Monetary Policy, Economic Uncertainty, and Firms R&D Expenditure

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Abstract

This paper studies the response of firms' research and development (R&D) expenditure to monetary policy shocks in the US economy. Empirical results suggest that a 20 basis point increase in the interest rate decreases the aggregate R&D expenditure by 0.6 percent, which leads to a delayed drop in total factor productivity. Using Compustat firm-level data, I confirm that a monetary contraction leads to a persistent decline in US firms' R&D expenditure. The effect on R&D expenditure is stronger for interest rate hikes and when firms face higher uncertainty. This is because economic uncertainty decreases firms' leverage ratio and makes them more financially constrained, rendering R&D investment more vulnerable to contractionary policy shocks. I build a medium-scale DSGE model with endogenous output growth and financial frictions to interpret the empirical findings. The theoretical model highlights the importance of the credit channel for altering the effects of monetary policy on firms' investment in R&D in the presence of economic uncertainty.

JEL: E22, O32, G2

Keywords: Monetary Policy, Research and Development, Economic Uncertainty, Financial Constraint

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1 Introduction

Can monetary policy generate long-run effects on firms' productive capacity? Macroeconomists have traditionally focused on the impact of monetary policy on business cycle fluctuations and economic stability through short-lived nominal rigidities. However, theories of endogenous growth emphasize that fluctuations in investment and productivity during business cycles might generate hysteresis effect on the economy. Jordà et al. (2021) show that monetary policy can have a long-lived effect on the economy through deteriorating capital accumulation and total factor productivity (TFP). Yet, there is a definite need to understand how monetary policy influences TFP. While at short horizons variable utilization and markup dispersion explain part of TFP response (see e.g Meier and Reinelt (2022)), several studies highlight the importance of innovation and R&D expenditure as the main drivers of long-run TFP. Moran and Queralto (2018) show empirically that R&D tends to induce gradual, persistent increases in TFP in the US economy. Also, Huber (2018) finds that in Germany, banking distress caused a persistent decline in productivity through its effect on R&D. Therefore, understanding the impact of monetary policy on firms R&D expenditure is crucial in discussing its possible long-run effects.

The existing literature on the hysteresis effects of monetary policy disregards the economic conditions under which policy shocks take place and discusses the average effect of monetary contraction[1]. However, during the last few years, global economic uncertainty has surged due to the COVID19 pandemic and, more recently, the Russian war against Ukraine. The contemporaneous occurrence of high uncertainty and policy interventions has sparked a debate on the impact of uncertainty on the effectiveness of monetary policy shocks and their transmission mechanisms. The theoretical literature highlights two possible channels for the impact of uncertainty on the effectiveness of monetary policy: i) uncertainty weakens the effect of monetary policy due to the wait-and-see attitude and precautionary saving by investors (Vavra (2014) and Bloom (2014)), ii) the credit transmission channel theory that argues that monetary policy is more effective during high uncertainty periods since firms suffer from liquidity constraints due to stricter financial constraints (Bernanke et al. (1999), Brunnermeier and Sannikov (2014), and Burgard and Nockel (2019)). Given these considerations, I analyze whether the effects of monetary policy on R&D expenditure differ in periods of high and low economic uncertainty, measured by macroeconomic uncertainty indicator produced by Jurado et al. (2015) and updated by Ludvigson et al. (2021).

Firms' incentive to invest in R&D depends on the relative foregone cost versus the

[1]See Cerra et al. (2023) for a summary of the literature on the hysteresis effects of policy interventions

expected future benefit in terms of higher productive capacity. As monetary policy can potentially affect the relative cost or benefit of investing in new ideas, it can generate an effect on R&D investment and technological innovation. Several recent studies tried to incorporate this transmission channel of monetary policy in medium-scale New-Keynesian DSGE models with endogenous output growth [2]. Moreover, the trade-off between costs and expected benefits of R&D investments can crucially depend on the prevailing macroeconomic conditions. This paper, exploiting both the national account and firms' balance sheet data, investigates the state-dependent effects of monetary policy shocks on R&D expenditure in the US economy and explores possible mechanisms at play using a theoretical model.

Starting with the empirical investigation, this paper exploits the high-frequency shocks identified using restrictions on the comovement of interest rates and stock prices in a narrow window around FOMC announcements (see Jarociński and Karadi (2020)). The identified shocks recover exogenous changes in monetary policy that are unrelated to future fundamentals. Using quarterly data for the US economic indicators between 1990 to 2019, I estimate the dynamic responses of the real national accounts indicators to a contractionary monetary policy shock. Applying the local projection method (see, e.g., Jordà (2005)) and compatible with the existing literature, I show that a one standard deviation increase in the interest rate causes a significant decrease in the real GDP, private consumption, private investment and R&D expenditure up to four years after the realization of the shock. The negative effect on R&D expenditure reaches its maximum of 0.6 percent in response to a 20 basis point increase in the interest rate and dies out after 14 quarters. Furthermore, estimation results show that an exogenous increase in R&D expenditure induces an increase in the aggregate TFP after two years, providing a potential mechanism for the hysteresis effects of monetary policy shocks.

