they are positively correlated. Empirical results (not presented here) show that the first half has slightly smaller uncertainty using uncertainty measurement of Baker et al. (2016). The magnitude is also small and not significant. The VIX is larger for the first half than the second half, not significant, not big in magnitude (1.86 higher with a standard deviation of 7.6). However, more aggressive monetary policy actions can lead to higher VIX. This finding is not conclusive.

Dispersion about interest rate forecasts from Survey of Professional Forecast contains information about the private sector expectations of future monetary policy actions[43]. The problem in using this measurement as a proxy for the policymaker's uncertainty is that the dispersion includes uncertainty about the timing surprise (see Bernanke & Kuttner (2005) and Gurkaynak (2005)), which measures uncertainty about the timing of expected future monetary policy actions. Suppose, in the first case, one forecaster thinks the monetary policy action at the two coming FOMCs are (25,0) and (0,25) in basis points. So the disagreement between these two forecasters is not in the direction. The disagreement lies in the timing of the monetary policy actions. In the second case, suppose that the two forecasters think the monetary policy actions at the two coming FOMCs are (0,0) and (0,0). (0,0) can represent the forecaster's belief that there is for sure no monetary policy action, or the forecaster believes half and half probability are going upward or downward with the same magnitude. In the first case, we measure a dispersion, but they are both sure that the Fed will hike the interest rate, sooner or later. In the second case, we measure no dispersion while the actual uncertainty about monetary policy direction can be large.

uncertainty is more severe in the first half of the monetary policy sequence or not.

[43] This is also one of the methodologies employed in Baker et al. (2016).

## The Path Factor as a control

Omitted Variable in Local projections: Suppose that the true model is that:

$$y_t = \phi y_{t-1} + \alpha s_1 + \beta s_2$$

of which $s_1$ and $s_2$ are structural shocks. Estimation of parameters $\phi$, $\alpha$ and $\beta$ is standard if $s_1, s_2$ and $y_t$ are properly measured. Suppose now in a monetary policy shock setting, $s_1$ ,$s_2$ are the shocks to the target factor and the path factor separately. They are orthogonal to each other and have a separate effect on the output $y_t$. The first principal component $p_1 = as_1 + bs_2$ by assumption[44].

$$y_t = \phi y_{t-1} + \gamma p_1 = \phi y_{t-1} + \gamma(as_1 + bs_2)$$

Think about the two equations in a setting with $y_t$ is the change in treasury yields. The second equation in fact is more restrictive in a sense it impose a certain relation between the asset price responses to the target factor and to the path factor. Similar conclusions are true in a local projections setting. So conditional on that the target factor and the path factor might generate different effects on the dependent variables, a local projections with two factors is less restrictive rather local projections with only the first principal component as the shock.

[44]See Gürkaynak et al. (2005) for details of the rotation of principal components into target and path factors. Mathematically it's equivalent to express the first principal component as the combination of the target factor and the path factor.

# Tables

Table 2.10: Asset Price Responses to the Target Factor

| | 3MthT | 6MthT | 2yrT | 5yrT | 10yrT | 30yrT |
|---|---|---|---|---|---|---|
| Target Factor | 0.451*** | 0.471*** | 0.410*** | 0.219* | 0.0694 | -0.0291 |
| | (0.0847) | (0.0916) | (0.0933) | (0.0870) | (0.0620) | (0.0514) |
| Constant | -1.359*** | -1.284*** | -0.885 | -0.275 | -0.0865 | 0.107 |
| | (0.290) | (0.345) | (0.448) | (0.435) | (0.334) | (0.270) |
| Observations | 152 | 152 | 152 | 152 | 152 | 152 |
| Adjusted $R^2$ | 0.569 | 0.505 | 0.304 | 0.113 | 0.016 | -0.000 |

Notes: *Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Sample is all monetary policy announcements from July 1991 to June 2008, all FOMC announcements except September 17, 2001. The Target and Path Factors are defined in the main text following Gürkaynak et al. (2005). The target factor captures the shocks in the federal funds rate level, and the path factor captures most of the remaining information in the set of futures rate movements other than the level change.*

Table 2.11: Asset Price Responses to the Target Factor and Path Factor

| | 3MthT | 6MthT | 2yrT | 5yrT | 10yrT | 30yrT |
|---|---|---|---|---|---|---|
| Target Factor | 0.452*** | 0.473*** | 0.413*** | 0.222*** | 0.0715* | -0.0278 |
| | (0.0593) | (0.0469) | (0.0267) | (0.0330) | (0.0296) | (0.0368) |
| Path Factor | -0.153*** | -0.241*** | -0.371*** | -0.344*** | -0.252*** | -0.162*** |
| | (0.0313) | (0.0294) | (0.0169) | (0.0235) | (0.0189) | (0.0190) |
| Constant | -1.376*** | -1.311*** | -0.926*** | -0.314 | -0.115 | 0.0891 |
| | (0.229) | (0.209) | (0.176) | (0.208) | (0.186) | (0.203) |
| Observations | 152 | 152 | 152 | 152 | 152 | 152 |
| Adjusted $R^2$ | 0.721 | 0.811 | 0.887 | 0.790 | 0.693 | 0.433 |

Notes: *Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Sample is all FOMC announcements from Feb 1991 to Jun 2008 excluding inter-meeting announcements and reversals. The Target and Path Factors are defined in the main text following Gürkaynak et al. (2005). The target factor captures the shocks in the federal funds rate level, and the path factor captures most of the remaining information in the set of futures rate movements other than the level change.*

Table 2.12: Asset Price Responses to the Target Factor and Path Factor excluding Inter-meeting Announcements

| | 3MthT | 6MthT | 2yrT | 5yrT | 10yrT | 30yrT |
|---|---|---|---|---|---|---|
| Target Factor | 0.628*** | 0.504*** | 0.447*** | 0.361*** | 0.235*** | 0.0852 |
| | (0.0965) | (0.107) | (0.0647) | (0.0728) | (0.0685) | (0.0640) |
| Path Factor | -0.0881*** | -0.144*** | -0.327*** | -0.321*** | -0.236*** | -0.155*** |
| | (0.0117) | (0.0271) | (0.0282) | (0.0335) | (0.0240) | (0.0222) |
| TF*firsthalf | -0.116 | 0.0164 | -0.0998 | -0.233** | -0.304*** | -0.241** |
| | (0.115) | (0.122) | (0.0855) | (0.0948) | (0.0907) | (0.0929) |
| PF*firsthalf | -0.0261 | -0.0593* | 0.0429 | 0.0620 | 0.0261 | 0.0256 |
| | (0.0291) | (0.0345) | (0.0310) | (0.0420) | (0.0354) | (0.0333) |
| Constant | -0.821*** | -0.600*** | -0.414** | -0.150 | -0.0901 | -0.0273 |
| | (0.192) | (0.179) | (0.162) | (0.170) | (0.163) | (0.177) |
| Observations | 137 | 137 | 137 | 137 | 137 | 137 |
| Adjusted $R^2$ | 0.712 | 0.754 | 0.851 | 0.798 | 0.721 | 0.471 |

Notes: *Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Sample is all FOMC announcements from Feb 1991 to Jun 2008* ***excluding inter-meeting announcements****. The Target and Path Factors are defined in the main text following Gürkaynak et al. (2005). The target factor captures the shocks in the federal funds rate level, and the path factor captures most of the remaining information in the set of futures rate movements other than the level change. Firsthalf is a dummy that indicates a certain monetary policy shock in the first half of monetary policy sequences. Of the 137 observations 69 are from the first half of monetary policy sequences.*

Table 2.13: Asset Price Responses to the Target Factor and Path Factor excluding Inter-meeting Announcements and Early Sample

| | 3MthT | 6MthT | 2yrT | 5yrT | 10yrT | 30yrT |
|---|---|---|---|---|---|---|
| Target Factor | 0.648*** | 0.574*** | 0.461*** | 0.391*** | 0.262*** | 0.0679 |
| | (0.102) | (0.0536) | (0.0820) | (0.0933) | (0.0862) | (0.0791) |
| Path Factor | -0.0886*** | -0.138*** | -0.357*** | -0.351*** | -0.259*** | -0.169*** |
| | (0.0102) | (0.0227) | (0.0322) | (0.0382) | (0.0272) | (0.0250) |
| TF*firsthalf | -0.118 | -0.0327 | -0.0897 | -0.247** | -0.321*** | -0.224** |
| | (0.121) | (0.0798) | (0.0985) | (0.110) | (0.103) | (0.102) |
| PF*firsthalf | -0.0281 | -0.0755** | 0.0573 | 0.0756 | 0.0357 | 0.0289 |
| | (0.0301) | (0.0335) | (0.0353) | (0.0467) | (0.0391) | (0.0362) |
| Constant | -0.836*** | -0.678*** | -0.478** | -0.158 | -0.0894 | -0.0132 |
| | (0.219) | (0.180) | (0.197) | (0.202) | (0.191) | (0.206) |
| Observations | 116 | 116 | 116 | 116 | 116 | 116 |
| Adjusted $R^2$ | 0.724 | 0.818 | 0.846 | 0.796 | 0.725 | 0.483 |

Notes: *Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Sample is all FOMC announcements from* ***Feb 1994 to Jun 2008 excluding inter-meeting announcements****. The Target and Path Factors are defined in the main text following Gürkaynak et al. (2005). The target factor captures the shocks in the federal funds rate level, and the path factor captures most of the remaining information in the set of futures rate movements other than the level change. Firsthalf is a dummy that indicates a certain monetary policy shock in the first half of monetary policy sequences. Of the 116 observations 66 are from the first half of monetary policy sequences.*

Table 2.14: Asset Price Responses to the Target Factor and Path Factor excluding Reversals

| | 3MthT | 6MthT | 2yrT | 5yrT | 10yrT | 30yrT |
|---|---|---|---|---|---|---|
| Target Factor | 0.609*** | 0.513*** | 0.309*** | 0.242*** | 0.152* | -0.00329 |
| | (0.0990) | (0.0515) | (0.0789) | (0.0894) | (0.0806) | (0.0734) |
| Path Factor | -0.0572*** | -0.0837*** | -0.210*** | -0.206*** | -0.152*** | -0.0991*** |
| | (0.00654) | (0.0132) | (0.0191) | (0.0227) | (0.0164) | (0.0150) |
| TF*firsthalf | -0.126 | -0.142* | -0.114 | -0.265** | -0.336*** | -0.253*** |
| | (0.123) | (0.0840) | (0.108) | (0.113) | (0.100) | (0.0959) |
| PF*firsthalf | 0.00107 | -0.0244 | 0.0465** | 0.0617** | 0.0382 | 0.0251 |
| | (0.0183) | (0.0192) | (0.0217) | (0.0287) | (0.0245) | (0.0225) |
| Constant | -0.819*** | -0.539*** | -0.335 | -0.0592 | -0.0486 | -0.0654 |
| | (0.206) | (0.174) | (0.205) | (0.205) | (0.194) | (0.200) |
| Observations | 108 | 108 | 108 | 108 | 108 | 108 |
| Adjusted $R^2$ | 0.700 | 0.762 | 0.810 | 0.776 | 0.711 | 0.528 |

Notes: *Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Sample is all FOMC announcements* ***from Feb 1994 to Jun 2008 excluding inter-meeting announcements and those reverse the direction of monetary policy****. The Target and Path Factors are defined in the main text following Gürkaynak et al. (2005). The target factor captures the shocks in the federal funds rate level, and the path factor captures most of the remaining information in the set of futures rate movements other than the level change. Firsthalf is a dummy that indicates a certain monetary policy shock in the first half of monetary policy sequences. Of the 108 observations 58 are from the first half of monetary policy sequences.*

Table 2.15: Asset Price Responses to the First Two Principal Components

| | 3MthT | 6MthT | 2yrT | 5yrT | 10yrT | 30yrT |
|---|---|---|---|---|---|---|
| Factor 1 | 0.251*** | 0.273*** | 0.441*** | 0.418*** | 0.302*** | 0.171*** |
| | (0.0319) | (0.0279) | (0.0411) | (0.0469) | (0.0383) | (0.0345) |
| Factor 2 | 0.655*** | 0.394*** | -0.473*** | -0.558*** | -0.452*** | -0.446*** |
| | (0.136) | (0.0890) | (0.134) | (0.160) | (0.126) | (0.117) |
| Factor1*firsthalf | -0.0333 | 0.00704 | -0.109** | -0.173*** | -0.150*** | -0.106** |
| | (0.0454) | (0.0384) | (0.0504) | (0.0561) | (0.0490) | (0.0461) |
| Factor2*firsthalf | -0.184 | -0.320** | 0.0360 | -0.122 | -0.332* | -0.266 |
| | (0.197) | (0.155) | (0.170) | (0.217) | (0.187) | (0.174) |
| Constant | -0.819*** | -0.539*** | -0.335 | -0.0592 | -0.0486 | -0.0654 |
| | (0.206) | (0.174) | (0.205) | (0.205) | (0.194) | (0.200) |
| Observations | 108 | 108 | 108 | 108 | 108 | 108 |
| Adjusted $R^2$ | 0.700 | 0.762 | 0.810 | 0.776 | 0.711 | 0.528 |

Notes: *Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Sample is all FOMC announcements from Feb 1994 to Jun 2008 excluding inter-meeting announcements and those reverse the direction of monetary policy. Factor 1 and Factor 2 are the first and second principal components respectively. Firsthalf is a dummy that indicates a certain monetary policy shock in the first half of monetary policy sequences. Of the 108 observations 58 are from the first half of monetary policy sequences.*

Table 2.16: Heterogeneous Responses of Asset Price to the Target and Path Factors

| | 3MthT | 6MthT | 2yrT | 5yrT | 10yrT | 30yrT |
|---|---|---|---|---|---|---|
| Target Factor | 0.363*** | 0.225** | 0.375*** | 0.233*** | 0.0792 | -0.164 |
| | (0.0569) | (0.1000) | (0.0546) | (0.0626) | (0.183) | (0.157) |
| Path Factor | -0.0397*** | -0.0945*** | -0.180*** | -0.175*** | -0.126*** | -0.0797*** |
| | (0.00788) | (0.0155) | (0.0101) | (0.00807) | (0.0145) | (0.0131) |
| TF*firsthalf | -0.00428 | 0.102 | -0.252 | -0.377*** | -0.320 | -0.169 |
| | (0.116) | (0.148) | (0.165) | (0.139) | (0.204) | (0.175) |
| PF*firsthalf | -0.0179 | -0.00147 | 0.00574 | 0.0132 | 0.00183 | -0.0131 |
| | (0.0285) | (0.0233) | (0.0217) | (0.0232) | (0.0302) | (0.0255) |
| TF*outputslack | 0.246** | 0.233 | -0.0673 | -0.00551 | 0.0632 | 0.197 |
| | (0.113) | (0.147) | (0.0928) | (0.105) | (0.197) | (0.171) |
| PF*outputslack | -0.0267** | 0.0106 | -0.0258 | -0.0275 | -0.0225 | -0.0200 |
| | (0.0133) | (0.0269) | (0.0261) | (0.0312) | (0.0255) | (0.0236) |
| TF*outputslack | -0.0122 | -0.150 | 0.183 | 0.246 | 0.0638 | -0.0255 |
| *FirstH | (0.185) | (0.196) | (0.190) | (0.179) | (0.236) | (0.223) |
| PF*outputslack | 0.0221 | -0.0322 | 0.0488 | 0.0600 | 0.0452 | 0.0549 |
| *FirstH | (0.0334) | (0.0351) | (0.0333) | (0.0428) | (0.0418) | (0.0377) |
| Constant | -0.787*** | -0.448** | -0.322* | -0.107 | -0.0761 | -0.0909 |
| | (0.182) | (0.184) | (0.187) | (0.178) | (0.160) | (0.174) |
| Observations | 129 | 129 | 129 | 129 | 129 | 129 |
| Adjusted $R^2$ | 0.695 | 0.669 | 0.816 | 0.784 | 0.705 | 0.524 |

Notes: *Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Sample is all monetary policy announcements from Feb 1991 to Jun 2008. The Target and Path Factors are defined in the main text following Gürkaynak et al. (2005). The target factor captures the shocks in the federal funds rate level, and the path factor captures most of the remaining information in the set of futures rate movements other than the level change. Firsthalf is a dummy that indicates a certain monetary policy shock in the first half of monetary policy sequences. "Output slack" is defined as negative detrended industrial production.*

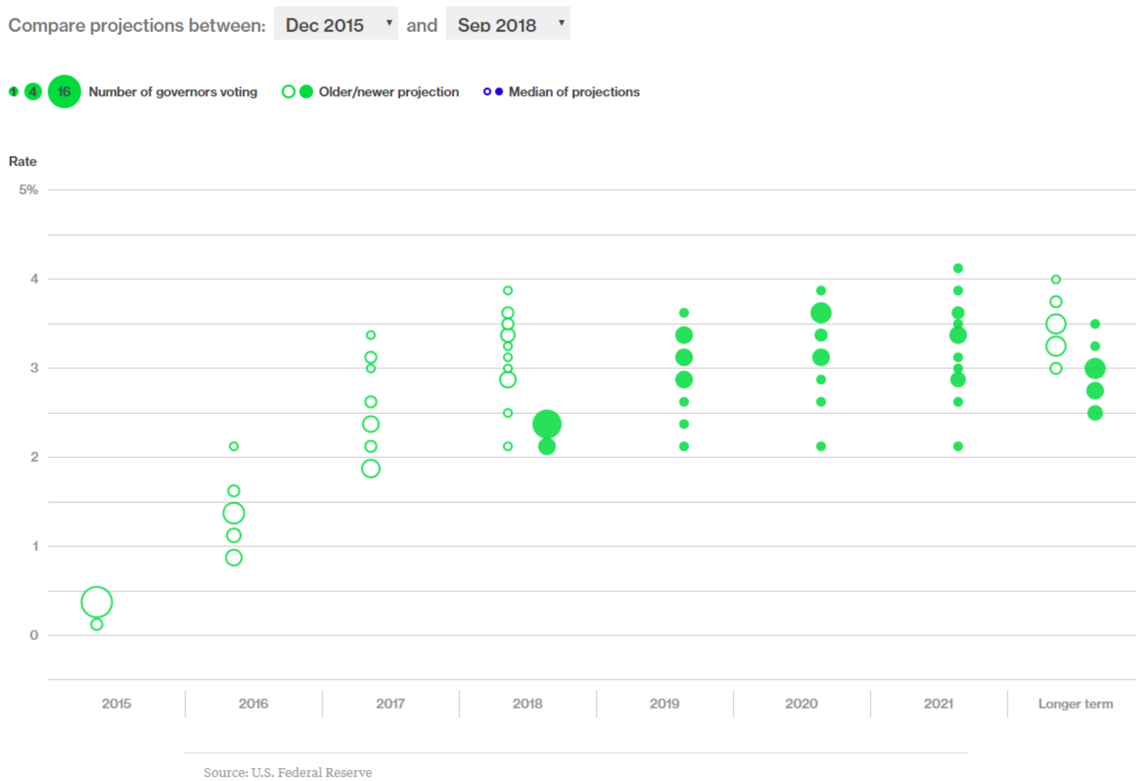
Table 2.17: SPF Forecast Yields on 3-month Treasury Bill

| Date | T-Bill1 | T-Bill2 | T-Bill3 | T-Bill4 | T-Bill5 | T-Bill6 | Direction |
|---|---|---|---|---|---|---|---|
| 1995Q3 | 5.60 | 5.48 | 5.50 | 5.50 | 5.53 | 5.51 | - |
| 1995Q4 | 5.37 | 5.35 | 5.20 | 5.12 | 5.10 | 5.10 | - |
| 1996Q1 | 5.26 | 4.94 | 4.78 | 4.70 | 4.71 | 4.78 | - |
| 1996Q2 | 4.93 | 5.00 | 5.09 | 5.10 | 5.07 | 5.00 | + |
| 1996Q3 | 5.02 | 5.12 | 5.20 | 5.28 | 5.25 | 5.23 | + |
| 1996Q4 | 5.10 | 5.04 | 5.15 | 5.20 | 5.20 | 5.10 | 0 |
| 1997Q1 | 4.98 | 5.04 | 5.07 | 5.08 | 5.05 | 5.01 | + |
| 1997Q2 | 5.06 | 5.26 | 5.47 | 5.50 | 5.50 | 5.40 | + |
| 1997Q3 | 5.05 | 5.10 | 5.25 | 5.37 | 5.25 | 5.19 | + |
| 1997Q4 | 5.05 | 5.10 | 5.20 | 5.26 | 5.28 | 5.24 | + |
| 1998Q1 | 5.09 | 5.10 | 5.10 | 5.09 | 5.10 | 5.10 | + |
| 1998Q2 | 5.05 | 5.07 | 5.09 | 5.18 | 5.18 | 5.13 | + |
| 1998Q3 | 4.98 | 5.00 | 5.01 | 5.05 | 5.10 | 5.16 | + |
| 1998Q4 | 4.82 | 4.27 | 4.20 | 4.11 | 4.20 | 4.16 | - |
| 1999Q1 | 4.25 | 4.40 | 4.40 | 4.42 | 4.39 | 4.41 | + |
| 1999Q2 | 4.41 | 4.48 | 4.50 | 4.50 | 4.55 | 4.57 | + |
| 1999Q3 | 4.45 | 4.71 | 4.90 | 4.90 | 4.90 | 4.93 | + |
| 1999Q4 | 4.65 | 4.90 | 5.05 | 5.08 | 5.10 | 5.12 | + |

Notes: *Data source: SPF (Survey of Professional Forecasters) forecast data from Philadelphia Fed. TBILL1-6 are the yields on 1-6 quarter ahead. Direction sign is determined by TBILL6 minus TBILL1.*