Next, I use Compustat firm-level balance-sheet data to analyse the firms' dynamic responses to a monetary policy shock in order to better understand firms' decisions on R&D investment and to examine possible sources of heterogeneities in response to different monetary policy shocks. I employ panel local projection and focus on firm-quarter observations for the publicly listed firms in the US and for the sample period 1990Q1-2019Q2. The estimation results suggest that the R&D to asset ratio decreases for more than one percent after a one standard deviation shock to the nominal interest rate. This effect persists for up to four years after the shock. It is more significant for the federal funds component and the large-scale asset purchasing component of the monetary policy shock. In contrast, the effect of the forward guidance component fades quickly. When looking at hikes versus cuts,

[2]See, for example, Moran and Queralto (2018), Bianchi et al. (2019), Jordà et al. (2021), Annicchiarico and Pelloni (2021), Garga and Singh (2021), and Queralto (2022) among others.

the result shows that contractionary policies have a stronger and more significant effect on R&D expenditure. This is important as it implies that on average monetary policies decrease firms innovative capacity and long-run productivity. Moreover, exploiting the cross-sectional dimension of the firm-level data, I show that firms in manufacturing, transportation, and service sectors exhibit a stronger response to monetary policy shocks, as do smaller firms, low quality firms, and firms with a lower leverage ratio.

According to the results of a state-dependent local projection, both in the aggregate economy and firm-level data, a contractionary monetary policy has a greater impact on reducing R&D investment during times of high uncertainty. Firms do not exhibit significant reaction in a stable economic environment, while they decrease their R&D investment up to four years after a contractionary monetary policy during uncertain times. A similar result holds when interacting monetary policy shocks with the macroeconomic uncertainty index, or using alternatively financial uncertainty indicators such as VIX. The data give support to the credit transmission channel theory. According to the empirical findings, firms invest less in tangible capital and keep less leverage during uncertain times. Leverage allows firms to acquire assets in excess of net worth. According to Geanakoplos (2010): "sometimes, especially in times of crisis, collateral rates (equivalently, margins or leverage) are far more important than interest rates." Hence, firms become more financially constrained due to a lower level of tangible capital. Along the arguments of Bernanke et al. (1999), Brunnermeier and Sannikov (2014), and Burgard and Nockel (2019), it is this financial constraint that renders monetary policy more contractionary during uncertain times.

The data hence suggest that interest rate hikes have persistent negative effects on R&D investment and those effects are exacerbated in times of macroeconomic uncertainty. I employ a medium-scale DSGE model with endogenous output growth and financial frictions to interpret the empirical results, and to highlight the importance of the credit channel for altering the effects of monetary policy on firms' investment in R&D in the presence of economic uncertainty. The model features sticky prices and endogenous growth through investment in R&D and financial frictions in the form of a borrowing constraint on production costs. Firms must borrow from banks to finance their production expenditure and the amount of their accumulated capital can be used as collateral for borrowing. An interest rate hike is contractionary in this environment not only through the traditional spending mechanism but also because interest rates are an important cost of production, as firms must borrow to finance their operation. This working capital constraint implies that interest rate changes affect directly firms' costs. Moreover, the working capital constraint serves to distinguish the role of the two types of capital in the economy: The accumulation of physical capital relaxes the financial constraint, while R&D investment increases the TFP of the economy.

When the nominal interest rate increases in this model, aggregate demand falls, and the real rate rises. Due to lower demand, firms decrease their production and are discouraged from more investment. As a result, both investment in physical capital and R&D decreases. However, since the accumulation of physical capital affects the borrowing constraint, firms recover their physical capital quicker than R&D investment. Firms do not internalize the positive externality of their R&D investment on the other firms in the economy. Therefore, the decline in R&D decreases TFP growth which results in a lower level of economic growth.

I model macroeconomic uncertainty in the model as an increase in the volatility of TFP shocks. When TFP volatility increases, firms keep less collateralizable asset in equilibrium. Given that the financial constraint is directly related to the amount of capital firms keep, this implies a stringency in the financial constraints for them. As a result, in response to a monetary policy contraction, firms decrease their R&D investment more. This mechanism is compatible with the data patterns discussed previously: When uncertainty is high, financial constraints further deteriorate the response of R&D investment to the monetary policy contraction. This is because higher uncertainty about the realization of the TFP makes the returns to R&D investment more uncertain. On the other hand, more uncertainty related to the TFP shocks realization renders the need for capital accumulation more vital when monetary policy contracts. The combination of these two effects with the working capital channel exacerbates the negative effects of a monetary policy contraction in this environment.