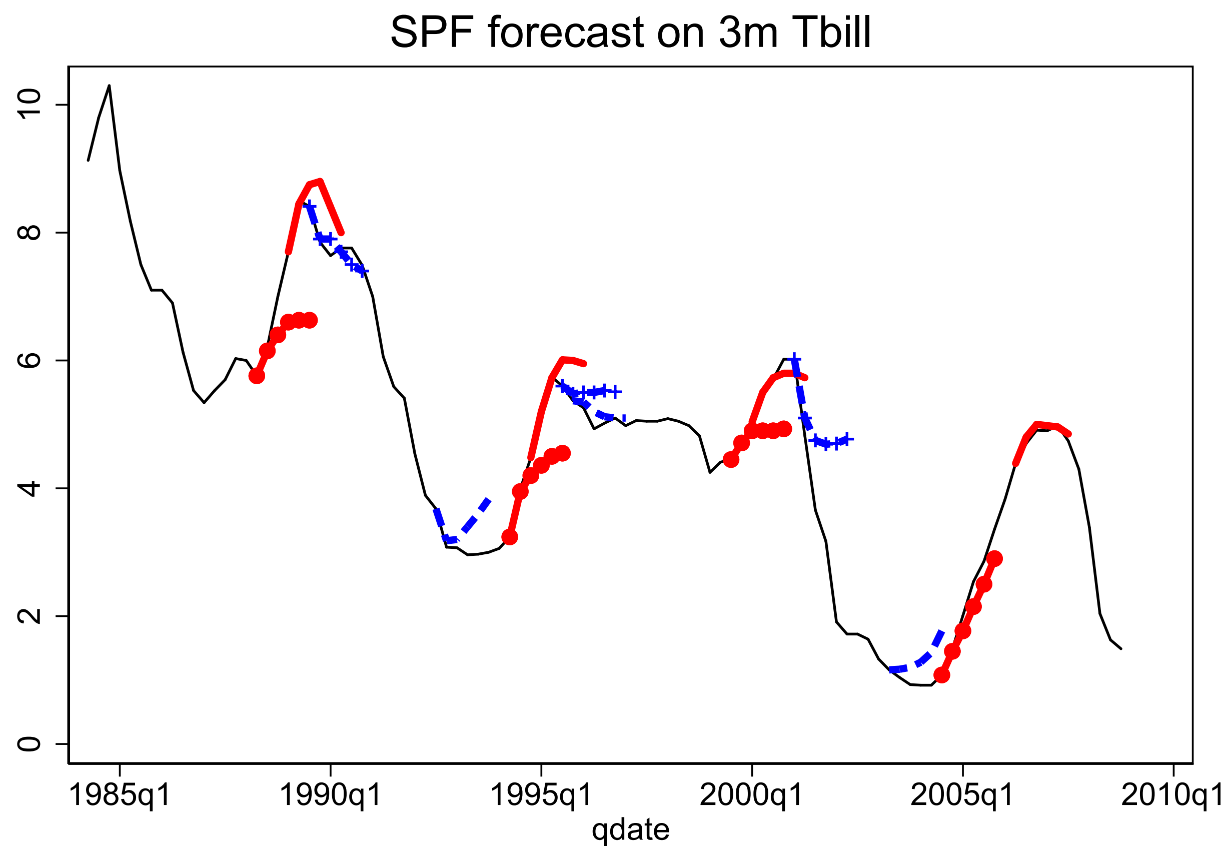
# Figures

Figure 2.5: The Fed's Dot Plots at Dec 2015 and Sep 2018



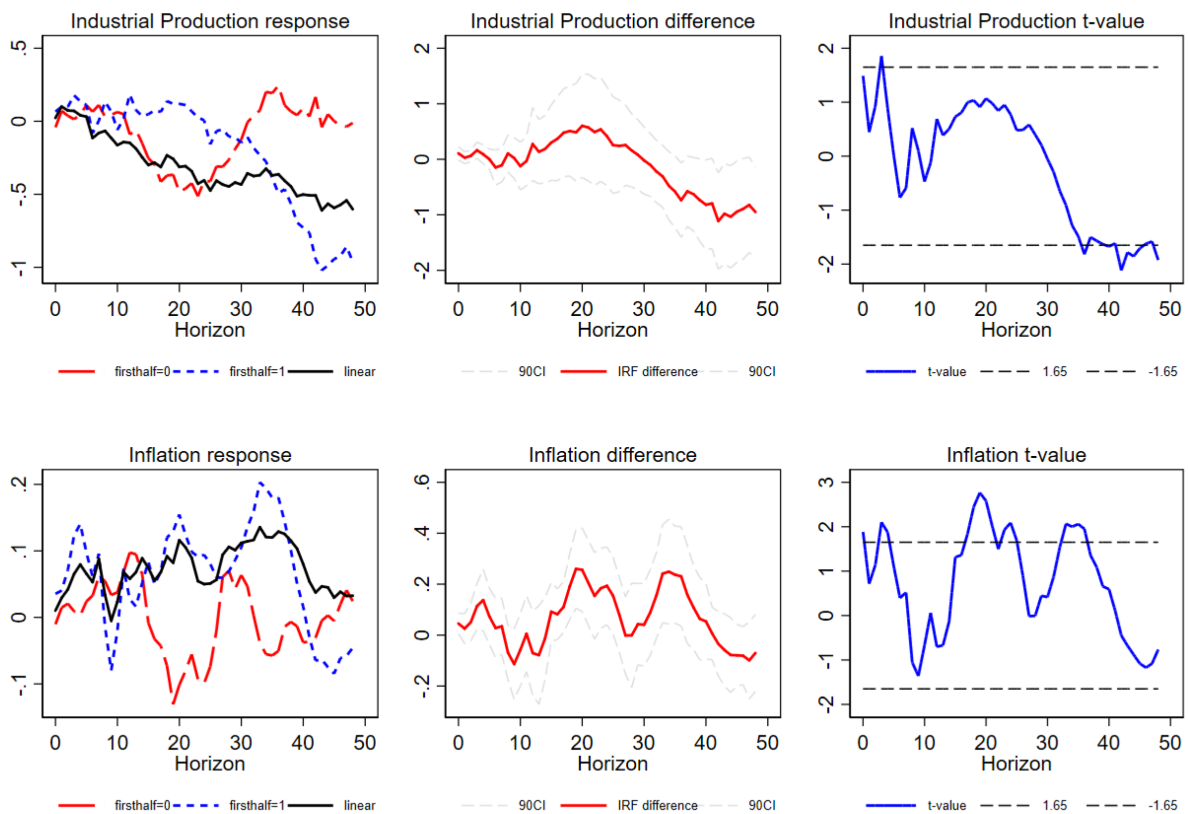

Notes: *Sources: The Fed's Dot Plots are from Bloomberg. December 2015 is the time when the Fed starts a hiking sequence, while September 2018 is second to the last action in this hiking sequence.*

Figure 2.6: SPF Forecasts of 3-month Treasury Yields across Monetary Policy Sequences



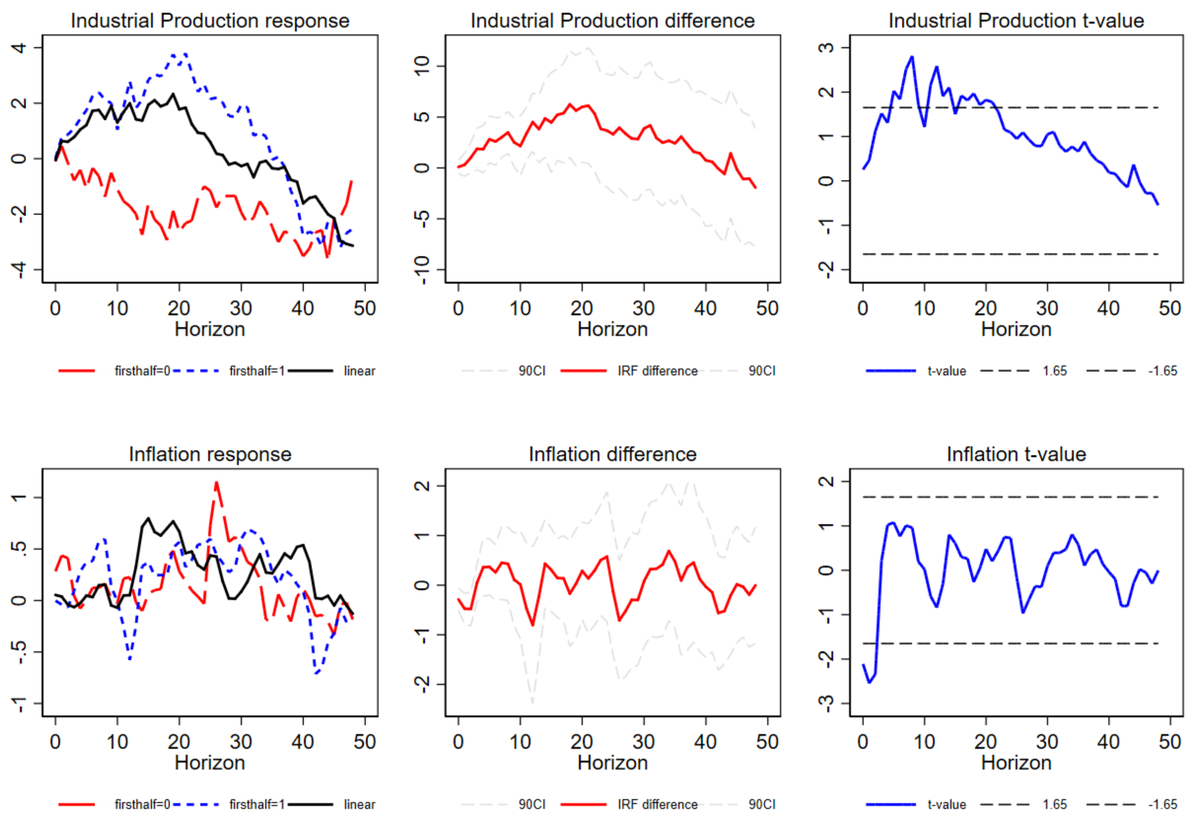

Notes: *Sources: Survey of Professional Forecasters forecast data from Philadelphia Fed. The data used here is the forecast on 3-month Treasury bill yields. The solid black line is the 3-month Tbill rate. The red line with circle in it is the forecast at the start of a hiking sequence, the solid red line is at the end of a hiking sequence. The dash blue line with + in it is the forecast at the start of a easing sequence, and the dash blue line is at the end of an easing sequence.*

Figure 2.7: State Dependent Local Projections Results using Barakchian-Crowe Shock



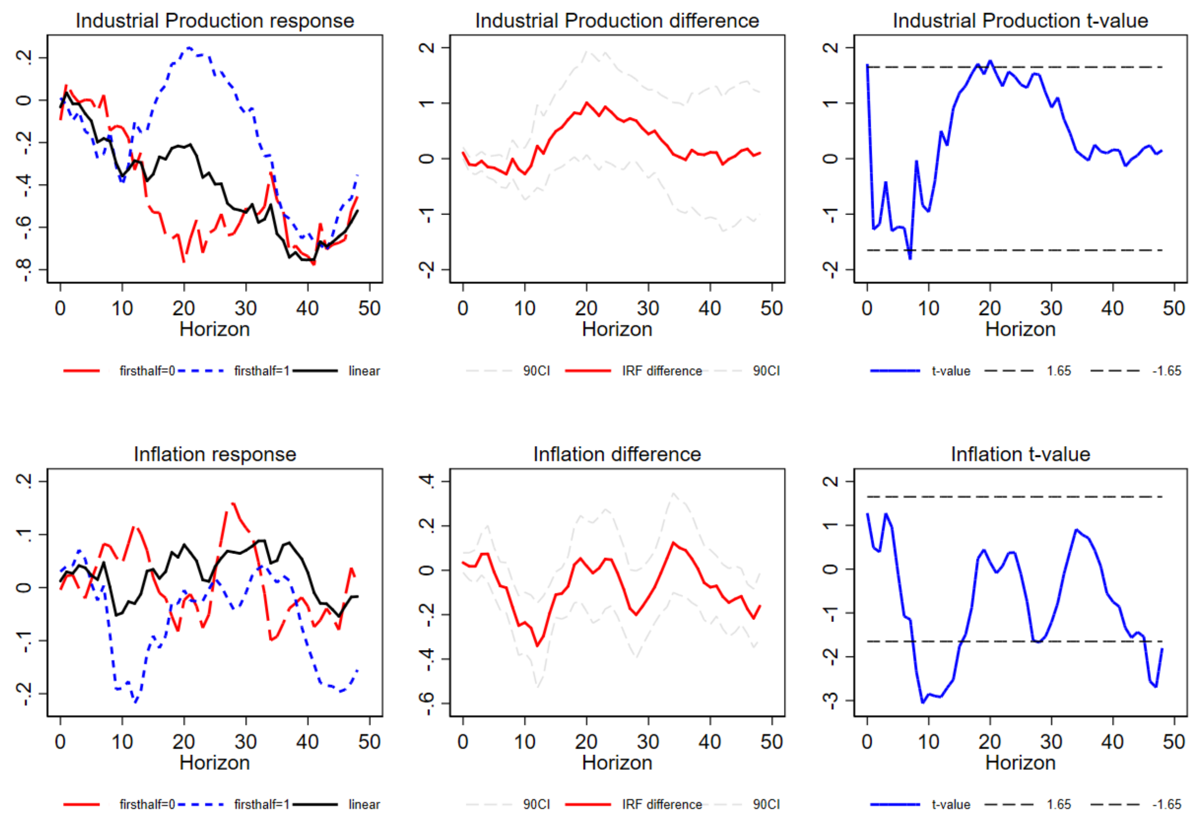

Notes: *State Dependent Local Projections results using Barakchian & Crowe (2013) shock (1st Principal Component) as monetary policy shocks. For the first column: the shortdash blue line is the impulse response for monetary policy shocks happening in the first half of monetary policy sequences, while the longdash red line is the impulse response of the monetary policy shocks happening in the second half of monetary policy sequences. The black line is the overall response in a linear model. For the second column: The red lines are the estimates for* $\gamma_1 = \beta_f^h - \beta_r^h$ *which captures the impulse responses of the first half minus the second half. The dashed gray lines are 90 percent confidence intervals. The last column are the t-value for* $\gamma_1$ *at certain horizon.*

Figure 2.8: State Dependent Local Projections Results using Romer-Romer Shock



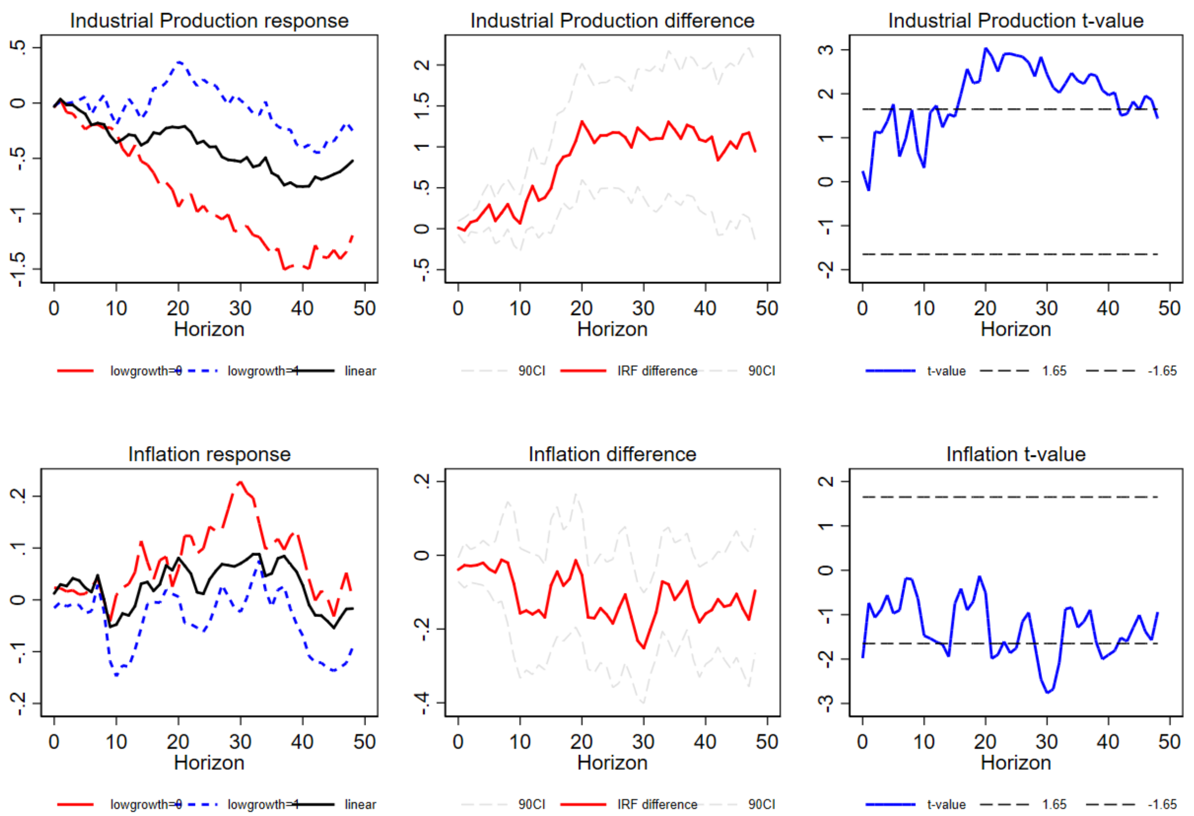

Notes: *State Dependent Local Projections results using Romer-Romer monetary policy shocks. For the first column: the shortdash blue line is the impulse response for monetary policy shocks happening in the first half of monetary policy sequences, while the longdash red line is the impulse response of the monetary policy shocks happening in the second half of monetary policy sequences. The black line is the overall response in a linear model. For the second column: The red lines are the estimates for* $\gamma_1 = \beta_f^h - \beta_r^h$ *which captures the impulse responses of the first half minus the second half. The dashed gray lines are 90 percent confidence intervals. The last column are the t-value for* $\gamma_1$ *at certain horizon.*

Figure 2.9: State Dependent Local Projections Results using the Path Factor as a Control



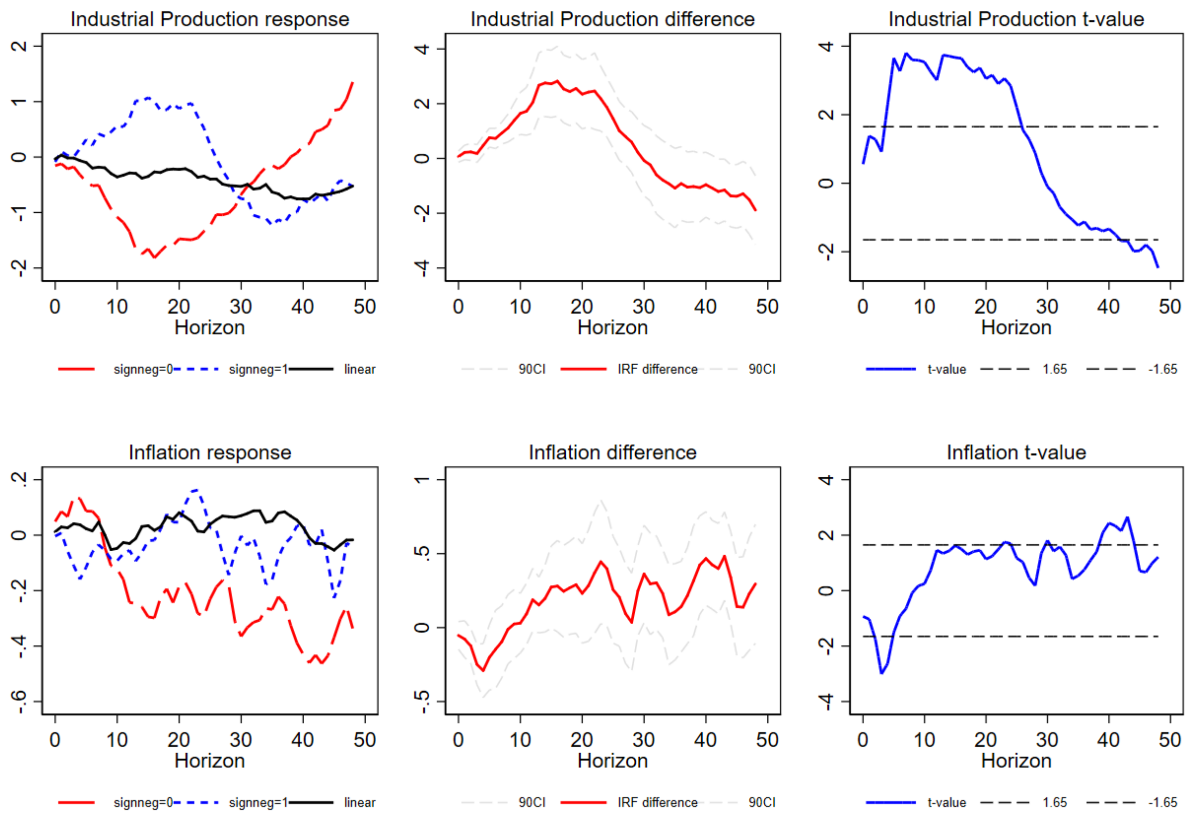

Notes: *State Dependent Local Projections results using the target factor as monetary policy shocks but with path factor as control in the regression. For the first column: the shortdash blue line is the impulse response for monetary policy shocks happening in the first half of monetary policy sequences, while the longdash red line is the impulse response of the monetary policy shocks happening in the second half of monetary policy sequences. The black line is the overall response in a linear model. For the second column: The red lines are the estimates for* $\gamma_1 = \beta_f^h - \beta_r^h$ *which captures the impulse responses of the first half minus the second half. The dashed gray lines are 90 percent confidence intervals. The last column are the t-value for* $\gamma_1$ *at certain horizon.*