Related Literature: This paper contributes to several strands of the literature on the transmission channels of monetary policy. First, and most closely, it contributes to the literature on the impact of monetary policy on productivity and firms' long-run productive capacity. Several studies highlight the effect of monetary policy shocks on the long-run economic growth through the lens of a New Keynesian model with endogenous growth (see, e.g., Bianchi et al. (2019), Garga and Singh (2021), Jordà et al. (2021), Annicchiarico and Pelloni (2021) and Queralto (2022)). The hysteresis effect of monetary policy in these models comes from its impact on the aggregate TFP. Jordà et al. (2021) using a panel database of 125 years and 17 advanced economies show that in response to an exogenous monetary contraction, the output stays below its pre-shock trend for more than twelve years, which attributes to its long-run effect on TFP, capital accumulation, and the productive capacity of the economy. They find that capital and TFP experience similar trajectories to output and are the main source of this hysteresis. To explain how monetary contraction affects productivity, some studies highlight the transmission mechanism through its effect on variable utilization, fixed costs, and misallocation (Christiano et al. (2005), Meier and Reinelt (2022)). Hartwig and Lieberknecht (2020) and Colciago and Silvestrini (2022) find that firms entry and exit following an exogenous monetary expansion explains part of the increase in TFP. Moran and Queralto (2018) and Garga and Singh (2021) on the other hand, highlight the importnace of R&D expenditure as a main driver of the aggregate TFP. Compared to this literature, I provide firm-level data on the effects of monetary policy on firms R&D investment, discuss its heterogeneity based on their sectors of activity and financial constraints, and shows its state-dependency in the presence of macroeconomic uncertainty.

Second, it contributes to the literature on the transmission of monetary shocks under different economic uncertainty conditions. Aastveit et al. (2017), Pellegrino (2018), Lien et al. (2021), and Fang (2022) among others, have shown that the effectiveness of monetary policy shocks is significantly reduced in a context of high uncertainty. This result supports the predictions of several theoretical studies (see Vavra (2014), and Aastveit et al. (2017)). Baley and Blanco (2019), on the other hand, discusses that by generating cross-sectional dispersion in firms' adjustment frequency, the idiosyncratic uncertainty cycles amplify the real effects of nominal shocks for firms. Moreover, Hauzenberger et al. (2021) show that quantitative easing is more effective during uncertain times. This paper, however, focuses on the dynamic response of firms' R&D expenditures and its transmission mechanism under different levels of economic uncertainty. To the best of my knowledge, this is the first study connecting macroeconomic uncertainty and the hysteresis effects of monetary policy shocks. Furthermore, this paper discusses how financial frictions during uncertain times amplifies the contractionary effect of monetary policy on R&D investment and contributes to the literature on the importance of financial markets in the transmissions of monetary policy (see e.g. Jeenas (2019a), Jeenas (2019b), Ottonello and Winberry (2020), and Döttling and Ratnovski (2023)).

The remainder of the paper is structured as follows. Section 2 describes the dataset. Section 3 provides empirical results both in the aggregate and firm-level data. Section 4 describes the DSGE model and the simulation results. Section 5 discusses the potential mechanism, while section 6 provides some robustness checks, and section 7 concludes. An Online Appendix gathers additional results discussed in the main text, as well as the outputs of some robustness checks.

2 Data

Aggregate Economy

To analyze the aggregate data, I utilize the US quarterly national accounts data from 1990:Q1 to 2019:Q2 for the following variables: output, private consumption, private investment, R&D expenditure, consumer price index, and short-run interest rate. All national account variables are seasonally adjusted and are in real terms. The sample period is restricted by the available monetary plicy shocks based on FOMC announcements. Aggregate data are collected from NIPA and FRED datasets. For more details on data sources and summary statistics, see the Online Appendix.

I employed two distinct indices to measure economic uncertainty. The main economic uncertainty index is the three-month ahead index proposed by Jurado et al. (2015) and updated by Ludvigson et al. (2021). Jurado et al. (2015) define uncertainty as the common volatility in the unforecastable component of numerous macroeconomic indicators. As an alternative, I use the volatility index (VIX) created by the Chicago Board Options Exchange (CBOE), which is considered a proxy for financial uncertainty. VIX measures 30 days of the expected volatility of the S&P 500 index. It does so by using S&P 500 options listed on the CBOE exchange as an input. Figure 17 in the Online Appendix illustrates that these two indices co-move very closely in the 1990-2019 sample period.

Monetary Policy Shocks

I use the updated data for monetary policy shocks by Jarociński and Karadi (2020) from 1990:Q1 to 2019:Q2 identified based on high-frequency negative co-movement of interest rates and stock prices in a narrow window around the FOMC announcements. They use the unanticipated components of FOMC press releases at a specific time, which will necessarily be correlated with the structural monetary policy shock hitting the economy at that particular moment. By measuring these components in a narrow window around the announcements, they make the identifying assumption that the measurements are uncorrelated with other structural shocks. Moreover, this paper uses different types of monetary policy shocks identified in Jarocinski (2021) using the leptokurtic nature of the financial data to label monetary policy shocks ex-post into standard fed fund shocks, Odyssean forward guidance, and large-scale asset purchases shocks.