Figure 2.10: Heterogeneous Effects of Monetary Policy Shocks: Low Growth



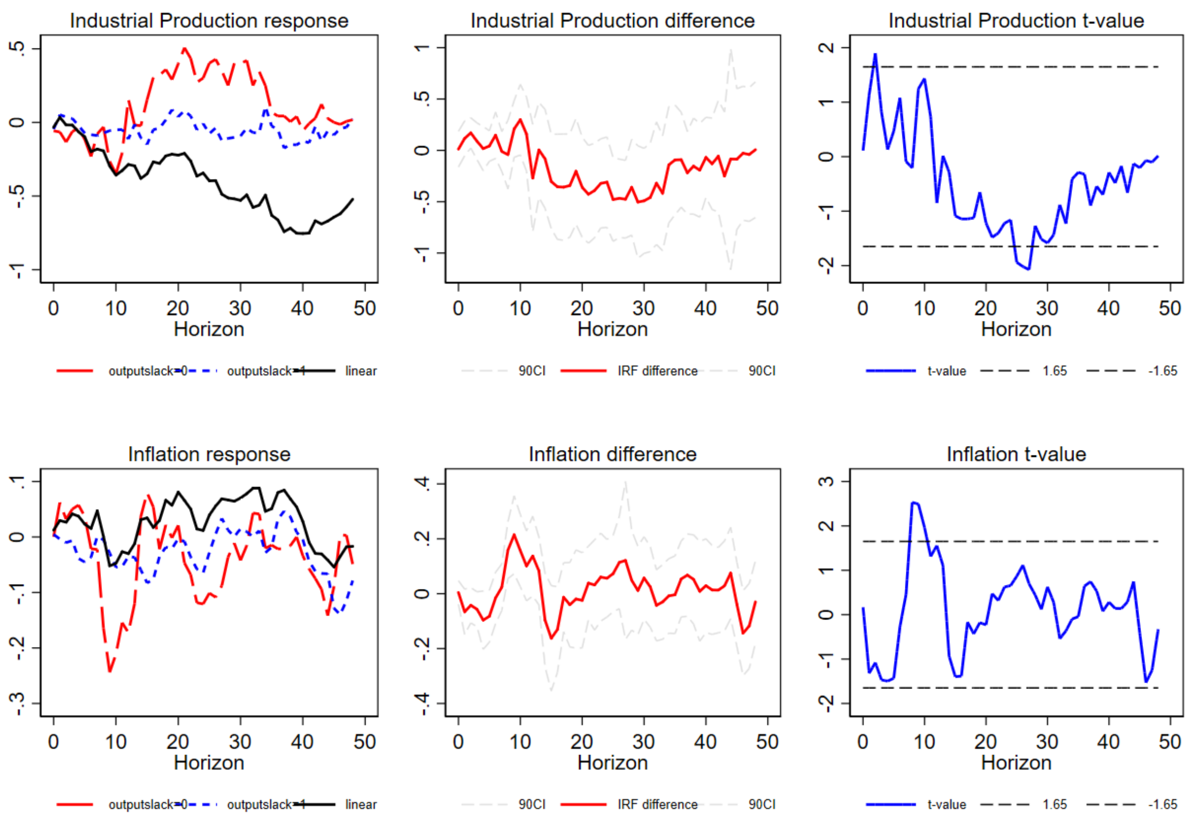

Notes: *For the first column: the shortdash blue line is the impulse response for monetary policy shocks happening in low growth period, while the longdash red line is the impulse response of the monetary policy shocks happening in high growth period. The black line is the overall response in a linear model. For the second column: The red lines are the estimates for* $\gamma_1 = \beta_f^h - \beta_r^h$ *which captures the impulse responses of low growth period minus high growth period. The dashed gray lines are 90 percent confidence intervals. The last column are the t-value for* $\gamma_1$ *at certain horizon.*

Figure 2.11: Heterogeneous Effects of Monetary Policy Shocks: Contractionary Shock



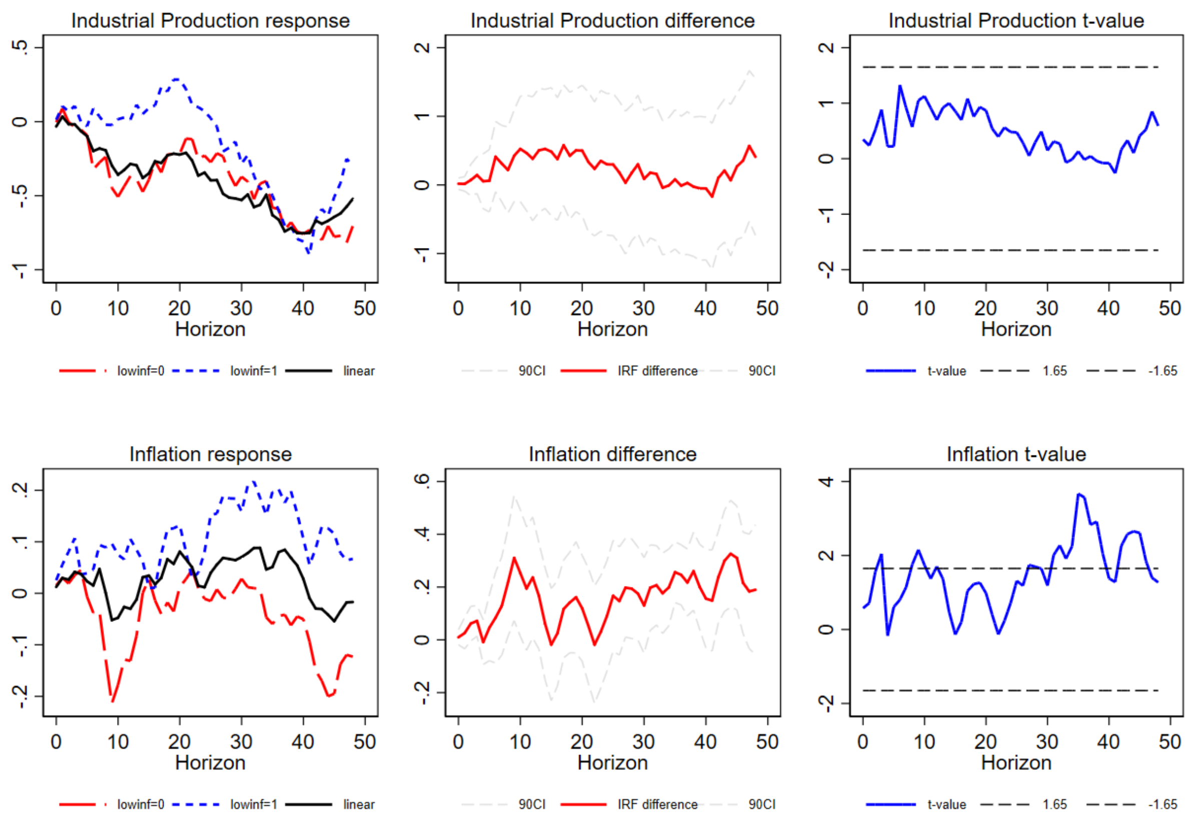

Notes: *For the first column: the shortdash blue line is the impulse response for contractionary monetary policy shocks, while the longdash red line is the impulse response of the expansionary monetary policy shocks. The black line is the overall response in a linear model. For the second column: The red lines are the estimates for* $\gamma_1 = \beta_f^h - \beta_r^h$ *which captures the impulse responses of contractionary monetary policy shocks minus expansionary shocks. The dashed gray lines are 90 percent confidence intervals. The last column are the t-value for* $\gamma_1$ *at certain horizon.*

Figure 2.12: Heterogeneous Effects of Monetary Policy Shocks: Output Slack




Notes: *For the first column: the shortdash blue line is the impulse response for monetary policy shocks happening in output slack period, while the longdash red line is the impulse response of the monetary policy shocks not in output slack period. The black line is the overall response in a linear model. For the second column: The red lines are the estimates for* $\gamma_1 = \beta_f^h - \beta_r^h$ *which captures the impulse responses of output slack period minus those not in output slack. The dashed gray lines are 90 percent confidence intervals. The last column are the t-value for* $\gamma_1$ *at certain horizon.*

Figure 2.13: Heterogeneous Effects of Monetary Policy Shocks: Low Inflation




Notes: *For the first column: the shortdash blue line is the impulse response for monetary policy shocks happening in low inflation period, while the longdash red line is the impulse response of the monetary policy shocks happening in high inflation period. The black line is the overall response in a linear model. For the second column: The red lines are the estimates for* $\gamma_1 = \beta_f^h - \beta_r^h$ *which captures the impulse responses of low inflation period minus high inflation period. The dashed gray lines are 90 percent confidence intervals. The last column are the t-value for* $\gamma_1$ *at certain horizon.*

# Chapter 3

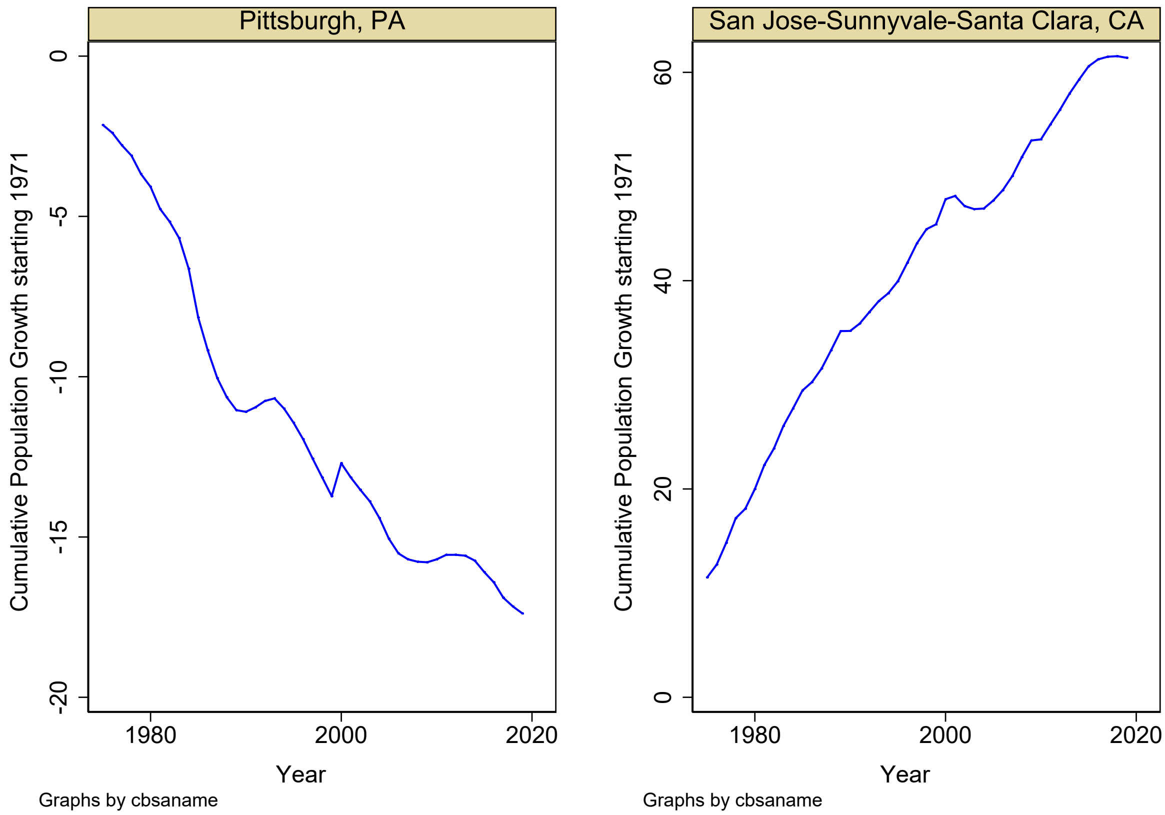
# Urban Growth, Urban Decline and Heterogeneous Monetary Policy Effects

## 3.1 Introduction

Some urban areas grow, others decline. The Pittsburgh area had a population of 2.84 million in 1970 and ends up with a population of 2.42 million in 2019, a total decline of more than 15% (the left graph of Figure 3.1). In contrast, the San Jose area had a population of 1.08 million in 1970 and ends up with a population of 1.99 million in 2019, a total growth of more than 60% (the right graph of Figure 3.1). There are also areas like Rochester with limited population growth over this period (around 7%). The question asked in this paper is: do the same interest rate reductions have the same effects on house prices in San Jose as compared to Pittsburgh?

How monetary policy affects the real economy is a critical question in macroeconomics. Given the importance of housing market fluctuations in driving the business cycle (Leamer (2007) and Leamer (2015)), a natural step to understand the transmission of monetary

Figure 3.1: Cumulative Population Growth for CBSA Pittsburgh and San Jose




policy is to investigate its effects on housing markets. The urban economics literature has shown much regional heterogeneity in house prices due to a wide range of local factors, for example, urban decline measured by population loss. The heterogeneous regional effects of monetary policy on housing prices are less studied. Fischer et al. (2019) and Aastveit & Anundsen (2018) have investigated how the effects of monetary policy are affected by the housing supply elasticity as measured in Saiz (2010). Exploring the regional heterogeneity of monetary policy effects is not yet at an end. Our paper contributes to this area by investigating how the effects of monetary policy can be affected by urban growth: Are areas with growing populations more or less sensitive to interest rate reductions? Our question is in spirit similar to Cloyne et al. (2020) where they study the fiscal effects conditional on the monetary policy responses. They are interested in the interaction of two short-run demand management policies while we are interested in the interaction of one short-run demand management policy with long-run population trends.

We investigate this question using US data and find strong evidence that house prices in areas with population growth are more sensitive to monetary policy shocks. In order to show heterogeneous effects for growing areas versus declining areas, we use the local projections method of Jordà (2005) adjusted to allow for state dependence (similar as Tenreyro & Thwaites (2016) for monetary policy, Auerbach & Gorodnichenko (2012a) and Ramey & Zubairy (2018) for fiscal policy). The monetary policy shock we use is the Romer-Romer shock (Romer & Romer (2004)) updated by Wieland & Yang (2020). Our results show that monetary policy generates larger responses for growing areas, and results are robust to different definitions of urban growth.

What mechanism explains these findings? A possible candidate to explain regional heterogeneity in monetary policy effects is the housing supply elasticity. For the same demand shock, different housing supply elasticites can affect the local supply, affecting the equilibrium quantity and price. For example, inelastic areas cannot provide a large number of new housing units when there is a positive demand shock in the housing market. Hence, prices go up by more in these areas comparing to elastic supply areas. Low housing supply elasticity areas may have more house price responses to monetary policy. If low housing supply areas coincide with growing areas, a greater sensitivity to monetary policy in growing areas can potentially be explained by the low housing supply elasticity. However, we show the housing supply elasticity is not the main driver for our results, although it plays a role in house prices response to monetary policy. Instead, we propose a different story to explain our empirical findings, and we show that our empirical results remain after controlling the effects of housing supply elasticity.

We suggest that, when combined with downward nominal rigidity in house prices, expectations driven by the long-run population trend explains larger impacts of monetary policy on growing urban areas. For growing areas, households know that house prices are likely to rise in the future. When there are interest rate cuts, more households are likely to purchase a house compared to a situation when there is no expectation of future house price increases. So the house price responses are amplified. In contrast, the effects are attenuated for an interest rate rise as people are less likely to sell their houses as they know house prices will rebound as there are people flowing in this area. For declining urban areas, the expectation of declining house prices attenuates the effects of expansionary monetary policy shocks and amplifies contractionary monetary policy shocks. What the downward nominal rigidity does is to prevent the house price from falling too far when declining house price expectations meet contractionary monetary shocks. We also find empirical support for this explanation. This explanation based on the long-run population trend is different from a momentum effect (a momentum effect works similarly as the long-run expectation, but the momentum is formed based on the short-run prices instead of the long-run population trend). For example, house prices dropped for quarters or even years for San Jose during the dot-com bubble burst. The momentum idea suggests an additional downward pressure on prices after several house prices drops in a few quarters. However, the long-run expectation may suggest the opposite if households believe the population is on the growing trend.

The key message of our paper is that the effects of monetary policy depend on the regional population trends. The distribution of urban areas on the spectrum of urban growth to urban decline will affect the effects of monetary policy on aggregate house prices. Since the distribution of urban growth and urban decline can be affected by population growth, urbanization and immigration, the population factor may contribute to the varying effects of monetary policy, in addition to its long-run impact on the natural real rate. The varying distribution of urban growth adds an additional source to time-varying monetary policy effects. Moreover, heterogeneous regional sensitivity to monetary policy alone leads to different consumption responses to the same monetary policy across regions. This is a different channel to explain regional heterogeneity in consumption response to monetary policy compared to different leverage ratio explanation, which says households with different loan-to-value ratios extract a different fraction of the same increase in housing equity to consume (e.g. Beraja et al. (2019)).

This paper relates to several strands of literature. Population is one of the determinants of local housing prices. Glaeser & Gyourko (2005) emphasizes the potential difference between urban growth and decline and its implication on housing prices. The urban economics literature pays little attention to the role of monetary policy in housing markets while we focus on the effects of monetary policy on regional house prices. There are a growing literature on the housing markets as an aggregate and their consequences on the economy (Iacoviello (2005), Jordà et al. (2015), Jarocinski & Smets (2008)). There are also a strand of literature estimating effects of house prices on households borrowing or consumption using local level housing price as a variation (Mian & Sufi (2011), Mian et al. (2013), Cloyne et al. (2019) ,Guren et al. (2018) among others.) These papers do not focus on the regional heterogeneity or the potential reasons for regional heterogeneity in monetary policy effects on house prices. Another strand of literature comes closer to investigate heterogeneity across US housing markets (Del Negro & Otrok (2007), Fischer et al. (2019) and Aastveit & Anundsen (2018)). These papers focus on either disentangling the national and local components of the housing markets and then investigating the role of monetary policy, or emphasizing the local market responses to monetary policy and how the effects are affected by the housing supply elasticity. Our paper focuses on the interaction of monetary policy (short-run demand side) with local population trends (long-run demand side). Our goal is to understand how the effects of monetary policy can vary depending on the population trends in the local areas. Our paper also relates to the state-dependent monetary policy literature. Tenreyro & Thwaites (2016) paper studies the different monetary policy effects during expansion and recession. Angrist et al. (2018) shows contractionary monetary policy is more effective. Aastveit & Anundsen (2018) instead finds contractionary monetary policy is less effective for house prices. Furthermore, they also find the housing supply elasticity plays significant different roles for contractionary and expansionary monetary policy shocks. Unlike these papers focusing on the asymmetric effects between expansionary and contractionary monetary policy shocks, we focus on the effects of monetary policy interacting with local population trends. Goodhart & Hofmann (2008) find that the effects of shocks to money and credit are found to be stronger when house prices are booming using cross-country data. Although the house prices are related to the local population trend, they are not the same thing. The local population trend is our main focus.

The rest of the paper goes as follows. The following section presents the data and the baseline empirical results. Section 3.3 presents an explanation and supporting empirical evidence. Section 3.4 discusses the role of housing supply elasticity in our setting. Section 3.5 concludes.

## 3.2 Data and Baseline Results

We investigate this question using US data. The CBSA level house price is the dependent variable of interest. House Prices data are seasonally adjusted, monthly, Core-Based Statistical Area (CBSA) data, from 1975 to 2020. The data are from Freddie Mac. Population data are annual, CBSA level data from 1975 to 2020. The data are from the US Census Bureau. We classify a CBSA as in urban growth if the cumulative population growth from 1975 to 2019 in this area is larger than a specific cutoff. The baseline results are based on the cumulative population growth above the 25th percentile and the 50th percentile of all CBSAs, and we later vary the cutoff to check the sensitivity of the results. Also, we switch to a different definition for urban growth to avoid the ex-post way of classifying urban growth. We want to investigate the response of local house prices to monetary policy shocks, especially how these responses differ conditional on local population trends. We use the monthly series of Romer-Romer shock updated by Wieland & Yang (2020) as the monetary policy shocks. Then we apply the local projections method as of Jordà (2005) and allow for state-dependent effects as in Tenreyro & Thwaites (2016).

### 3.2.1 Monetary Policy Shocks

Although the central bankers may not respond to the house prices explicitly when they make policy decisions, interest rate movements may still be endogenous to house price movements. For the price movements can affect residential investment, which contributes significantly to the business cycle (Leamer (2007) and Leamer (2015)). Moreover, the house price movements will also generate households consumption responses through wealth effects or collateral channels (Iacoviello (2005), Cloyne et al. (2019)). To investigate the effects of monetary policy on house prices, we need exogenous monetary policy shocks. We take the Romer-Romer shock series as in Romer & Romer (2004). They measure the change in the Fed's target interest rate at each Federal Open Market Committee (FOMC) meeting. They then regress this change in the policy rate target on a set of variables that are believed to be the full set of factors the Fed considers when making policy decisions. These variables included in the set are real-time data and forecasts of past, current, and future inflation, output growth, and unemployment. The residuals from this regression constitute their measure of monetary policy shocks. This monthly series later is updated by Wieland & Yang (2020) to the end of 2007, which marks the endpoint of our sample period. The Romer-Romer shock is widely used for identifying the effects of monetary policy in the literature.

### 3.2.2 House Prices and Urban Growth

What drives our interest in understanding the effects of monetary policy interacting with the local population trend is that population dynamics have important implications on house prices. At the same time, the population dynamics work at a lower frequency than the monetary policy shocks. This allows the possibility of understanding monetary policy in an environment set by the local population trend. As the examples at the beginning of the paper illustrate, the population in the San Jose area has continuously grown to the current level with only two short slow-downs during the dot-com bubble burst and the Great Financial Crisis period. Will monetary policy have different effects on San Jose as compared to the

Pittsburgh area, where there has been a declining trend? Before we formally investigate this question, we check the connection between regional population trend and the local house price, and then we explain how we define urban growth.

As emphasized in Glaeser & Gyourko (2005) and Glaeser et al. (2006), the population of a city is almost perfectly correlated with the size of its housing stock across space and over time. The $R^2$ and estimated elasticity of regressing the log number of housing units on the population is almost one. The $R^2$ and estimated elasticity of regressing the growth rate of housing units on the population growth is high across decades (see Figure 3.2 a table from Glaeser et al. (2006)).

Figure 3.2: Housing and Population from Glaeser et al. (2006)

**Table 1.** Metropolitan area housing and population since 1970: levels and changes

Levels: log housing units$_t$ = $\alpha_t + \beta$ log population$_t$ + $\varepsilon_t$

| Year (*t*) | $\beta$ (standard error) | $R^2$ |
|---|---|---|
| 1970 | 0.995 (0.005) | 0.99 |
| 1980 | 0.997 (0.005) | 0.99 |
| 1990 | 0.995 (0.005) | 0.99 |
| 2000 | 0.981 (0.005) | 0.99 |

Changes: log change housing units$_t$ = $\alpha_t + \beta$ log change population$_t$ + $\varepsilon_t$

| Decade (*t*) | $\beta$ (standard error) | $R^2$ |
|---|---|---|
| 1970–1980 | 1.041 (0.014) | 0.95 |
| 1980–1990 | 0.861 (0.018) | 0.88 |
| 1990–2000 | 0.765 (0.021) | 0.81 |

*Note*: Sample includes 316 metropolitan areas within the continental United States. Metropolitan area boundaries are based on their 1999 definitions, as issued by the Office of Management and Budget.

The strong and significant relationship between housing units and population suggests current population growth will be translated into housing demand either at the current period or in future periods. Thus the local population trend will have important implications on residential investment, house prices and households' expectations about them. This paper mainly focuses on the price side and we leave the quantity side about the residential investment, housing starts for future research.

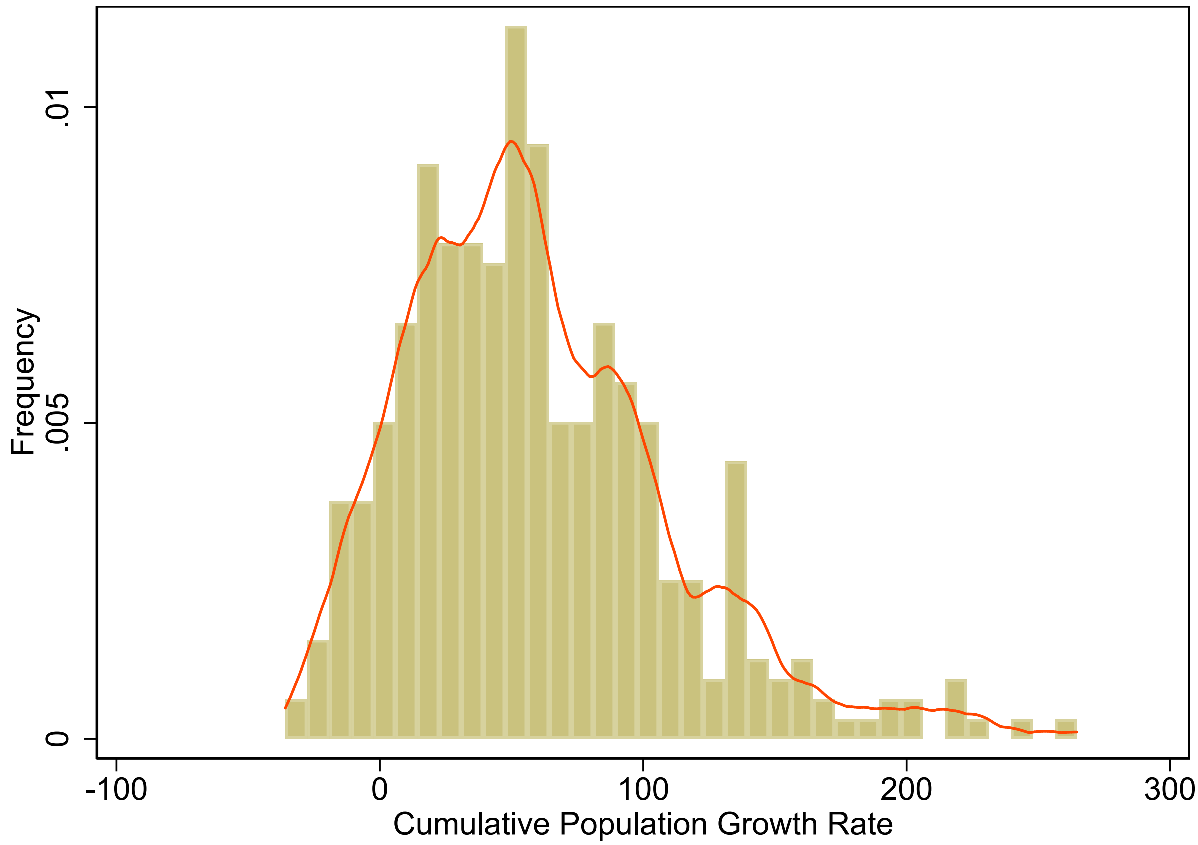
We calculate the cumulative population growth from 1970-2019 for each CBSA. The average of cumulative population growth is 59.4%, the min is -35.9% and the max is 264.7% (Figure 3.3). The distribution is skewed toward the positive domain. This is consistent with Glaeser & Gyourko (2005). Population declines much less slowly than it grows. The distribution of urban growth may also be attributed to the particular population dynamics in the US during this specific period. In 1970, the urbanization rate for the US was 73.6%, 82.46% in 2019, a total increase slightly less than 10%. In 1970 the total population was 209 million, and 319 million in 2019. Across time, there are in total around 110 million people urbanized. We also provide list of the top and bottom 5% CBSAs on the population growth with a population larger than 100,000 in 1975 (see Table 3.5 and Table 3.6 in the appendix). The fastest-growing area is the Las Vegas (NV) area, with a cumulative population growth of 217.5%. In contrast, the fastest-declining area is Johnstown (PA), with a cumulative decline of more than 35.9%.

We check the relation between house prices and population growth by regressing the cumulative house price growth over the cumulative population growth from 1975 to 2019.

$$y_i = \alpha + \beta * x_i + u_i$$

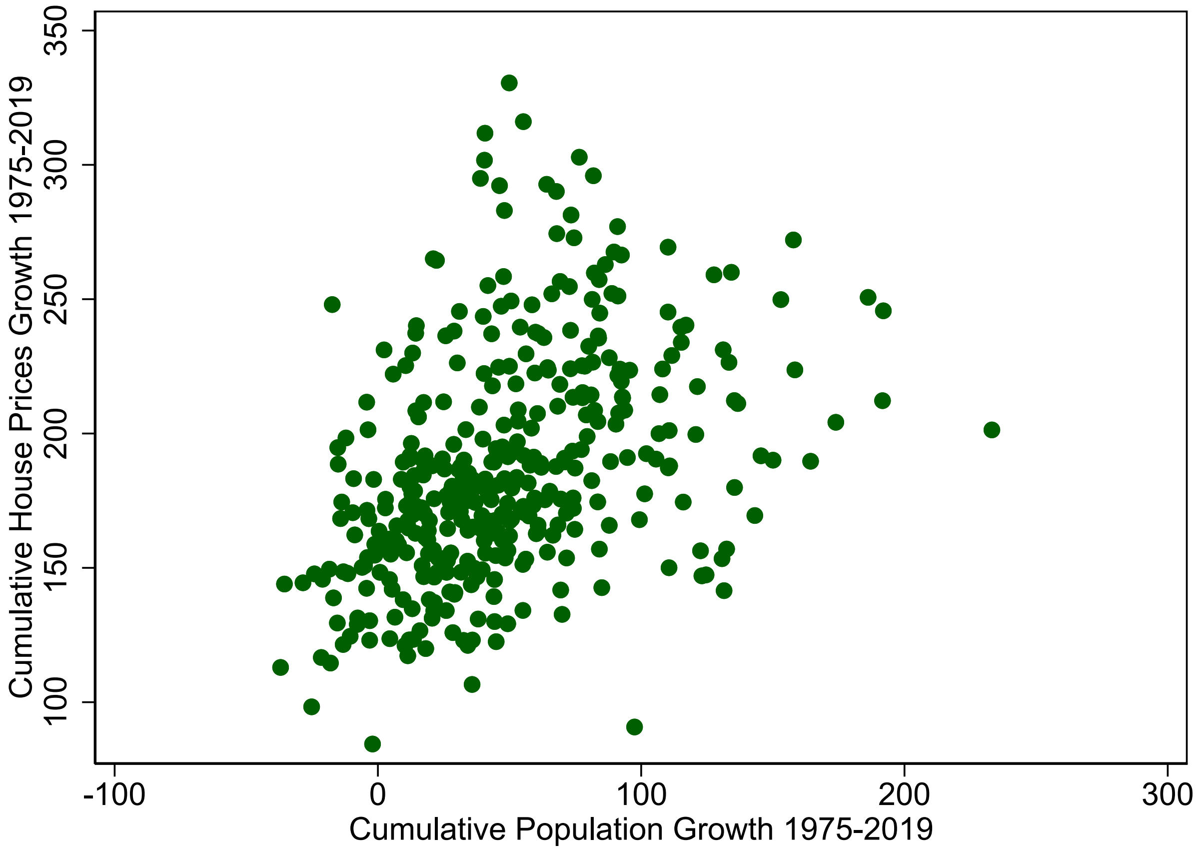
$y_i$ is the cumulative house price growth for CBSA $i$. $x_i$ is the cumulative population growth. The coefficient is 0.41 and statistically significant (as column 1 in Table 3.8). A 0.41 percent increase in house prices is associated with one percent population growth. This pattern can be seen clearly from the following figure (Figure 3.4). A point in this figure corresponds to a CBSA.

Figure 3.3: Distribution of Cumulative Population Growth 1975-2019




The local population trend creates a long-run (relative to the monetary policy shock) demand which puts pressure on the house prices. Moreover, these local population trends differ from each other significantly. Figure 3.12 in the appendix shows the population for local areas with a negative but less than ten percent cumulative population between 1970 and 2019. Figure 3.13 shows local areas with cumulative population growth between 100% and 120% for the same period. These different population trends create different pressures on the local house prices in these areas. We want to investigate the effect of monetary policy conditional on the existing long-run demand caused by the local population trend. Suppose the long-run demand driven by population and the short-run demand coming from monetary policy are orthogonal, the effects of monetary policy should be independent of the population

Figure 3.4: Cumulative House Price Growth and Cumulative Population Growth 1975-2019




Notes: *Cumulative nominal house price growth rate in percentage on the y axis. Cumulative population growth rate in percentage on the x axis.*

trend. However, these two demands may interact with each other. For example, in an area with a population increase, households know that the house price will increase. However, they can not purchase a house due to the tight monetary policy stance. For instance, it is difficult to get credit from banks and the cost of mortgage is high. A loosening of the monetary policy will make a larger fraction of households to fulfill their demands. However, the situation will be different if households see a long-run declining trend in house prices. Loosening monetary policy is not getting a significant fraction of households into purchasing a house anyway.

In order to empirically test whether the effects of monetary policy depend on the local population trends, we need to classify areas as urban growth and urban decline. We calculate the cumulative population growth from 1970 to 2019 for each CBSA, and then we classify growing areas as those with the cumulative population growth larger than a specific cutoff. The rest is in urban decline. In the baseline, we use the 25th and 50th percentile of all CBSA cumulative population growth. Later we also use different cutoffs as sensitivity checks. The way we use to classify urban growth is ex-post. Readers may be concerned whether households know the local population trend ex-ante. We think there may be some structural change that leads to specific population trends which households can observe. The population flows in or out slowly, so households get a sense of the local population trend. To answer this question directly, we again classify urban growth using real-time data at a certain point. We calculate the average cumulative population growth of the past three years and compare it with the current year's population growth. If the average is below the current population growth, we think these areas are growing, otherwise declining. These definitions of urban decline are different from the definition in Glaeser & Gyourko (2005) which is defined as the house price below the construction cost.

### 3.2.3 Baseline Specification

The local population trend has important implications on local house prices. Monetary policy will also generate movements in local house prices. We are interested in how the effects of the same monetary policy differ conditional on different local population trends. We first estimate a simple linear model of house prices to monetary policy shocks using panel data. And then we shift to the state-dependent monetary policy to test whether there are significantly different responses of local house prices to monetary policy conditional on the area is growing or declining[1].

[1]"state-dependent" here refers mainly to the estimation method. We are interested in the heterogeneous effects depending on urban growth. But the empirical strategy is essentially the same as to state-dependent monetary policy method.

The linear model is as follows:

$$y_{i,t+h} = \alpha_i + \beta^h \epsilon_t + \phi' x_{i,t} + u_{i,t+h} \tag{3.1}$$

$y_{i,t+h}$ is the dependent variable of interest. $y_{i,t+h}$ here is the cumulative house price growth rate from $t$ to $t+h$. $\epsilon_t$ is the monetary policy shock (the Romer-Romer shock). $\alpha_i$ is the CBSA fixed effect. $\beta^h$ captures the cumulative house price growth to a monetary policy shock $h$ months after the shock happens. We use Driscoll-Kraay standard errors to allow for possible spatial correlations and serial correlations. The data used in the local projections is panel data instead of time series data. We do not include the month-CBSA level fixed effect. The key idea is to explore the effects of monetary policy. However, the monetary policy shock is common to all CBSAs in a certain month[2]. $x$ includes lags of the variables in $y$ and lags of monetary policy shocks. We include 12 lags (as suggested in Coibion (2012)) for monthly data.

We then use state-dependent local projections to explore the heterogeneous responses depending on urban growth or decline. Specifically, I estimate:

$$y_{i,t+h} = \alpha_i + \beta_g^h I_{i,t} * \epsilon_t + \beta_d^h (1 - I_{i,t}) * \epsilon_t + \phi' x_{i,t} + u_{i,t+h} \tag{3.2}$$

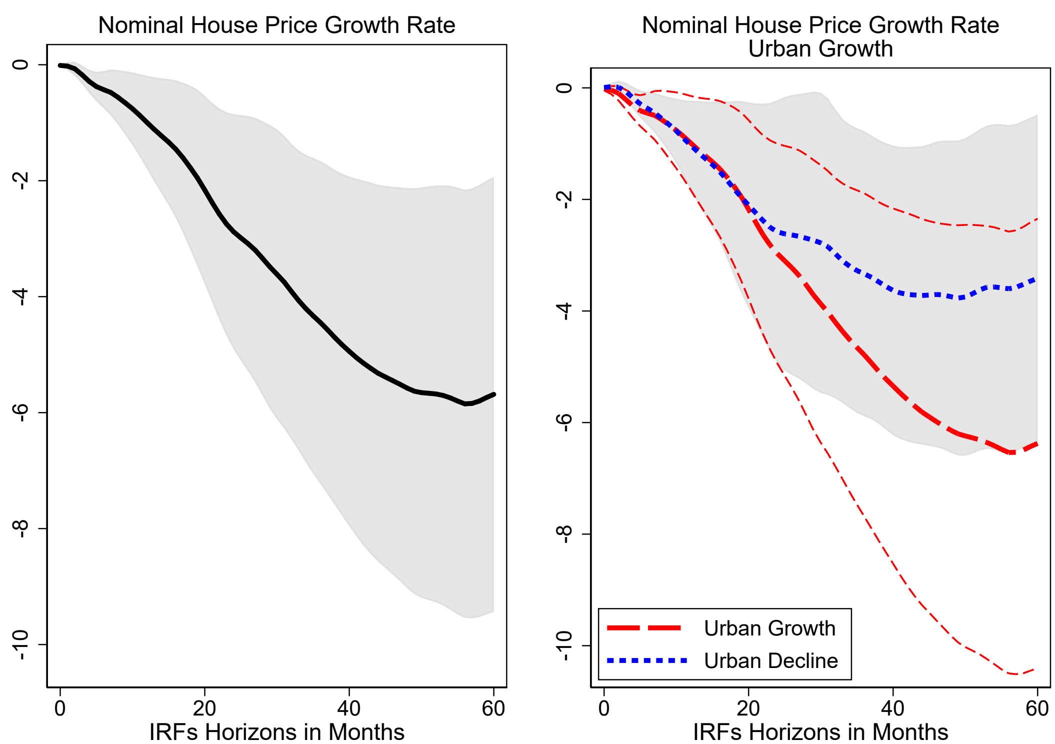
$I$ is a dummy variable, and $I_{i,t} = 1$ indicates CBSA $i$ at time $t$ is in urban growth, 0 for urban decline. The urban growth here is not a time-varying state as in other papers studying the state-dependent monetary policy, but a characteristic for certain CBSA areas. Only when we switch to the different approach of identifying urban growth comparing the current population growth with the average of past three years population growth, the urban growth dummy is time-varying for a particular CBSA. The parameters of interest are $\beta_g^h$ and $\beta_d^h$. $\beta_g^h$ captures the cumulative house price growth to a monetary policy shock $h$ months after the shock happens for growing areas. $\beta_d^h$ is the counterpart for declining areas. We are

[2] Goodhart & Hofmann (2008) discuss a similar issue in a different setting.

interested in whether $\beta_g^h$ and $\beta_d^h$ are different and the reason for the possible difference.

### 3.2.4 Results

Figure 3.5: Monetary Policy Effects: Urban Growth (25th Percentile Cutoff)




Notes: *Impulse responses of house price to monetary policy shocks. The black line in the left graph corresponds to the linear model. The long-dash red line in the right graph corresponds to the impulse responses for growing areas, and the short-dash blue line is for declining areas. Urban growth is defined as cumulative population growth larger than the 25th percentile for all CBSAs.*

The general results are presented in Figure 3.5. The black line in the left graph corresponds to $\beta^h$ in equation 3.1. Generally, the nominal house prices decrease by less than 6% in 5 years in response to 1% interest rate increase. The overall effects are a combination of effects for growing areas and declining areas. The house prices drop by more than 6% in growing areas. And the house prices in declining areas drop by less than 4%, much less than the response in growing areas. In the right graph, the long-dash red line corresponds to $\beta_g^h$, and the short-dash blue line corresponds to $\beta_d^h$ in equation 3.2. The shaded areas and the two red dash lines are the 95% error bands.

Table 3.1: Cumulative Impulse Responses of House Price (1)

| Horizon | Linear | Urban growth | Urban decline | P-value for difference |
|---|---|---|---|---|
| 6 | -0.43 | -0.45 | -0.37 | 0.57 |
| 12 | -0.99 | -0.99 | -1.03 | 0.89 |
| 18 | -1.77 | -1.77 | -1.81 | 0.92 |
| 24 | -2.88 | -2.97 | -2.58 | 0.56 |
| 30 | -3.61 | -3.87 | -2.78 | 0.15 |
| 36 | -4.45 | -4.79 | -3.33 | 0.07 |
| 42 | -5.15 | -5.59 | -3.70 | 0.04 |
| 48 | -5.58 | -6.14 | -3.74 | 0.02 |
| 54 | -5.75 | -6.42 | -3.57 | 0.01 |
| 60 | -5.68 | -6.37 | -3.41 | 0.01 |

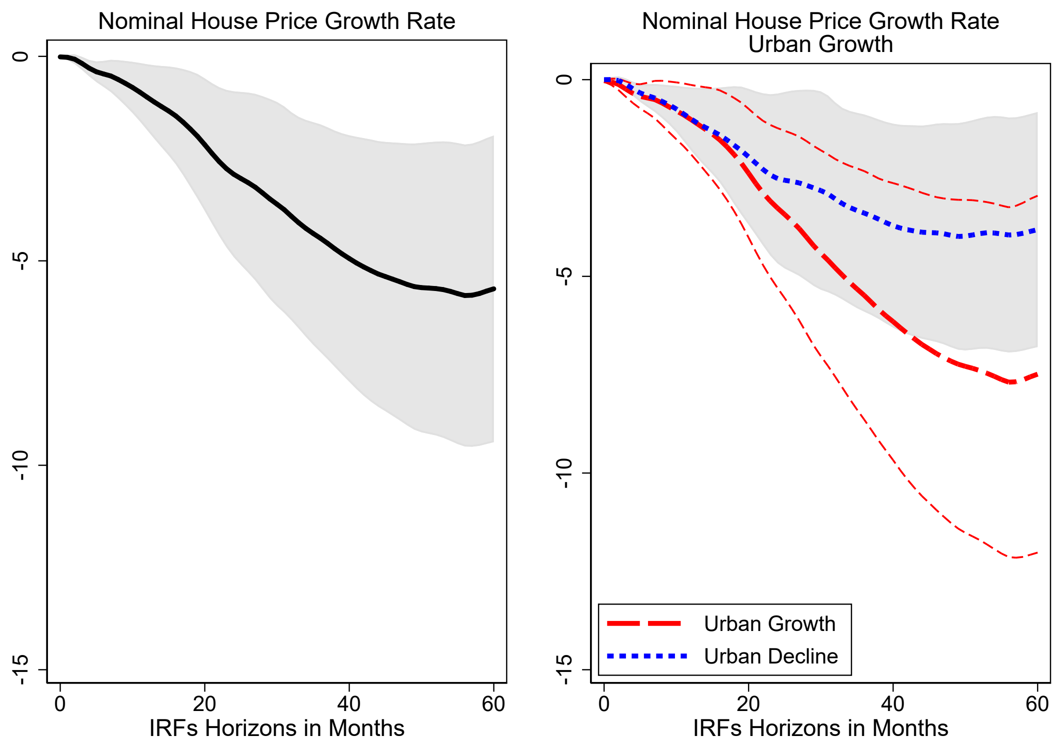
Notes: *Urban growth here is defined as cumulative population growth larger than 25th percentile. Column 1 is the selected horizon; Column 2 is the impulse responses for the linear model; Column 3 is the impulse responses for urban growth; Column 4 is the impulse responses for urban decline; Column 5 is the p-value for the difference between urban growth and decline.*

Table 3.1 shows the responses at different selected horizons and the p-value of the difference between the responses to monetary policy during urban growth and urban decline. 48 months after one percentage shock in the policy rate, house prices decrease by 6.14% for growing areas and 3.74% for declining areas. The difference in responses is 2.4%, statistically significant as indicated by the small p-value.

### 3.2.5 Robustness and Sensitivity Checks

The above results are based on that we classify as urban growth areas if the cumulative population growth is above the 25th percentile. This cutoff seems to be arbitrary. We perform different types of robustness and sensitivity checks. We first vary the cutoffs for urban growth. We try cutoffs at 0%, 50th percentile, and 75th percentile. We also try a different approach to define urban growth. We classify a year for specific CBSA area urban

Figure 3.6: Monetary Policy Effects: Urban Growth (50th Percentile Cutoff)




Notes: *Impulse responses of house price to monetary policy shock. The black line in the left graph corresponds to the linear model. The long-dash red line in the right graph corresponds to the impulse responses for growing areas, and the short-dash blue line is for declining areas. Urban growth is defined as cumulative population growth larger than the 50th percentile for all CBSAs.*

growth if the current year cumulative population growth is above the average of cumulative population growth rate for the past three years. Households may notice the area is growing if the total population is above the average of the past three years. This approach avoids concerns about the ex-post way of defining population growth. Urban growth using this approach is more in line with a *state* as in the state-dependent monetary policy literature. A certain area can be in urban growth at a certain time and in urban decline at another point in time. Figures 3.15 and Figure 3.16 in the appendix show urban growth and decline defined this way for the Rochester area and San Jose area. The results hold for all these different ways of classifying urban growth. We provide the results (Figure 3.6 and Table 3.2) in the main text when we classify urban growth as those above the 50th percentile. All other robustness checks are in the appendix.