The data on monetary policy shocks are available at a monthly frequency. To aggregate them to a quarterly frequency, I computed a weighted average of the monthly observations within each quarter, where the weights decrease for each month in a quarter. Following Ottonello and Winberry (2020) I put a higher weight on the earlier shocks assuming that firms need some time to react to the monetary policy shock). Figure 17 illustrates the evolution of the identified shocks over time. In the Online Appendix, I also show that the main results are robust to different weighting schemes and to using other identified monetary policy shocks in this literature.

Firm-level Data

I use quarterly firm-level data from the Compustat database, which contains information on publicly listed US incorporated firms. The sampled period spans from 1990Q1 to 2019Q2 and excludes firms active in utilities (SIC codes 4900-4999) and financial firms (SIC codes 6000-6999). The main advantages of Compustat data are that they are available in quarterly frequency, it is an (unbalanced) panel, and it contains rich balance-sheet information of firms which allows to analyze firms' heterogeneous responses. To my knowledge, Compustat is the only US dataset that includes quarterly data on firms' R&D expenditures. However, a limitation of the Compustat data is that it only covers publicly listed firms.

The main measure of firms' R&D expenditure is denoted XRDQ in the Compustat dataset, which represents the company's total expenditure on research and development of new or improved product lines and methods of production. In addition, this study incorporates information on firms' total capital, sales, total assets, liquidity, total debt, S&P Quality Ranking, and fiscal quarters. The analysis focuses on firms that exist for at least 40 quarters in the sample and have at least 20 observations for their R&D expenditure. Moreover, following Ottonello and Winberry (2020) all outlier observations and extreme values are excluded. The final sample comprises more than 106,000 observations from 1,775 distinct US firms. The average R&D to asset ratio in the sample is 4% with a 6% standard deviation, and the median value is 2.4%. See the Online Appendix for more details on firm-level data and applied filters.

3 Empirical Results

I start by analyzing the dynamic effects of the monetary policy shocks on the real GDP, private investment, private consumption, and research and development expenditure in the aggregate economy. To control for potentially confounding events other than the monetary policy shocks that may affect the macroeconomic indicators and to provide a more causal interpretation to the results, I follow Jordà (2005) and adopt local projections (LP) for the longest possible sample I have available, that is, 1990Q1 - 2019Q2. For each variable and each horizon $h \geq 0$, I estimate the following linear LP model:

$$S_{t+h} = \alpha_h + t_{q,h} + \beta_h \eta_t + \sum_{k=1}^{4} \Theta_{k,h} \text{Controls}_{t-k} + \varepsilon_{t+h}, \quad h = 0, 1, 2, ... \tag{1}$$

Where S_{t+h} is the variable of interest at time $t+h$ (including GDP, investment, consumption, and R&D expenditure), $t_{q,h}$ is a quarter fixed effect, η_t denotes monetary policy shock at time t identified by the high-frequency financial data as explained in the previous section, and control variables include lags of GDP, consumption, investment, R&D expenditure, CPI, and current value and lags of changes in the fed fund rate. All variables are at the logarithm level, and the standard errors are corrected for heteroskedasticity and serial correlation.

3.1 Aggregate Results

Figure 1 shows the dynamic response of the GDP, consumption, investment, and R&D expenditures, all in real terms, to a one standard deviation shock to the monetary policy (which is roughly equal to a 20 basis point increase in the interest rate). Consistent with macroeconomic theories and existing empirical findings, GDP, consumption, and investment decrease, with their maximum drop occurring two years after the realization of the shock. GDP and consumption decrease by up to 0.4 percent, while private investment decreases by more than 2 percent two years after the monetary policy shock. This effect is significant for almost 15 quarters, after which the variables return to their pre-shock levels.