Table 3.2: Cumulative Impulse Responses of House Price (2)

| Horizon | Linear | Urban growth | Urban decline | P-value for difference |
|---|---|---|---|---|
| 6 | -0.43 | -0.46 | -0.41 | 0.69 |
| 12 | -0.99 | -1.01 | -1.00 | 0.95 |
| 18 | -1.77 | -1.90 | -1.67 | 0.63 |
| 24 | -2.88 | -3.26 | -2.51 | 0.27 |
| 30 | -3.61 | -4.41 | -2.82 | 0.05 |
| 36 | -4.45 | -5.48 | -3.39 | 0.02 |
| 42 | -5.15 | -6.46 | -3.81 | 0.01 |
| 48 | -5.58 | -7.15 | -3.96 | 0.01 |
| 54 | -5.75 | -7.54 | -3.90 | 0.00 |
| 60 | -5.68 | -7.49 | -3.81 | 0.01 |

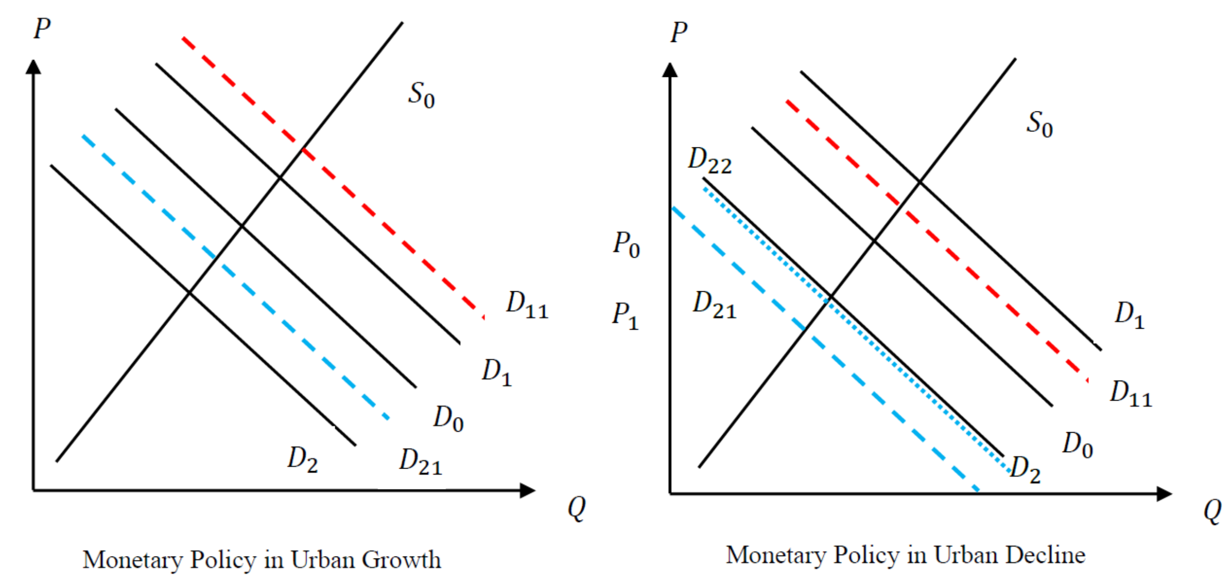
Notes: *Urban growth here is defined as cumulative population growth larger than 50th percentile. Column 1 is the selected horizon; Column 2 is the impulse responses for the linear model; Column 3 is the impulse responses for urban growth; Column 4 is the impulse responses for urban decline; Column 5 is the p-value for the difference between urban growth and decline.*

There are asymmetric effects of monetary policy between expansionary and contractionary shocks, evidenced by Angrist et al. (2018). Asymmetric effects also present for regional housing markets as in Aastveit & Anundsen (2018). Our results have little chance been explained by this asymmetric since all areas experience the same monetary policy shock at the same time.

## 3.3 Explanation and Further Evidence

How should we think about the above empirical results? We argue that the long-run population trends pin down the expectations of house price growth. Suppose households know that the population is growing for certain areas, this population growth provides strong support for house prices. If the central bank cuts the interest rates, it reduces the cost of the mortgage, thus increasing the short-run demand. The population trend amplifies the expansionary monetary policy shock. There may be a larger fraction of households, relative to declining areas, believes the house price will grow in the long run, and they now take the chance of loose monetary policy stance to buy houses. In contrast, for declining areas, the population trend attenuates the effects of expansionary monetary policy shocks. When it comes to a contractionary monetary policy shock, the growing population trend will attenuate its effect, and the declining population trend will amplify its effect. The idea is shown in Figure 3.7. The left graph is for the urban growth case. An expansionary monetary policy shock moves the demand from $D_0$ to $D_1$, and the local population trend in urban growth amplifies the effect of monetary policy, moving the demand further to $D_{11}$. A contractionary monetary policy shock will move the demand to $D_2$, and the local population trend will pull up the demand to $D_{21}$.

Figure 3.7: Monetary Policy during Urban Growth and Urban Decline




The local population trend in declining areas works in the opposite direction as those in growing areas. The right graph is for the urban decline case. An expansionary monetary policy shock moves the demand from $D_0$ to $D_1$, and the local population trend in urban decline attenuates the effect of monetary policy, moving the demand to $D_{11}$. A contractionary monetary policy shock will move the demand to $D_2$, and the local population trend will further push down the demand to $D_{21}$. Suppose this is the only mechanism behind it, the overall effect for urban growth and urban decline should be of similar magnitude: the distances between $D_{21}$ and $D_{11}$ are the same in the left and right graphs.

Another required ingredient at work is the downward nominal rigidity[3]. The downward nominal rigidity stops the amplified effects when the declining population trend interacts with the contractionary monetary policy. If there were downward nominal rigidity in house prices, it should not matter that much whether there is one force or two forces driving the decline. In the right graph for declining areas, the nominal downward rigidity stops the demand curve from moving to $D_{21}$ and keeps the demand curve at $D_{22}$. Now, as we can see from these graphs, growing areas are more sensitive to monetary policy on average. The same monetary policy shock will move the demand in between $D_{11}$ and $D_{21}$ for urban growth, and $D_{11}$ and $D_{22}$ for urban decline. The distance between $D_{11}$ and $D_{21}$ in the left graph is larger than the distance between $D_{11}$ and $D_{22}$ in the right graph.

This explanation provides some testable predictions:

**(1)** expansionary monetary policy shocks increase house prices in growing areas more than in declining areas. Distance between $D_{11}$ and $D_0$ is larger in the left graph than in the right graph.

**(2)** contractionary monetary policy shocks decrease house prices in growing areas less than in declining areas. Distance between $D_{21}$ and $D_0$ is smaller in the left graph than the distance between $D_{22}$ and $D_0$ in the right graph.

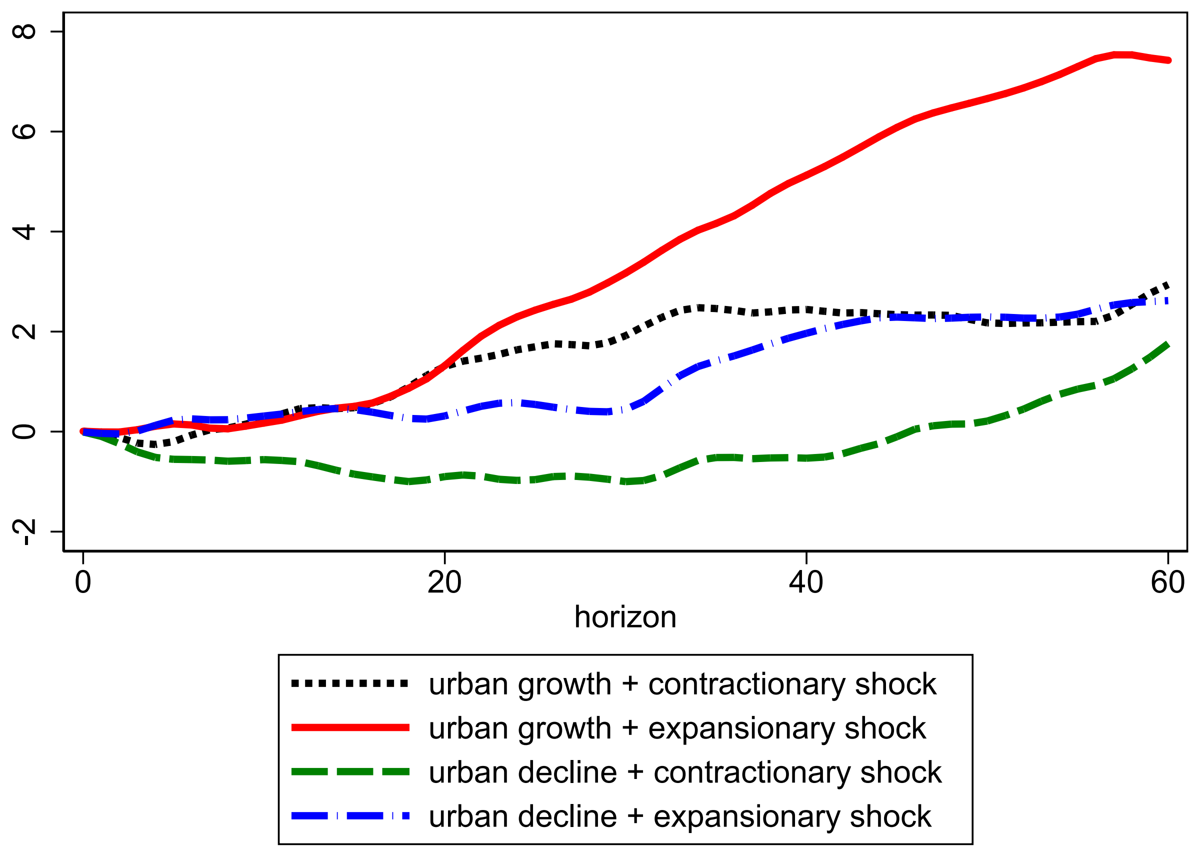
[3]Some literature suggests different search and financial friction in hot housing markets. We are not providing the micro foundation at this step, but this can be done and tested using regional data on housing quantity.

We now perform local projections conditional on two states as follows:

$$y_{i,t+h} = \alpha_i + \beta^h_{g,c} I_{g,i,t} I_{c,i,t} * \epsilon_t + \beta^h_{d,c}(1 - I_{g,i,t}) I_{c,i,t} * \epsilon_t \\ + \beta^h_{g,e} I_{g,i,t}(1 - I_{c,i,t}) * \epsilon_t + \beta^h_{d,e}(1 - I_{g,i,t})(1 - I_{c,i,t}) * \epsilon_t + \phi' x_{i,t} + u_{i,t+h}$$

We include dummies indicating urban growth and contractionary monetary policy shock and their interaction in the control $x_{i,t}$. The subscript $g$ is for urban growth, $d$ for urban decline, $c$ for contractionary monetary policy shock, and $e$ for expansionary shock. $I_{g,i,t}$ is an indicator for urban growth for CBSA $i$ at $t$. $I_{c,i,t}$ is an indicator for contractionary monetary policy, i.e the monetary policy shock $\epsilon_t$ is positive.

Figure 3.8: House Price Responses to Monetary Policy: Urban Growth and Expansionary Shocks




The results are presented in Figure 3.8. The solid red line corresponds to $\beta^h_{g,e}$, the house price response in growing area to expansionary monetary policy shocks. The long-dash dot blue line corresponds to $\beta^h_{d,e}$, the house price response in declining area to expansionary monetary policy shocks. The dot black line corresponds to $\beta^h_{g,c}$, the house price response in growing area to contractionary monetary policy shocks. The long-dash green dash line corresponds to $\beta^h_{d,c}$, the house price response in declining area to contractionary monetary policy shocks. The solid red line is above the long-dash dot blue line means the same expansionary monetary policy shock increases house prices in growing areas more than in declining areas. This confirms testable prediction (1) discussed above. The dot black line is above the long-dash green dash line confirms the testable prediction (2). Contractionary monetary policy is more potent in decrease house prices in declining areas than growing areas. The impulse responses for selected horizons are in Table 3.3[4].

Table 3.3: IRFs for Urban Growth and Contractionary Shocks

| h | Urban growth Contractionary shock | Urban growth Expansionary shock | Urban decline Contractionary shock | Urban decline Expansionary shock |
|---|---|---|---|---|
| 6 | -0.07 | 0.13 | -0.56 | 0.26 |
| 12 | 0.46 | 0.32 | -0.60 | 0.40 |
| 18 | 0.89 | 0.87 | -1.00 | 0.26 |
| 24 | 1.64 | 2.30 | -0.98 | 0.58 |
| 30 | 1.92 | 3.17 | -1.00 | 0.45 |
| 36 | 2.42 | 4.32 | -0.52 | 1.51 |
| 42 | 2.37 | 5.49 | -0.44 | 2.14 |
| 48 | 2.33 | 6.47 | 0.15 | 2.27 |
| 54 | 2.19 | 7.14 | 0.75 | 2.29 |
| 60 | 2.94 | 7.42 | 1.76 | 2.62 |

Notes: *Column 1 is the selected horizon; Column 2-5 is the impulse responses for urban growth and/or expansionary shocks. Urban growth here is defined as cumulative population growth larger than 50th percentile.*

[4] The results for contractionary monetary policy shock in growing areas (the black dash line) are slightly at odds with traditional effects of monetary policy. A contractionary shock does not push down the house price at all. This may be because the monetary policy shock is measured by regressing the change in policy rate on aggregate variables such as output. An area with higher than average output may "interpret" a contractionary monetary policy for the whole economy as an expansionary monetary policy shock for the local area. However, this is not the main interest of this paper.

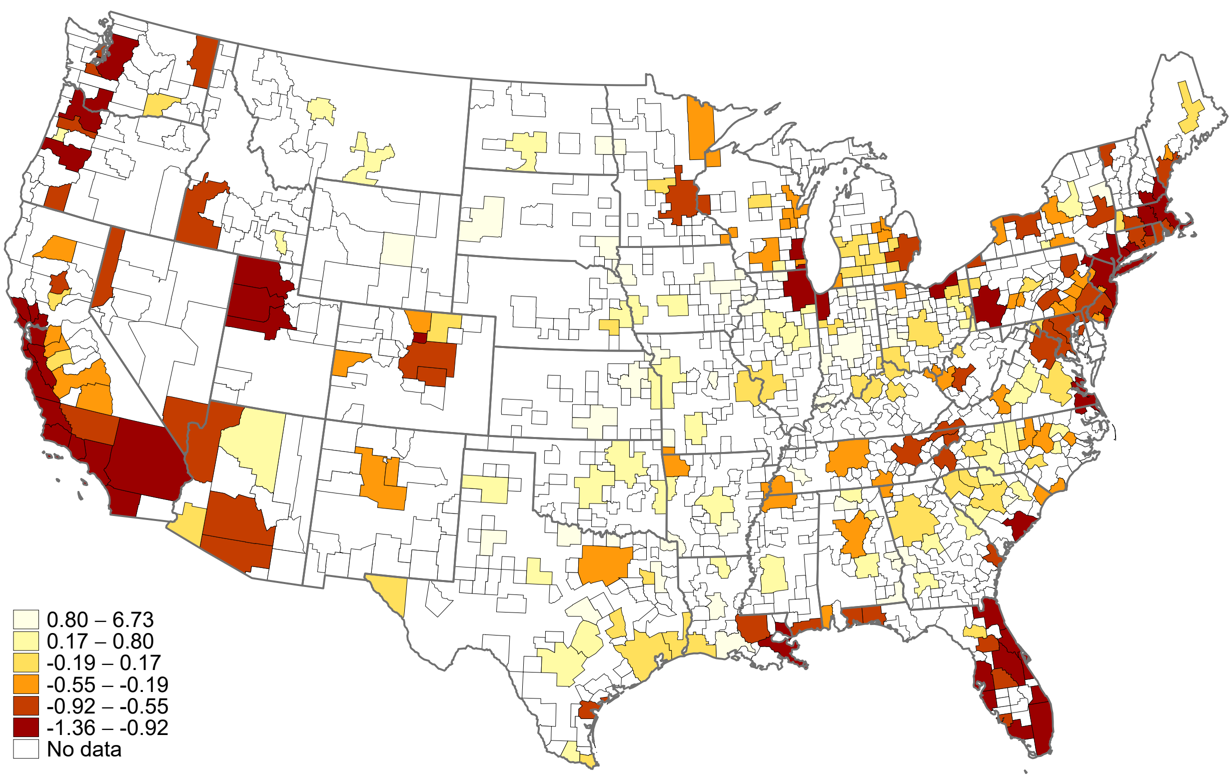
## 3.4 The Housing Supply Elasticity in Urban Growth and Decline

The housing supply elasticity plays a role in generating regional variation in house prices (Mian & Sufi (2011), Guren et al. (2018)). It also plays a role in explaining heterogeneous regional responses to expansionary monetary policy as in Aastveit & Anundsen (2018). The reason why it matters is simple. An expansionary monetary policy shock will lead to a higher demand for houses, thus drives up house prices. Areas with high supply elasticity will see less house prices increase in equilibrium as more supply (and/or expectation about more supply) presents in these areas. Aastveit & Anundsen (2018) also shows that the housing supply elasticity is not playing an important role in house prices response to contractionary monetary policy shocks. So, in general, low housing supply elasticity areas should be more sensitive to monetary policy. Are inelastic supply areas those growing urbans?

If the housing supply elasticity binds housing supply like a hard wall, then urban growth should be negatively related to housing supply elasticity. Inelastic areas cannot experience a large population growth for a limited housing supply. If this were the case, then the urban growth sub-sample should be biased toward high supply elasticity areas. Since house prices in high elastic areas respond less to monetary policy shocks, our results that growing urban areas are more responsive to monetary policy cannot be driven by the housing supply elasticity. However, urban growth, in fact, is positively correlated with inelastic supply.

Maps of normalized Saiz elasticity (Figure 3.9) and cumulative population growth over 1975-2019 (Figure 3.10) show that the high cumulative population growth positively relates to low housing supply elasticity. The population seems to flow into more inelastic areas. The darker areas in Figure 3.9 are areas with inelastic housing supply (the west, northeastern, and Florida). The darker areas in Figure 3.10 are areas with higher population growth (the west, Florida, Texas). The northwestern does not have as high population growth as some areas in California. This may be because these areas in 1970 have a large population to begin with. High population growth areas coincide with low housing supply areas. This can also be seen from a scatter plot of cumulative population growth and Saiz elasticity (Figure 3.20 in the appendix). So the sensitivity of house prices to monetary policy in these areas may be attributed to not only urban growth but also the housing supply elasticity. In order to show that the different housing supply elasticity does not fully explain the more sensitivity to monetary policy for urban growth, we perform additional tests. We first test the role of housing supply elasticity in connecting house price growth and population growth. Then we investigate the role of housing supply elasticity in the heterogeneous effects of monetary policy during urban growth or decline.

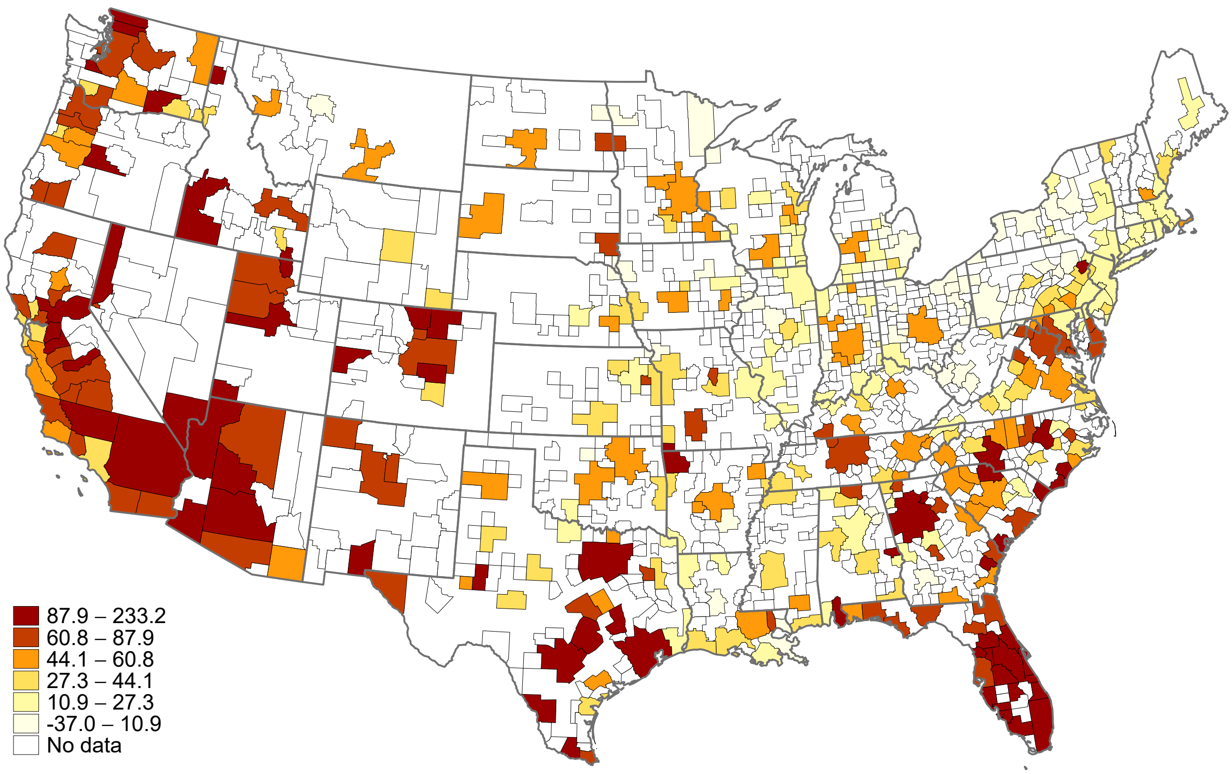
Figure 3.9: Normalized Saiz Elasticity




We check the role of housing supply elasticity in understanding house prices during urban growth and urban decline.

$$y_i = \alpha + \beta * x_i + \beta_E * x_i * \gamma_i + u_i$$

Figure 3.10: Cumulative Population Growth 1975-2019




of which $y_i$ is the cumulative house price growth for CBSA $i$. $x_i$ is the cumulative population growth. $\gamma_i$ is the normalized Saiz elasticity. $\beta_E$ is the parameter of interest here. The estimated $\beta$ is 0.87, statistically significant. And the estimated $\beta_E$ is -0.23, also statistically significant (as column 2 in Table 3.8). This is to say, for an area with the mean Saiz elasticity, a one percent increase in the cumulative population growth is associated with a 0.87 percent increase in house price. Moreover, if the area has a one-standard-deviation elasticity higher than the mean Saiz elasticity. The house price growth rate for one percent population growth is 0.23 percent lower. The higher the housing supply elasticity, the lower the house price growth.

Glaeser & Gyourko (2005) points out the asymmetry between urban growth and urban decline. We test this asymmetry using our data:

$$y_i = \alpha + \beta_g I_{g,i} x_i + \beta_d (1 - I_{g,i}) x_i + u_i$$

of which $I_{g,i}$ indicates a positive cumulative population growth. $\beta_g$ captures the effects of the cumulative population growth on cumulative house prices growth for urban growth. $\beta_d$ captures the same thing for urban decline. The estimations for $\beta_g$ and $\beta_d$ are 0.38 and 1.17 respectively, statistically significant (as column 3 in Table 3.8). For unit percentage increase in population, house price increases by 0.38 percent. For unit percentage decline in population, house price declines 1.17 percent, higher than the population decline. We confirm Glaeser & Gyourko (2005) results using our data that house prices increase less than population growth for urban growth and house prices decrease more than population decline for urban decline.

We then check the role of elasticity in a setting with both urban growth and urban decline:

$$
\begin{aligned}
y_i = \alpha &+ \beta_g I_{g,i} x_i + \beta_d (1 - I_{g,i}) x_i \\
&+ \beta_{g,E} I_{g,i} x_i \gamma_i + \beta_{d,E} (1 - I_{g,i}) x_i \gamma_i + u_i
\end{aligned}
$$

of which $\gamma_i$ is the housing supply elasticity. Column 4 in Table 3.8 presents the estimates for $\beta_g$, $\beta_d$, $\beta_{g,E}$, and $\beta_{d,E}$. They are 0.86, 0.44, -0.26 and 0.32 respectively. A one percentage increase in population will increase the house price by 0.86 percent for areas with average housing supply elasticity. And if the same population increase happens in areas with a housing supply elasticity one standard deviation higher than the average, the increase in house prices will be reduced by 0.26 percent (the net increase in house price will be 0.6 percent). A one percentage decline in population will decrease house prices by 0.44 percent on average. And if the housing supply elasticity increases by one standard deviation, the decline in house price will be increased by 0.32 percent. This means the housing supply elasticity attenuates the house price increase to population growth. Furthermore, the housing supply elasticity amplifies the house price decrease to a decline in the population. We confirm that urban decline is not a mirror image of urban growth, and we extend Glaeser & Gyourko

(2005) results to emphasize that the housing supply elasticity does play a role.

Next, we formally include the role of housing supply elasticity in investigating the impact of monetary policy on house prices. To check the role housing supply elasticity plays house price responses to monetary policy.

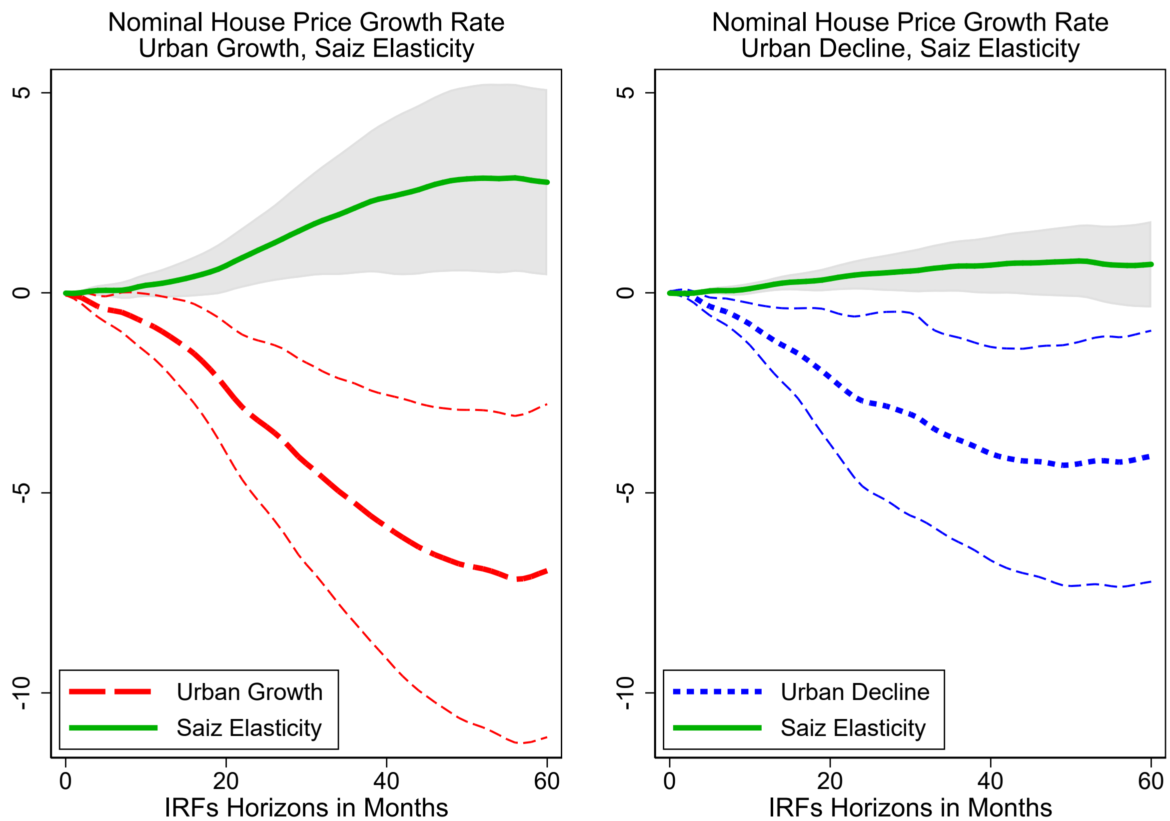
$$y_{i,t+h} = \alpha_i + \beta_g^h I_{i,g} * \epsilon_t + \beta_d^h (1 - I_{i,g}) * \epsilon_t$$
$$+ \beta_{g,E}^h I_{i,g} * \gamma_i * \epsilon_t + \beta_{d,E}^h (1 - I_{g,i}) * \gamma_i * \epsilon_t + u_i$$

$g$ indicates urban growth, and $d$ indicates urban decline. $\gamma_i$ is the normalized Saiz housing supply elasticity for CBSA $i$, which is time-invariant. $\beta_g^h$ capture the impulse response of house prices to monetary policy with the average housing supply elasticity for the growing area. And $\beta_{g,E}^h$ captures the marginal response of house prices to monetary policy shocks for urban growth if the housing supply elasticity were to increase by one standard deviation. Similar economic meaning applies when we change the $g$ to $d$. The coefficients of interest are $\beta_{g,E}$ and $\beta_{d,E}$. They capture the additional responses to monetary policy if the CBSA has a housing supply elasticity one standard deviation higher than the average. The results are presented in Figure 3.11 and Table 3.4.

The long-dash red line in the left graph of Figure 3.11 corresponds to impulse response to monetary policy for growing areas with average housing supply elasticity. And the short-dash blue line in the right graph corresponds to impulse response to monetary policy for declining areas. The solid green line in both graphs captures the marginal effects one standard deviation of supply elasticity can add to the effect of monetary policy on house prices. We also provides sensitivity checks using different classifications of urban growth (Figure 3.22 and Figure 3.24).

Columns two and three in Table 3.4 are the impulse responses for urban growth and decline at selected horizons. There are less response for urban decline comparing to urban growth. We also find that the housing supply elasticity plays a more important role in

Figure 3.11: Monetary Policy Effects: Urban Growth (50th Percentile Cutoff) and Housing Supply Elasticity




Notes: *Impulse responses of house price to monetary policy shock. Urban growth is defined as cumulative population growth larger than the 50th percentile for all CBSAs. The long-dash red line in the left graph corresponds to the impulse responses for growing areas with mean housing supply elasticity, and the short-dash blue line in the right graph is for declining areas. The solid green lines correspond to the marginal impulse responses if the housing supply elasticity increases by one standard deviation from the average housing supply elasticity.*

responses to monetary policy for growing areas than for declining areas. Columns five and six in Table 3.4 shows the marginal monetary policy responses if the area had a one standard deviation housing supply elasticity higher than the mean. For example, 54 months after the shock, one standard deviation increase in housing supply elasticity will decrease the house price response by 2.58 as to 6.05 (42.6%) for growing urbans. In contrast, one standard deviation increase in housing supply elasticity will decrease the house price response by 0.74

as to 3.63 (20.4%) for declining urbans. The p-value is 0.09 for the different roles the housing supply elasticity plays in urban growth versus urban decline.

Table 3.4: Cumulative Impulse Responses of House Price with Housing Supply Elasticity

| h | Urban growth | Urban decline | P-value for difference | Elasticity for urban growth | Elasticity for urban decline | P-value for elasticity difference |
|---|---|---|---|---|---|---|
| 6 | -0.45 | -0.38 | 0.70 | -0.01 | 0.05 | 0.48 |
| 12 | -0.91 | -0.93 | 0.94 | 0.15 | 0.17 | 0.92 |
| 18 | -1.68 | -1.56 | 0.78 | 0.38 | 0.29 | 0.76 |
| 24 | -2.81 | -2.37 | 0.46 | 0.90 | 0.46 | 0.25 |
| 30 | -3.72 | -2.62 | 0.11 | 1.42 | 0.54 | 0.08 |
| 36 | -4.54 | -3.17 | 0.08 | 1.88 | 0.68 | 0.08 |
| 42 | -5.27 | -3.59 | 0.08 | 2.22 | 0.74 | 0.10 |
| 48 | -5.80 | -3.73 | 0.06 | 2.55 | 0.79 | 0.08 |
| 54 | -6.05 | -3.63 | 0.04 | 2.58 | 0.74 | 0.09 |
| 60 | -5.98 | -3.54 | 0.05 | 2.49 | 0.73 | 0.11 |

Notes: *Urban growth here is defined as cumulative population growth larger than 50th percentile. The first p-value in the fourth column is for the difference between monetary policy effects for urban growth and urban decline of an area with unit elasticity. The fifth and sixth columns are the coefficients before interaction term of elasticity with monetary policy shocks. The second p-value captures the different role the housing supply elasticity plays during urban grow and urban decline.*

More importantly, the difference remains for urban growth and urban decline, even for areas with the same average housing supply elasticity. And we test the difference between the two responses at different horizons. The p-value for the difference suggests that the response for urban growth is significantly larger for areas with the average housing supply elasticity. For example, after 54 months of monetary policy shock, the house price decreases by 6.05% for urban growth and 3.63% for urban decline. And the p-value is 0.04. We can compare this result with previous result in Table 3.2 in which the role of housing supply elasticity is not controlled. For average growing areas compared with declining areas, after 54 months of monetary policy shock, the house price decreases by 7.54% for urban growth and 3.90% for urban decline. And the p-value is 0.00. After we switch our focus to the house prices responses only for areas with average elasticity, the difference between urban growth and decline shrinks from 3.64% to 2.42%[5], the p-value for the difference increase from 0.00 to 0.04. This suggests both urban growth and the housing supply elasticity contribute to the overall different responses to monetary policy shocks between growing areas and declining areas.

As a piece of evidence for our explanation in Section 3.3, we test the two testable predictions. The results have been presented in Figure 3.8 and discussed in above text. However, those results do not control for the fact that urban growth correlates with the housing supply elasticity. Now we perform similar tests taking into account the role of housing supply elasticity. Specifically, we now perform local projections conditional on two states as follows:

$$
\begin{aligned}
y_{i,t+h} = \alpha_i &+ \beta^h_{g,c} I_{g,i,t} I_{c,i,t} * \epsilon_t + \beta^h_{d,c}(1 - I_{g,i,t}) I_{c,i,t} * \epsilon_t \\
&+ \beta^h_{g,e} I_{g,i,t}(1 - I_{c,i,t}) * \epsilon_t + \beta^h_{d,e}(1 - I_{g,i,t})(1 - I_{c,i,t}) * \epsilon_t \\
&+ \beta^h_{g,c,E} I_{g,i,t} I_{c,i,t} * \epsilon_t * \gamma_i + \beta^h_{d,c,E}(1 - I_{g,i,t}) I_{c,i,t} * \epsilon_t * \gamma_i \\
&+ \beta^h_{g,e,E} I_{g,i,t}(1 - I_{c,i,t}) * \epsilon_t * \gamma_i + \beta^h_{d,e,E}(1 - I_{g,i,t})(1 - I_{c,i,t}) * \epsilon_t * \gamma_i \\
&+ \phi' x_{i,t} + u_{i,t+h}
\end{aligned}
$$

We are still interested in $\beta^h_{g,e}$, $\beta^h_{d,e}$, $\beta^h_{g,c}$, and $\beta^h_{d,c}$. $\beta^h_{g,e}$ captures house price responses to expansionary monetary policy shocks in growing areas. $\beta^h_{d,e}$ captures the responses to expansionary shocks in declining areas. Similarly, $\beta^h_{g,c}$ and $\beta^h_{d,c}$ captures the responses to contractionary shocks in growing areas and declining areas, respectively. But now these coefficients capture the responses for areas with the average housing supply elasticity. We find evidence consistent with the testable predictions which suggests our previous results are not driven by the housing supply elasticity. The results are in Figure 3.25.

[5] 3.64=7.54-3.90, 2.42=6.05-3.63 at $h = 54$

## 3.5 Conclusion

This paper finds that house prices in growing areas are more sensitive to monetary policy. Moreover, this is not explained by the different housing supply elasticity across areas. The heterogeneous regional responses of house prices to monetary policy can arise from different local population trends. This has important implications for understanding monetary policy transmission and adds to understand the regional heterogeneity of house price dynamics. Policymakers may want to keep an eye on the distribution of local population trends when making relevant decisions.

The explanation we provide is of reduced form without micro-foundations. We can potentially micro-found our explanation following two directions. The first is the search framework as in Piazzesi & Schneider (2009) with an innovation that the regional market tightness is connected with the local population trends. A second approach is to combine the collateral constraints for housing markets of Iacoviello (2005) and the belief disagreements interacted with collateral constraints as in Simsek (2013). Another potential empirical improvement is to control the role of credit supply in house prices as credit supply is emphasized as an important factor affecting house prices (Mian & Sufi (2009), Favara & Imbs (2015), Justiniano et al. (2019) among others).

House price movements are vital for residential investment decisions, which is a critical factor for business cycles. There is also important information lying in the quantity side of the story. Is there more housing supply in urban growth areas? Are houses listed in the market a constant fraction of existing housing stocks, or does the fraction vary with time and over the business cycle? These are questions for future research.

# Tables

Table 3.5: The Top Five Percent of Urban Growth

| CBSA Name | Cumulative Population Growth |
|---|---|
| Las Vegas-Henderson-Paradise, NV | 217.5 |
| Cape Coral-Fort Myers, FL | 204.6 |
| Port St. Lucie, FL | 187.5 |
| Austin-Round Rock, TX | 175.7 |
| Beach-Conway-North Myrtle Beach, SC-NC | 169.7 |
| Orlando-Kissimmee-Sanford, FL | 164.0 |
| McAllen-Edinburg-Mission, TX | 159.7 |
| Phoenix-Mesa-Scottsdale, AZ | 159.2 |
| Provo-Orem, UT | 154.8 |
| Raleigh, NC | 150.2 |
| Riverside-San Bernardino-Ontario, CA | 143.5 |
| Fort Collins, CO | 140.7 |
| Boise City, ID | 139.0 |

Notes: *Cumulative population growth is from 1975 to 2019. These CBSAs are those with population larger than 100 thousand in 1975.*

Table 3.6: The Bottom Five Percent of Urban Growth

| CBSA Name | Cumulative Population Growth |
|---|---|
| Johnstown, PA | -35.9 |
| Weirton-Steubenville, WV-OH | -35.7 |
| Wheeling, WV-OH | -26.7 |
| Charleston, WV | -23.6 |
| Youngstown-Warren-Boardman, OH-PA | -21.3 |
| Elmira, NY | -19.4 |
| Decatur, IL | -18.2 |
| Buffalo-Cheektowaga-Niagara Falls, NY | -17.8 |
| Pittsfield, MA | -17.7 |
| Pine Bluff, AR | -17.5 |
| Pittsburgh, PA | -17.4 |
| Utica-Rome, NY | -15.9 |
| Springfield, OH | -15.8 |

Notes: *Cumulative population growth is from 1975 to 2019. These CBSAs are those with population larger than 100 thousand in 1975.*

Table 3.7: Cumulative Impulse Responses of House Price (3)

| Horizon | Linear | Urban growth | Urban decline | P-value for difference |
|---|---|---|---|---|
| 6 | -0.43 | -0.53 | -0.41 | 0.45 |
| 12 | -0.99 | -1.18 | -0.95 | 0.52 |
| 18 | -1.77 | -2.25 | -1.64 | 0.32 |
| 24 | -2.88 | -3.99 | -2.52 | 0.08 |
| 30 | -3.61 | -5.55 | -2.97 | 0.01 |
| 36 | -4.45 | -6.94 | -3.59 | 0.00 |
| 42 | -5.15 | -8.17 | -4.11 | 0.00 |
| 48 | -5.58 | -9.11 | -4.35 | 0.00 |
| 54 | -5.75 | -9.58 | -4.40 | 0.00 |
| 60 | -5.68 | -9.46 | -4.34 | 0.00 |

Notes: *Urban growth here is defined as cumulative population growth larger than 75th percentile. Column 1 is the selected horizons; Column 2 is the impulse responses for the linear model; Column 3 is the impulse responses for urban growth; Column 4 is the impulse responses for urban decline; Column 5 is the p-value for the difference between urban growth and decline.*

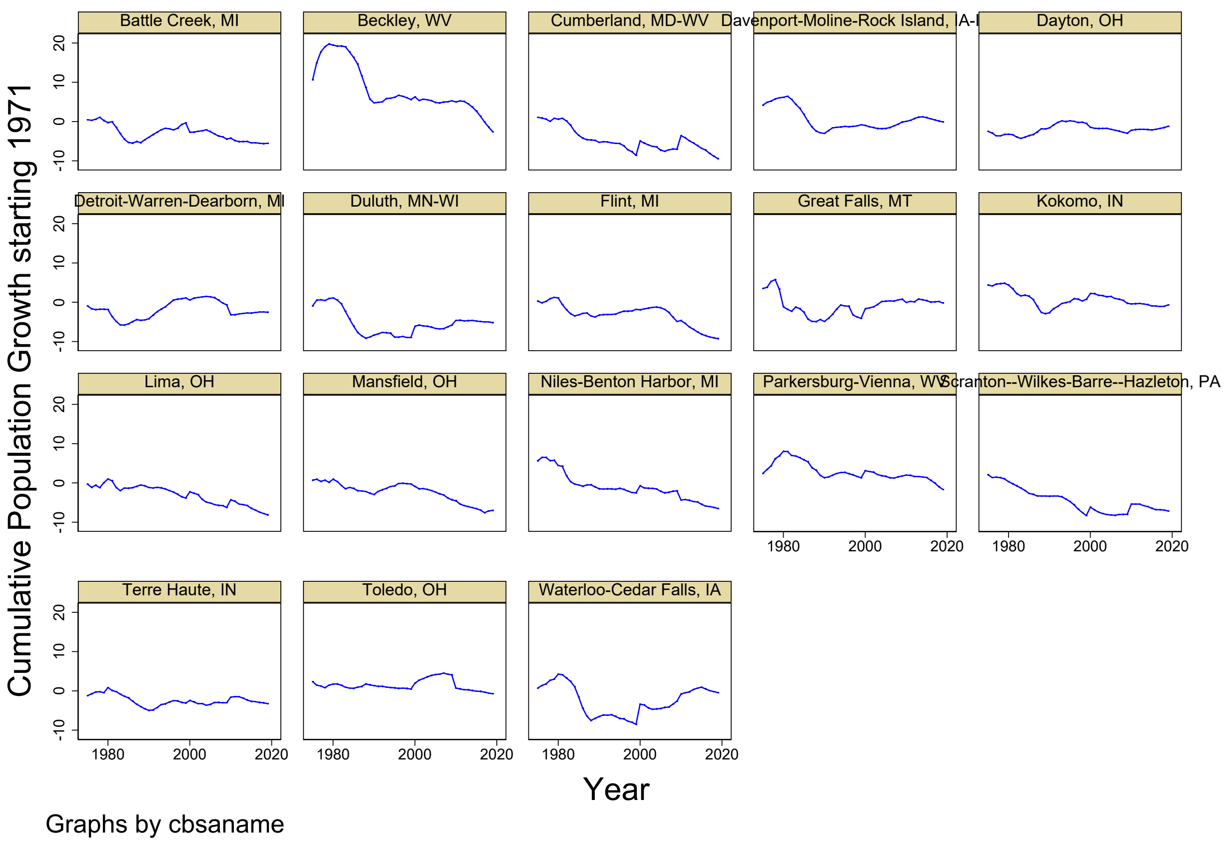
Table 3.8: House Price Growth and Population Growth

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | $y_i$ | $y_i$ | $y_i$ | $y_i$ |
| Cumulative Population Growth 1975-2019 | 0.41*** | 0.87*** | | |
| | (0.05) | (0.10) | | |
| Cumulative Population Growth * Elasticity | | -0.23*** | | |
| | | (0.04) | | |
| Positive Cumulative Population Growth | | | 0.38*** | 0.86*** |
| | | | (0.05) | (0.10) |
| Negative Cumulative Population Growth | | | 1.17*** | 0.44 |
| | | | (0.33) | (0.47) |
| Positive Population Growth * Elasticity | | | | -0.26*** |
| | | | | (0.04) |
| Negative Population Growth * Elasticity | | | | 0.32*** |
| | | | | (0.09) |
| Constant | 167.09*** | 172.24*** | 170.01*** | 178.57*** |
| | (2.74) | (3.43) | (3.18) | (4.01) |
| Observations | 382 | 270 | 382 | 270 |

Notes: $y_i$ *is the cumulative house prices growth for CBSA* $i$. *Column 1 is the simple regression of cumulative house price growth on cumulative population growth. Column 2 tests the general role of housing supply elasticity. Column 3 tests house prices growth on population growth rate conditional on urban growth and urban decline. Column 4 tests the general role of housing supply elasticity conditional on urban growth and urban decline.*