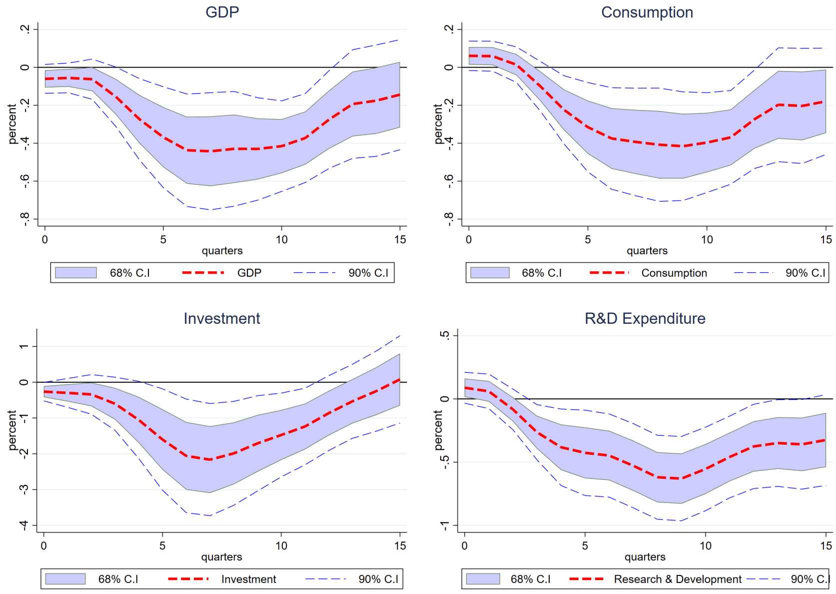
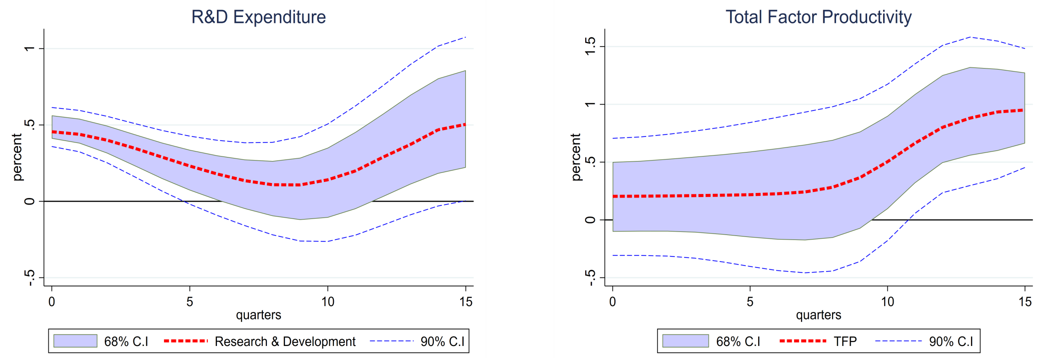


Figure 1: Effect of a one standard deviation contractionary monetary policy shock on real GDP, private consumption, private investment, and *R&D* expenditure for the period 1990Q1-2019Q2 using LP in the equation 1. Robust standard errors are corrected for serial correlation, and response functions are smoothed by a centered moving average.

The findings also indicate that a contractionary monetary policy shock has a persistent and significant negative impact on private R&D expenditure in the aggregate economy. The real R&D expenditure falls by 0.6 percent 2 years after the shock, and the effect dissipates after almost four years. This result shows that monetary policy shock has significant and persistent consequences on aggregate R&D expenditure, and as a result, on total factor productivity, and can potentially induce a long-run effect in the economy. Figure 2 presents the result of an exogenous shock to total R&D expenditure and its effect of the aggregate TFP[3]. According to the results, a 0.5 percent increase in R&D expenditure induces an increase of one percent in TFP after two years and the effect persists over time.

[3]Exogenous shock to R&D is identified as residuals of projecting R&D expenditure on its own lags, and current value and lags of GDP, investment, consumption, interest rate, and TFP.



(a) R&D expenditure

(b) aggregate TFP

Figure 2: Effect of a one standard deviation shock to the R&D expenditure on the aggregate TFP for the time period 1990Q1-2019Q2 using LP in equation 1. Robust standard errors are corrected for heteroskedasticity, and serial correlation and response functions are smoothed by a centered moving average.

Figure 19 in the Online Appendix displays the dynamic response of the same macroeconomic variables to the different components of the policy announcement shock. A similar pattern is observed in response to the federal fund rate and forward guidance components of the monetary policy shocks, while the effect of the large-scale asset purchasing (LSAP) component is not statistically significant at conventional levels. This result can be due to the fact that the values for LSAP shocks are mostly zero for the years before the financial crisis. However, the effect of LSAP shocks for the sample period after 2007 indicates a significant effect on the macroeconomic indicators and on R&D expenditures.

3.1.1 Nonlinear results based on economic uncertainty

In this section, I investigate whether the monetary policy-R&D investment relationship is affected by the level of macroeconomic uncertainty. In what follows, I add a measure of economic uncertainty (U_t) to the control variables in the specification of equation 1 and interact monetary policy shocks with all the control variables. The parameter of interest is λ_h which shows in each horizon how the effect of an exogenous monetary policy shock on R&D expenditure changes when the economic uncertainty index increases by one standard deviation. In other words, for any $h \geq 0$, I estimate the following regression:

$$S_{t+h} = \alpha_h + t_{q,h} + \beta_h \eta_t + \sum_{k=1}^{4} (\Theta_{k,h} + \Gamma_h \eta_t)\text{Controls}_{t-k} + (\sigma_h + \lambda_h \eta_t) U_{t-1} + \varepsilon_{t+h} \qquad (2)$$

The parameter λ_h represents the interaction effect between economic uncertainty and monetary policy shocks at each time horizon h. I use the updated three months ahead aggregate macroeconomic uncertainty index by Ludvigson et al. (2021) as the economic uncertainty measure. This index captures the common time-varying volatility in the unforecastable component of a large number of macroeconomic indicators. The interacting effect of economic uncertainty on the effectiveness of monetary policy is presented in the left graph of Figure 3. One year after a contractionary monetary policy shock, a one-unit increase in the standardized uncertainty index results in a 2 percent higher decline in the R&D expenditure. Notably, as the average effect on R&D is approximately 0.6 percent, this finding implies that a one standard deviation increase in the uncertainty index makes the coefficient more than three times larger than the average effect. Moreover, this result remains robust when using the VIX financial uncertainty index as the interaction variable. Please refer to Figure 24 in the Online Appendix for additional results.