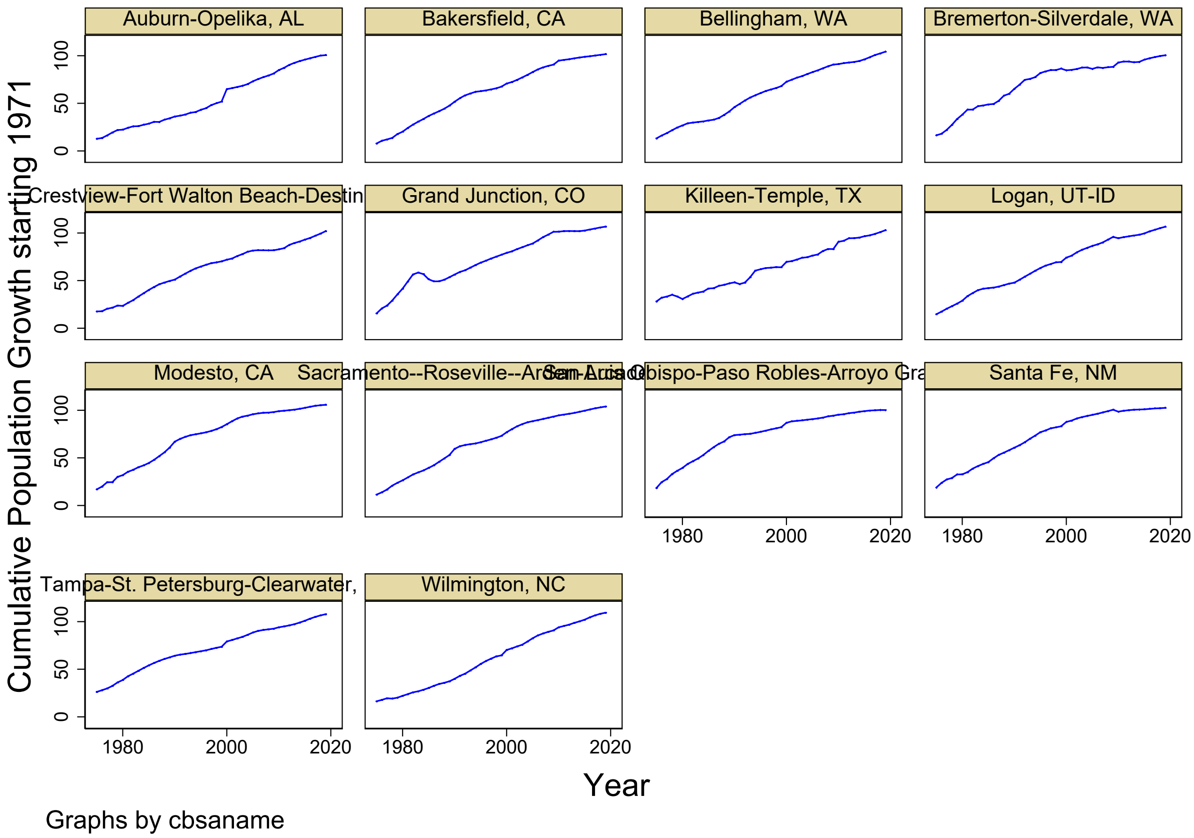
# Figures

Figure 3.12: Urban Decline: Cumulative Population Growth 1970-2019 between -10 to 0 Percent



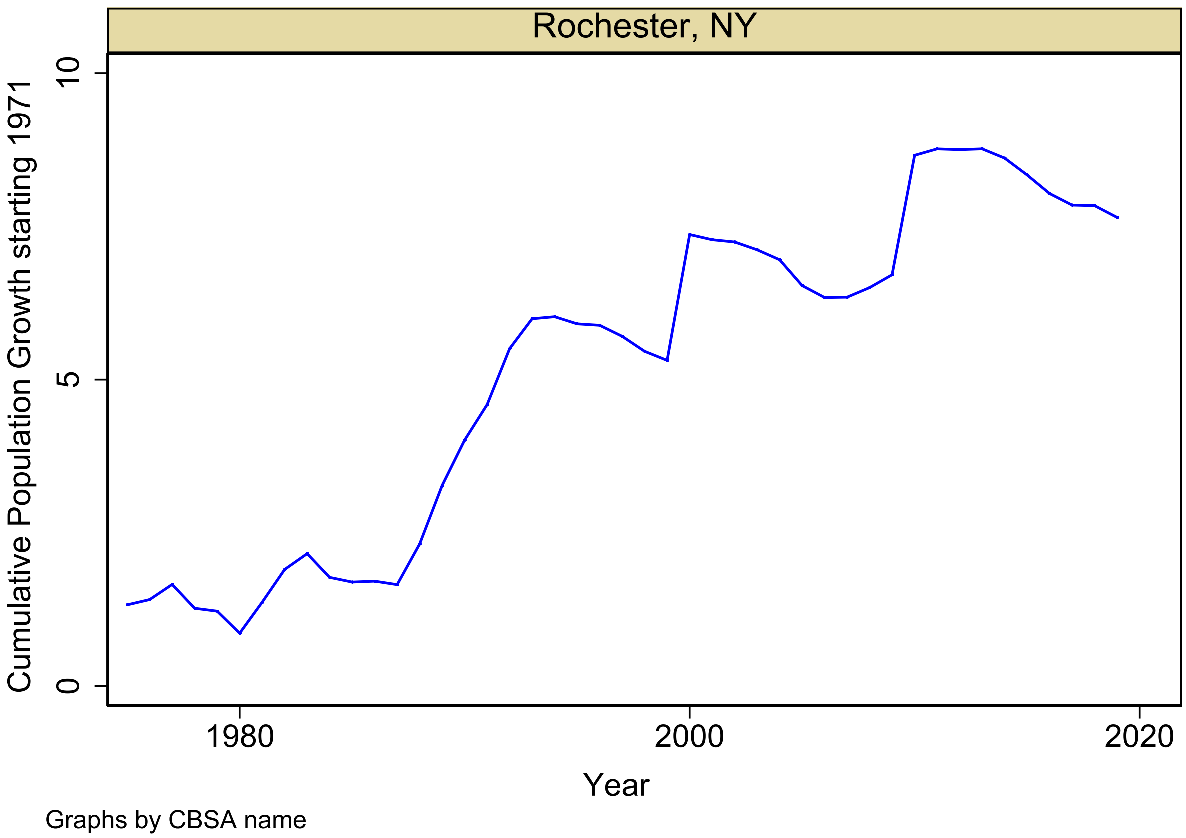

Notes: *Cumulative population growth rate in percentage on the y axis.*

Figure 3.13: Urban Growth: Cumulative Population Growth 1970-2019 between 100 to 120 Percent



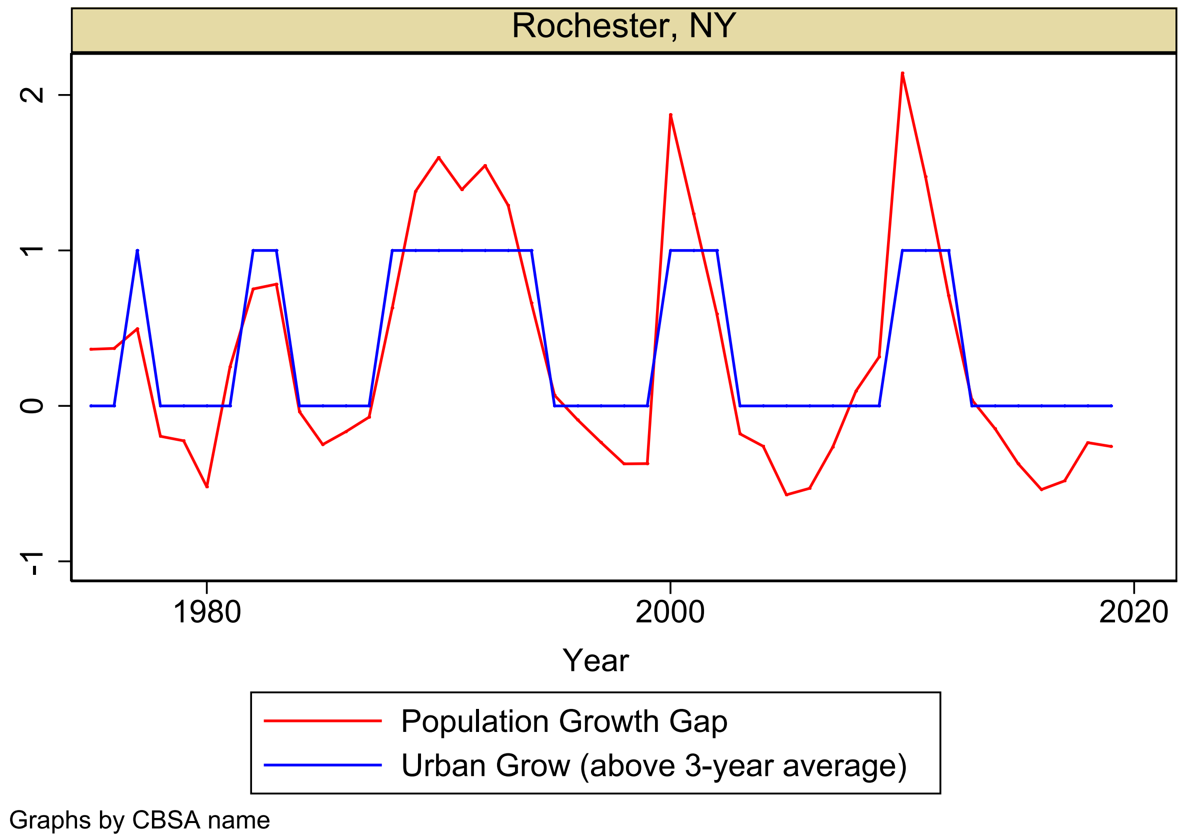

Notes: *Cumulative population growth rate in percentage on the y axis.*

Figure 3.14: Cumulative Population Growth for CBSA Rochester



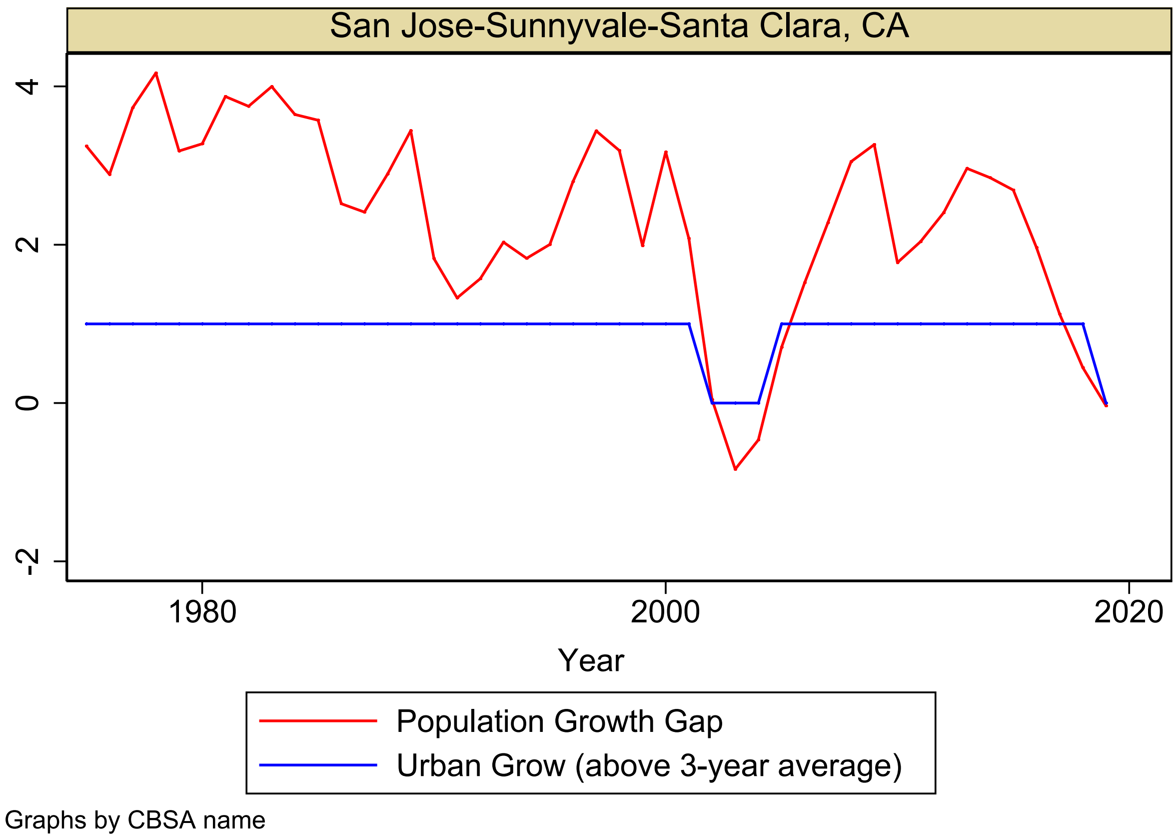

Notes: *Cumulative population growth rate in percentage on the y axis.*

Figure 3.15: Urban Growth and Decline for CBSA Rochester



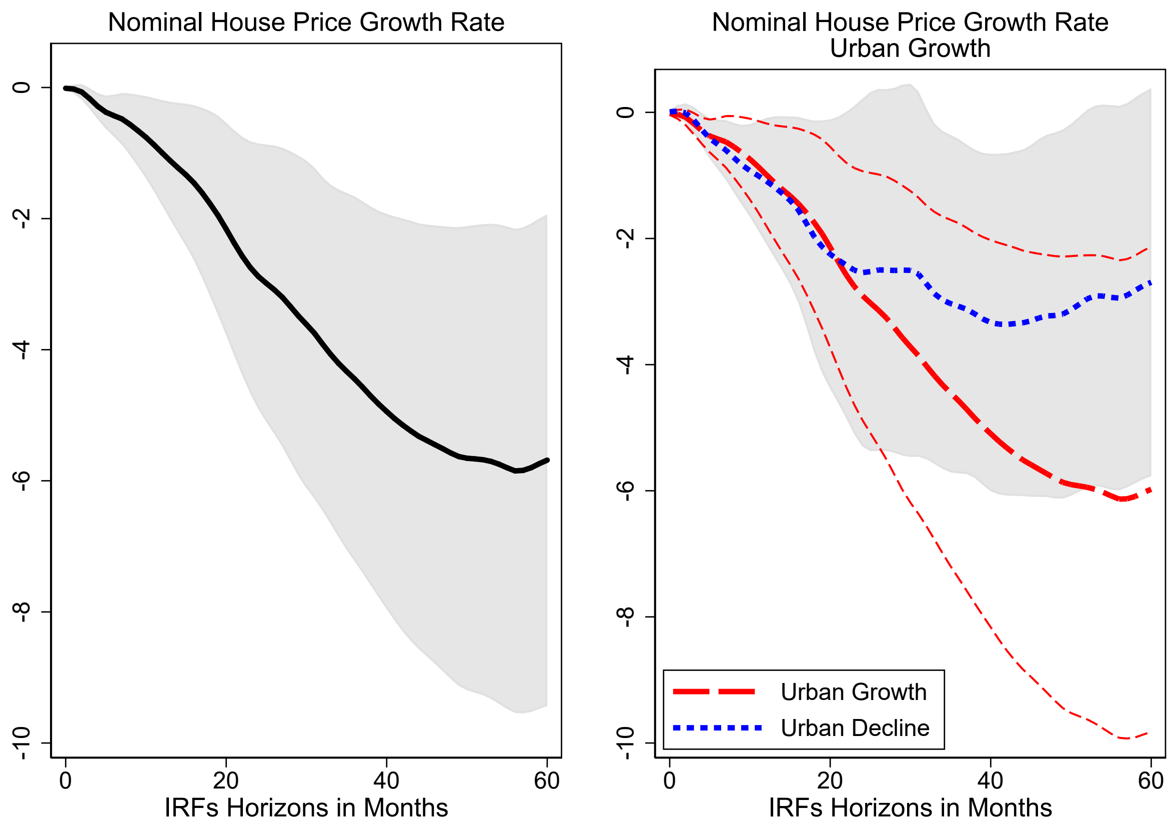

Notes: *Population growth gap is defined as current year cumulative population growth minus the average of past three years. Urban growth equals one if the population growth gap larger than its 25th percentile, and equals zero otherwise.*

Figure 3.16: Urban Growth and Decline for CBSA San Jose



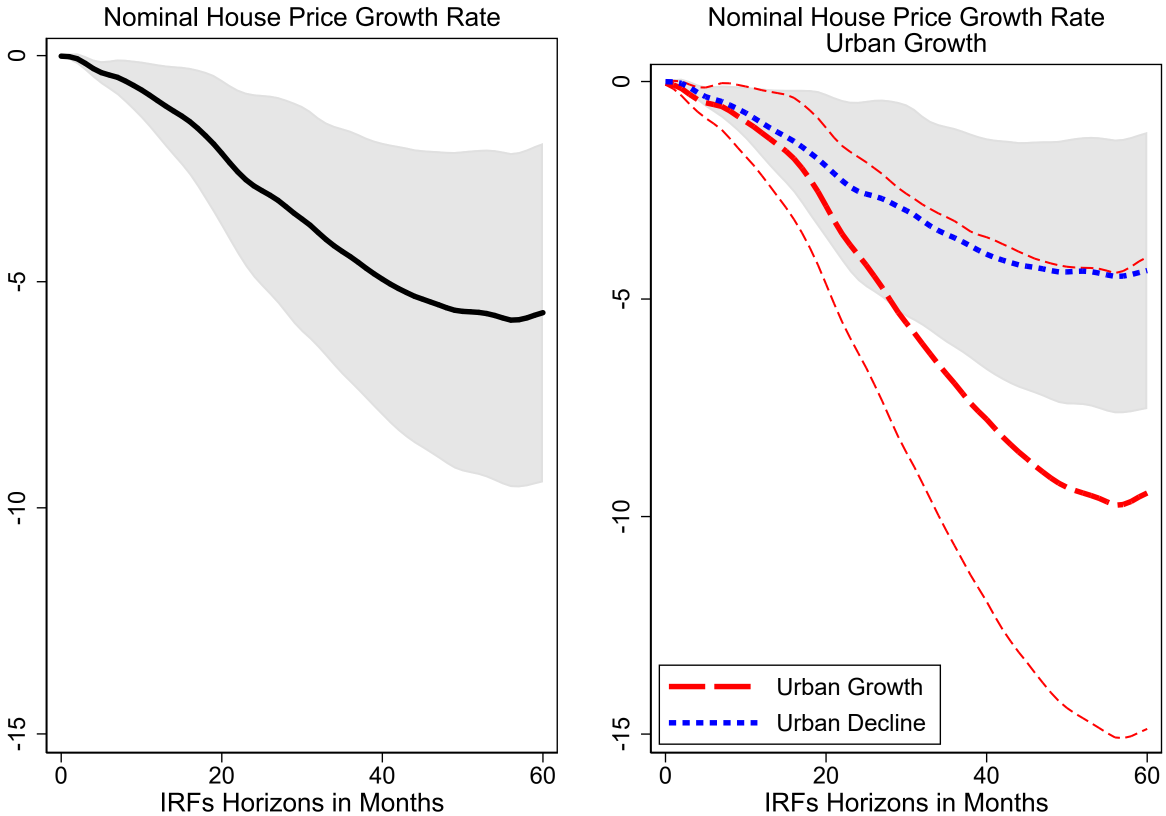

Notes: *Population growth gap is defined as current year cumulative population growth minus the average of past three years. Urban growth equals one if the population growth gap larger than its 25th percentile, and equals zero otherwise.*

Figure 3.17: Monetary Policy Effects: Urban Growth (0 Percent Cutoff)



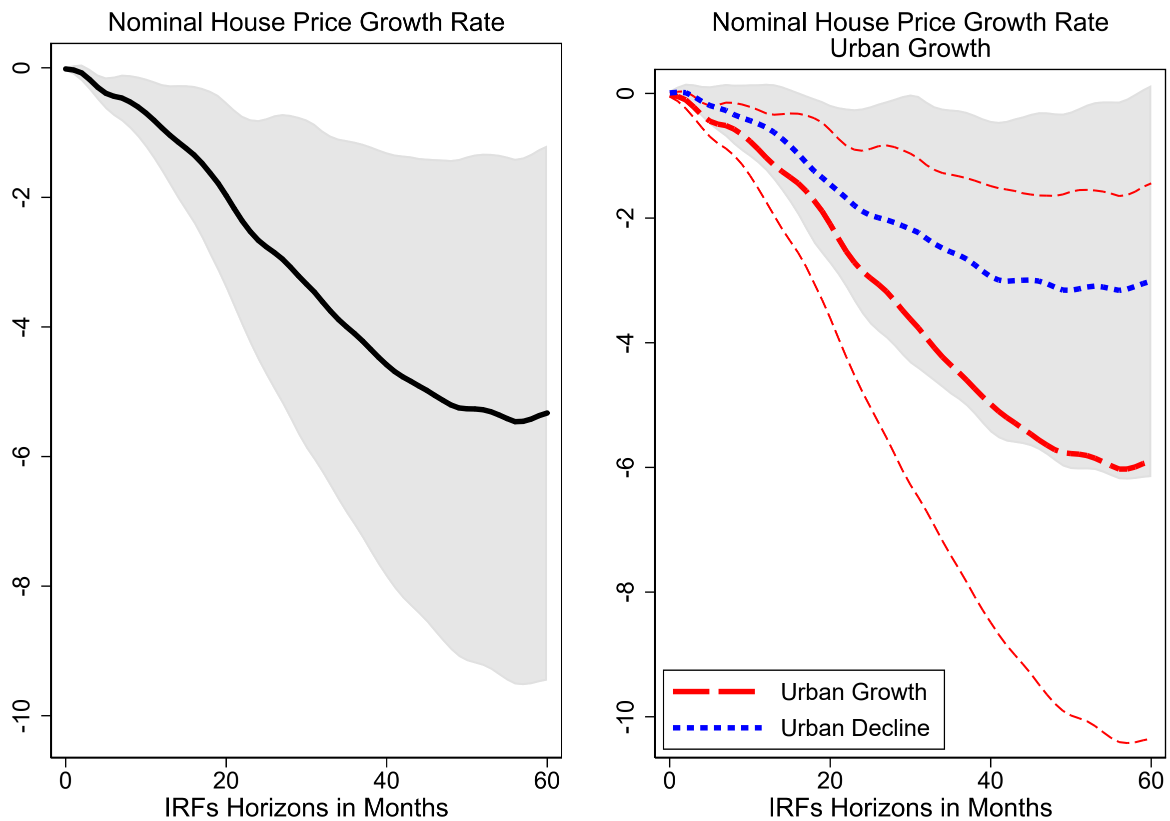

Notes: *Impulse responses of house price to monetary policy shocks. The black line in the left graph corresponds to the linear model. The long-dash red line in the right graph corresponds to the impulse responses for growing areas, and the short-dash blue line is for declining areas. Urban growth is defined as cumulative population growth larger than 0.*

Figure 3.18: Monetary Policy Effects: Urban Growth (75th Percentile Cutoff)



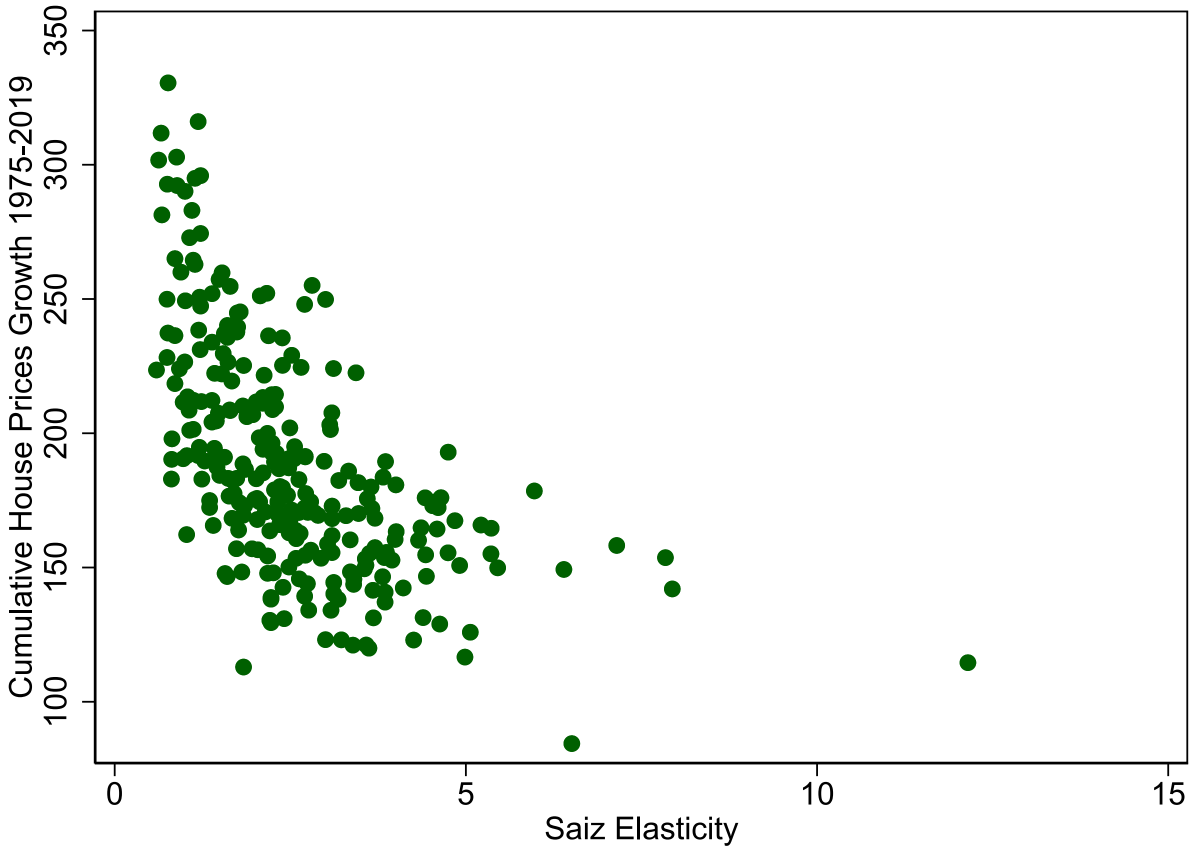

Notes: *Impulse responses of house price to monetary policy shocks. The black line in the left graph corresponds to the linear model. The long-dash red line in the right graph corresponds to the impulse responses for growing areas, and the short-dash blue line is for declining areas. Urban growth is defined as cumulative population growth larger than the 75th percentile for all CBSAs.*

Figure 3.19: Monetary Policy Effects: Urban Growth (above Average-Growth)



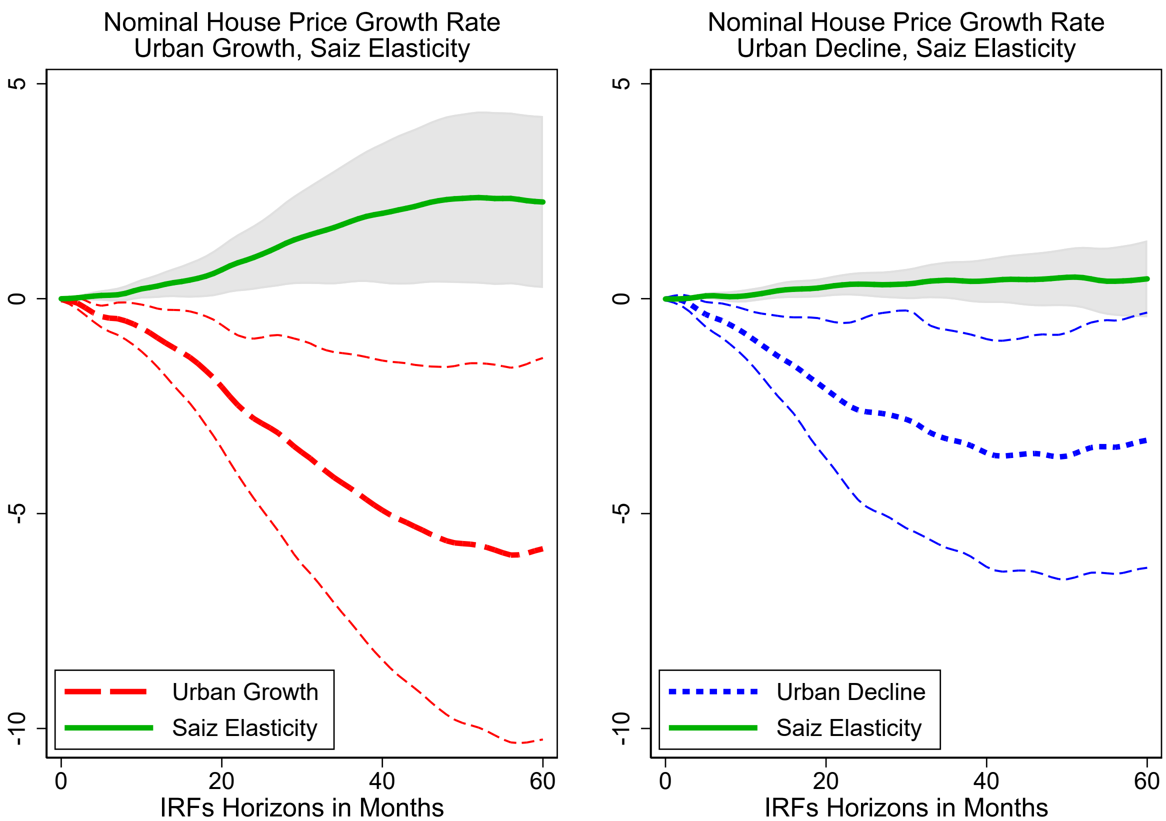

Notes: *Impulse responses of house price to monetary policy shocks. The black line in the left graph corresponds to the linear model. The long-dash red line in the right graph corresponds to the impulse responses for growing areas, and the short-dash blue line is for declining areas. Urban growth is defined as cumulative population growth larger than the average of past three years.*

Figure 3.20: Cumulative House Price Growth 1975-2019 and Saiz Elasticity



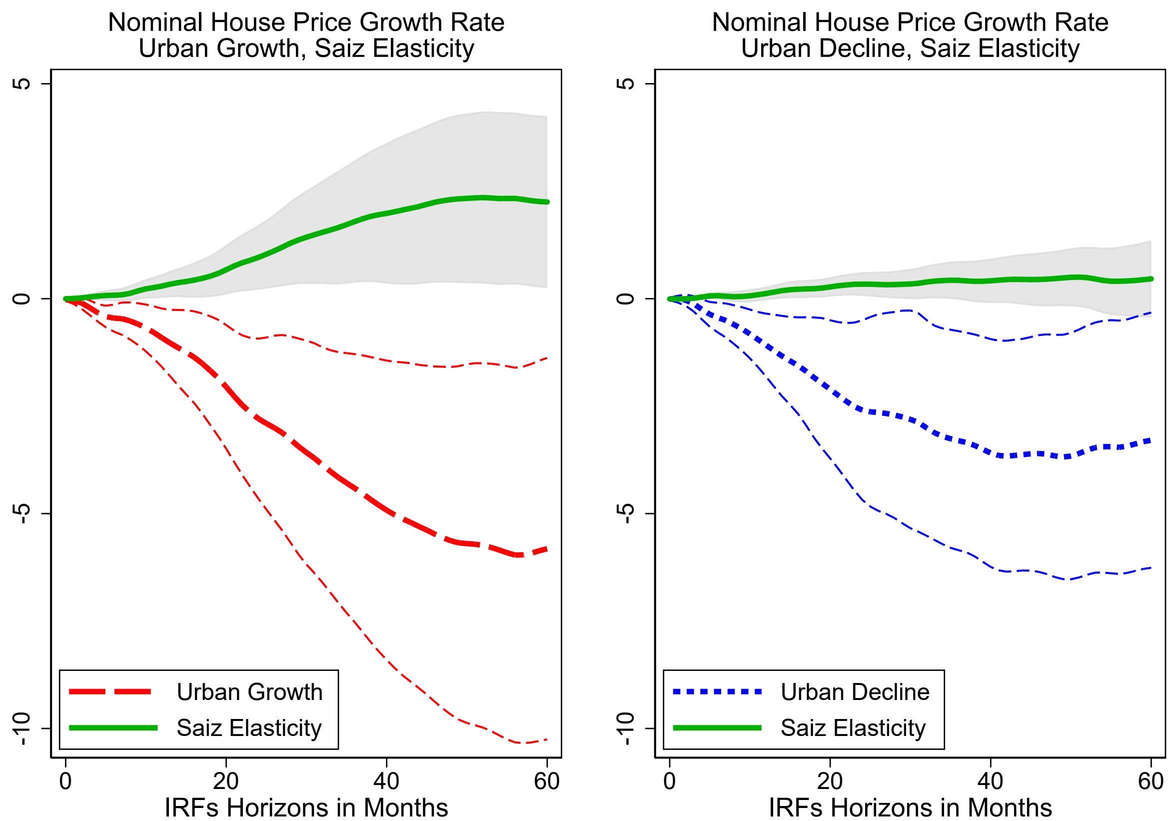

Notes: *Cumulative nominal house price growth rate in percentage on the y axis. The original Saiz elasticity, not normalized, on the x axis.*

Figure 3.21: Monetary Policy Effects: Urban Growth (0 Percent Cutoff) and the Housing Supply Elasticity



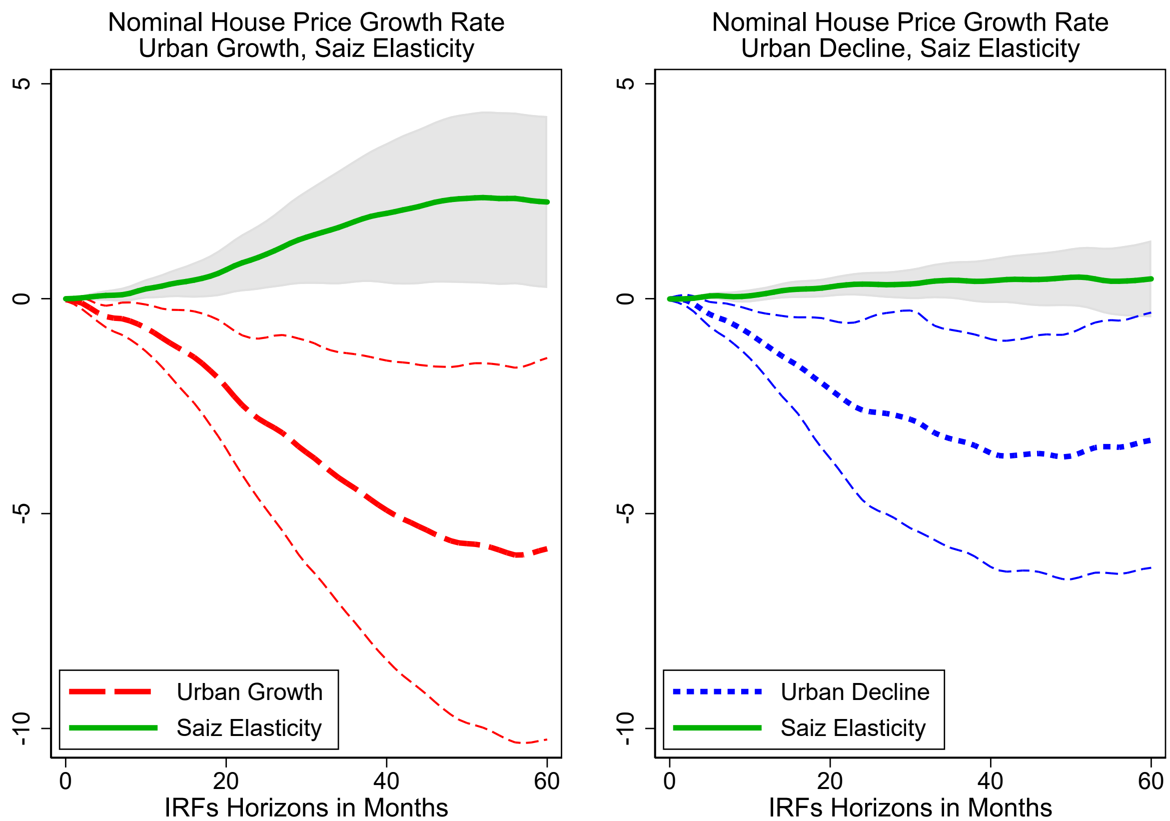

Notes: *Impulse responses of house price to monetary policy shock. Urban growth is defined as cumulative population growth larger than 0. The long-dash red line in the left graph corresponds to the impulse responses for growing areas with mean housing supply elasticity, and the short-dash blue line in the right graph is for declining areas. The solid green lines correspond to the marginal impulse responses if the housing supply elasticity increases by one standard deviation from the average housing supply elasticity.*

Figure 3.22: Monetary Policy Effects: Urban Growth (25th Percentile Cutoff) and the Housing Supply Elasticity



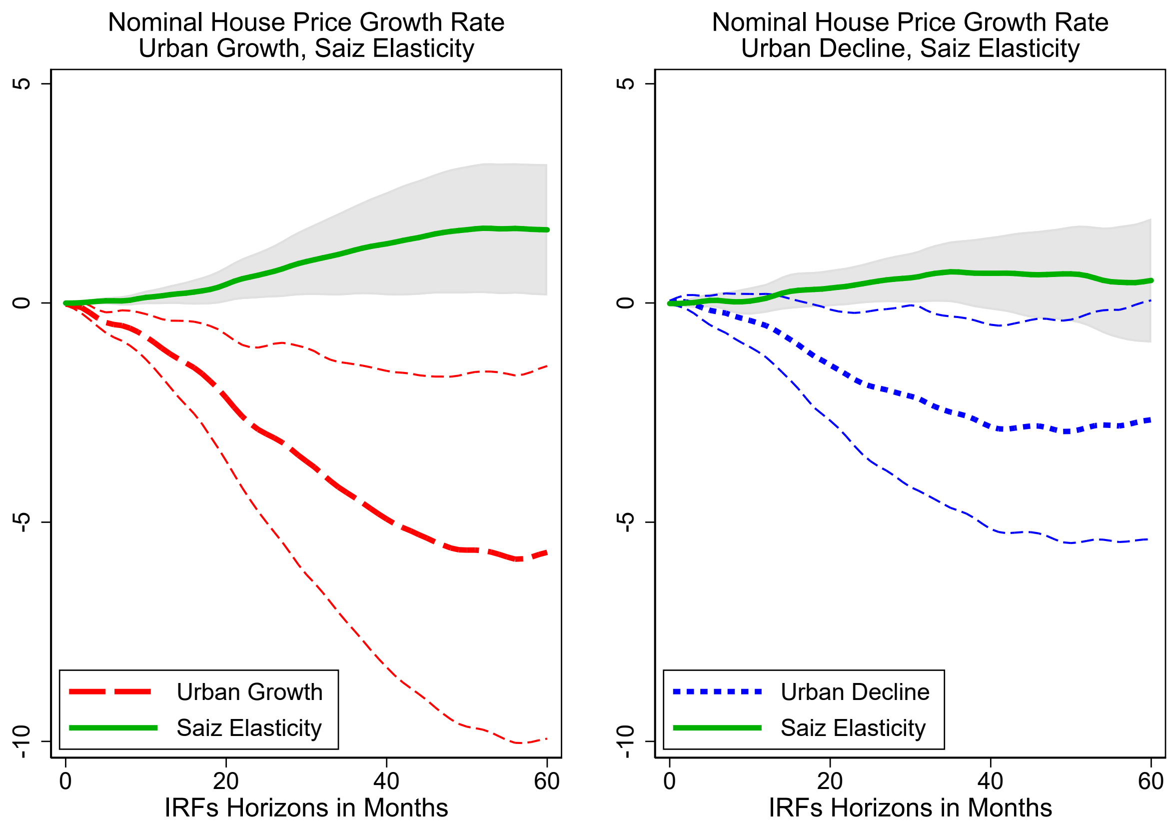

Notes: *Impulse responses of house price to monetary policy shock. Urban growth is defined as cumulative population growth larger than the 25th percentile for all CBSAs. The long-dash red line in the left graph corresponds to the impulse responses for growing areas with mean housing supply elasticity, and the short-dash blue line in the right graph is for declining areas. The solid green lines correspond to the marginal impulse responses if the housing supply elasticity increases by one standard deviation from the average housing supply elasticity.*

Figure 3.23: Monetary Policy Effects: Urban Growth (75th Percentile Cutoff) and the Housing Supply Elasticity



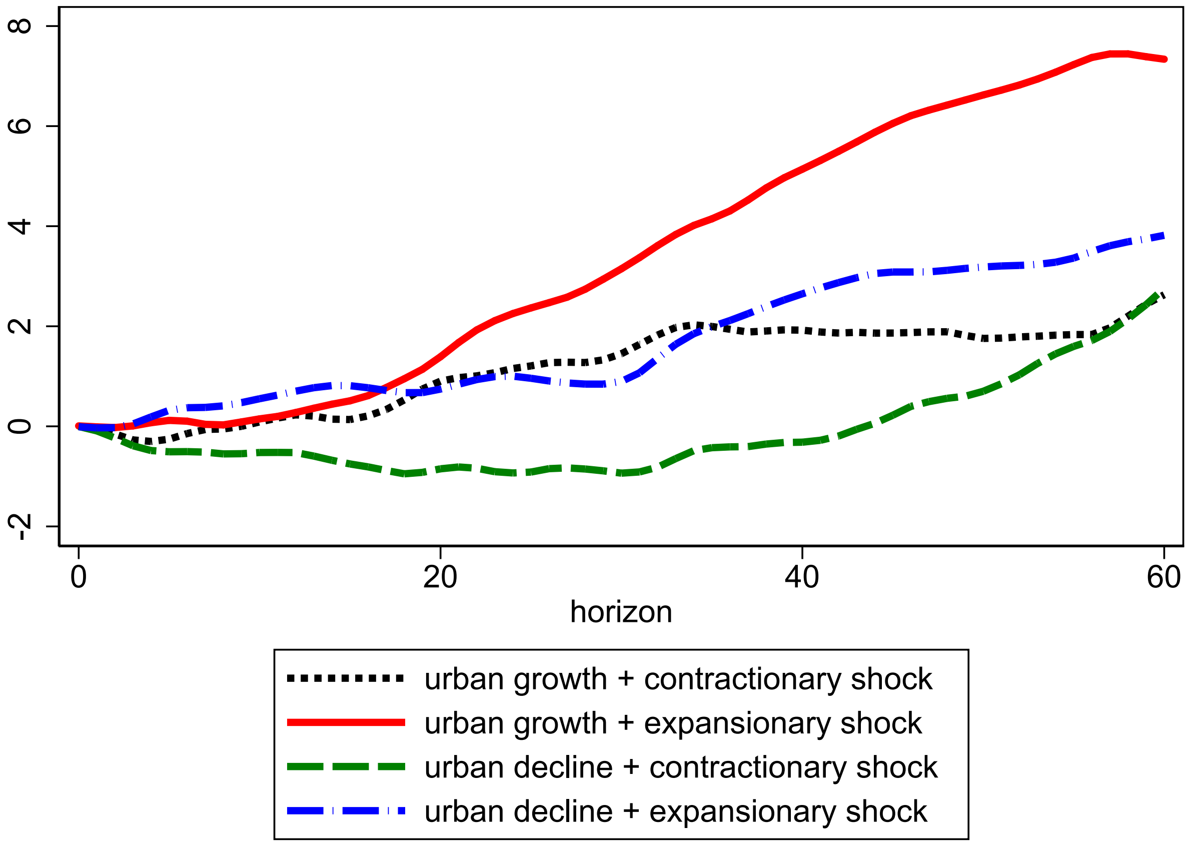

Notes: *Impulse responses of house price to monetary policy shock. Urban growth is defined as cumulative population growth larger than the 75th percentile for all CBSAs. The long-dash red line in the left graph corresponds to the impulse responses for growing areas with mean housing supply elasticity, and the short-dash blue line in the right graph is for declining areas. The solid green lines correspond to the marginal impulse responses if the housing supply elasticity increases by one standard deviation from the average housing supply elasticity.*

Figure 3.24: Monetary Policy Effects: Urban Growth (above Average-growth) and the Housing Supply Elasticity




Notes: *Impulse responses of house price to monetary policy shocks. Urban growth is defined as cumulative population growth larger than the average of past three years. The long-dash red line in the left graph corresponds to the impulse responses for growing areas with mean housing supply elasticity, and the short-dash blue line in the right graph is for declining areas. The solid green lines correspond to the marginal impulse responses if the housing supply elasticity increases by one standard deviation from the average housing supply elasticity.*

Figure 3.25: House Price Responses to Monetary Policy: Urban Growth, Expansionary Shocks, and the Housing Supply Elasticity




Notes: *The additional effects of the housing supply elasticity on the responses to monetary shocks are not graphed here.*

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