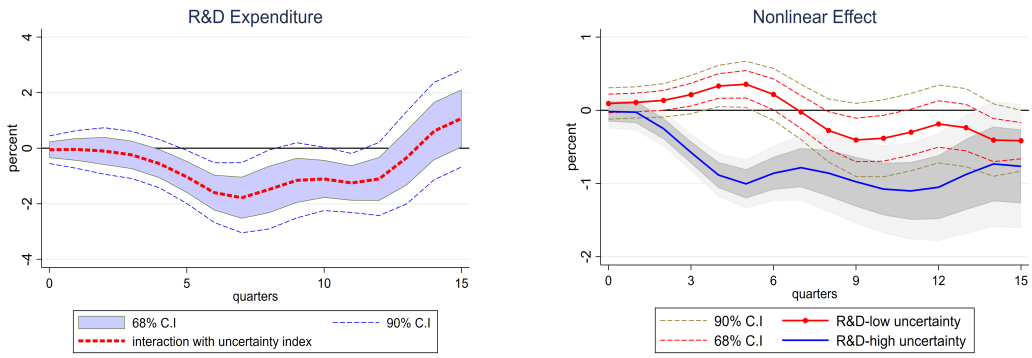
In order to provide additional insight into the state-dependency of the results based on economic uncertainty, I conduct a direct comparison of the coefficient of interest in Equation 1 between two distinct sub-samples and allow for time-varying coefficients according to the uncertainty measures. In particular, I use the following state-dependent LP specification for any $h \geq 0$:

$$S_{t+h} = I_{t-1}\left[\alpha_{A,h} + \beta_{A,h}\eta_t + \psi_{A,h}(L)X_t\right] + (1 - I_{t-1})\left[\alpha_{B,h} + \beta_{B,h}\eta_t + \psi_{B,h}(L)X_t\right] + \varepsilon_{t+h} \tag{3}$$

where X_t denotes all control variables at quarter t included in the linear specification explained before, $\psi(L)$ is the lag operator, and I_t is an indicator variable of economic uncertainty when the shock hits. This dummy variable equals 1 (i.e., $I_t = 1$) whenever the uncertainty index is higher than the median value for the whole sample.

The right graph in Figure 3 depicts the dynamic response of R&D expenditure to a contractionary monetary policy shock under high- ($\beta_{A,h}$) and low-uncertainty ($\beta_{B,h}$) periods. The impact of monetary policy shocks on R&D expenditures is primarily observed during high-uncertainty periods. Specifically, one year after a contractionary monetary policy shock during such periods, R&D expenditures decline by more than one percent, and this effect persists for more than four years. Notably, this estimated effect is roughly two times larger than the average effect illustrated in Figure 1. In contrast, the effect during low uncertainty periods is generally not significant across most estimation horizons. [4].

[4]However, for some quarters, the effect during low uncertainty times turns positive, though barely significant, and after eight quarters it becomes negative. The effect during high uncertainty is negative and persistent.



(a) interaction coefficient

(b) state-dependant result

Figure 3: left graph: effect of a one standard deviation contractionary shock to the policy interacted with the uncertainty index on the aggregate R&D expenditure for the time period 1990Q1-2019Q2 using LP in equation 2. Right graph: the state-dependant results. The solid blue line shows the effect in high uncertainty quarters, while the dashed red line shows the effect in the low uncertainty period. High uncertainty time is defined when the Ludvigson et al. (2021) uncertainty index is higher than the median value in the sample. Robust standard errors are corrected for heteroskedasticity, and serial correlation and response functions are smoothed by a centered moving average.

3.2 Firm-level Results

So far, I have shown a significant long-lasting effect of monetary policy shocks on the aggregate R&D expenditure. In this section, I use Compustat firm-level data for the US economy to confirm that firms' response for R&D expenditure is compatible with aggregate R&D dynamics. Looking at a more disaggregated level also enables me to discuss possible heterogeneities based on firms' characteristics and to investigate possible transition mechanisms behind the state-dependent results.

I draw the firm-level dataset from the quarterly Compustat universe of publicly listed US incorporated firms for the sampled period 1990Q1-2019Q2. Following Ottonello and Winberry (2020) I exclude firms active in utilities and financial firms, and I limit the observation to the firms that exist in the sample for at least ten years and report data for their R&D expenditure for at least five years in the sample period. This filtering process enables me to investigate the dynamic response of firms' R&D investment over time. The final sample comprises more than 106,000 firm-quarter observations for 1,775 distinct publicly listed firms. The main variable of interest is firms' R&D expenditure, denoted XRDQ in the Compustat dataset, and represents the total expenditure on research and development of new or improved product lines and production methods. To account for the heterogeneity in firms' sizes, I normalize R&D expenditures with firms' total assets. The final sample's average R&D to asset ratio is 4% with a 6% standard deviation. See the Online Appendix for more details the summary statistics of the firm-level data.

I estimate similar LP regressions as equation 1, where the dependent variable ($S_{j,t+h}$) is the cumulative growth of firm j's R&D expenditure (Log(R&D$_{t+h}$)-Log(R&D$_{t-1}$)) or total tangible capital (Log(K$_{t+h}$)-Log(K$_{t-1}$)) at horizon h. I include firm-level and aggregate-level control variables (following Ottonello and Winberry (2020)) to capture other important drivers of firms' R&D expenditure and potential compounding effects. For each horizon $h \geq 0$, I estimate the following regression:

$$S_{j,t+h} = \alpha_{j,h} + t_{q,h} + \beta_h \eta_t + \sum_{k=1}^{4} \Theta_{k,h} \text{Controls}_{j,t-k} + \gamma_h \text{size}_{j,t-1} + \lambda_h \text{liq}_{j,t-1} + \varepsilon_{j,t+h}, \quad h = 0, 1, 2, ... \tag{4}$$

where α_j denotes firm fixed effect, η_t denotes monetary policy shock at time t; control variables include the growth rate of firms' R&D expenditure, capital, and sales. Furthermore, to control for any compounding effects from aggregate shocks in the economy, I also control for the lags of unemployment rate and CPI in the US economy. To control for firms' size and liquidity when the monetary shock hits, I add the logarithm of firms' total assets as a proxy for firms' size and firms' liquidity to asset ratio in the regressions. Figure 4 depicts the dynamic responses relative to a one standard deviation contractionary monetary policy shock. Standard errors are clustered at the firm level.

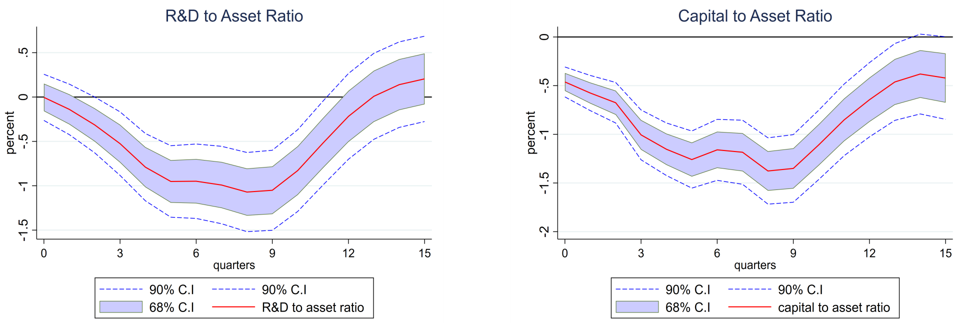
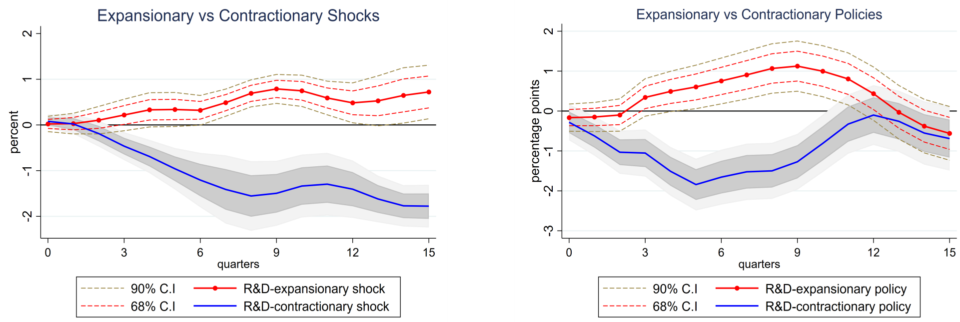


Figure 4: Effect of a one standard deviation shock to the monetary policy on *R&D* expenditure (left graph) and tangible capital (right graph) for the time period 1990Q1-2019Q2. Robust standard errors are clustered at firms level, and response functions are smoothed by a centered moving average.

In response to a contractionary monetary policy shock, firms decrease their R&D expenditure and tangible capital for up to three years after the shock hits. Firms react immediately by adjusting their capital, and after two quarters, they start to decrease their R&D investment. This finding is compatible with the aggregate results presented in Figure 1. Nine quarters after the realization of the shock, on average, R&D to asset ratio is 1 percent lower than its pre-shock level, and the effect fades away after 12 quarters. Firms' capital to asset ratio starts decreasing instantly and reached its maximum drop of 1.4 percent two years after the shock. Figure 5 shows that, in both the aggregate and firm-level analysis, the effect of monetary policy on R&D investment is attributed mainly to contractionary policies. In contrast, the effect of expansionary shocks is weaker and not significantly different from zero in the first six quarters. This result is is crucial because it suggests that monetary policy shocks have more than a short-run business cycle effect on R&D, and monetary contractions can exert a loner-run effect on the economy through their impact on innovation and productivity. Jordà et al. (2021) in a cross-country study show that monetary policy affects TFP, capital accumulation, and the productive capacity of the economy for a long time. According to their findings, in response to an exogenous monetary contraction, output declines and stays lower than its pre-shock trend for up to twelve years. Their paper also shows that capital and TFP dynamics experience similar trajectories to output.



(a) aggregate data

(b) firm-level data

Figure 5: left graph: effect of a one standard deviation contractionary monetary policy shock (blue lines) in comparison to expansionary monetary policy shock (red lines) on the aggregate R&D expenditure (left graph) and firms R&D expenditure (right graph) for the time period 1990Q1-2019Q2. Robust standard errors are clustered at firms level, and response functions are smoothed by a centered moving average.

Figure 6 depicts the dynamic response of firm-level R&D expenditure to the different types of monetary policy shocks as identified by Jarocinski (2021). The effect of the federal fund rate component is very similar to the impact of the average shocks. As shown in the second row of Figure 6, the forward guidance component of the policy shock has no significant effect on firms' R&D decisions, while large-scale asset purchasing programs have a significant effect in the first three quarters and dies out quickly. Moreover, Figure 26 in the Online Appendix shows that the information shock component of the changes in interest rate (as documented in Jarociński and Karadi (2020) based on high-frequency positive co-movement of interest rates and stock prices) has a short-run expansionary effect on R&D expenditure since it conveys signals about the potential increase of the aggregate demand in the future.

When comparing different industries, as shown in Figure 7, the results suggest that firms active in secondary industries (including manufacturing and construction) and tertiary industries (including services, transportation, wholesale and retailers) are significantly responding to a monetary policy shock. On the other hand, no significant effect is observed on firms in primary industries, including agriculture and mining. This result indicates that

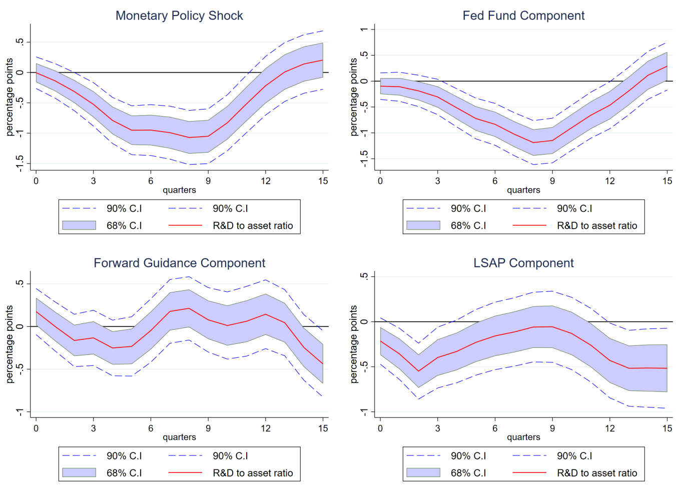
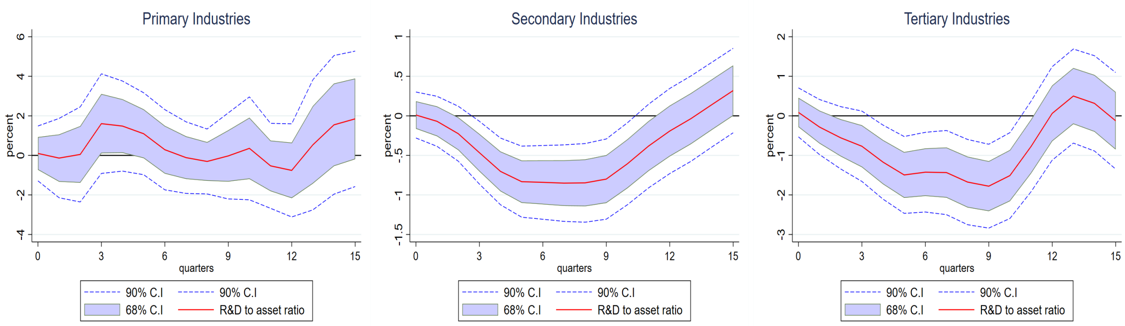


Figure 6: Effect of a one standard deviation contractionary shock to the different components of the monetary policy shock on firm's $R\&D$ expenditure for the time period 1990Q1-2019Q2. Robust standard errors are clustered at firms level, and response functions are smoothed by a centered moving average.

firms active in R&D-intensive industries are more likely to react to monetary policy shocks. [5]. Figure 32 in the Online Appendix shows that in particular manufacturing, services, and transportation are the most affected sectors among all the non-financial industries.



(a) Primary **(b)** Secondary **(c)** Tertiary

Figure 7: Effect of a one standard deviation shock to the monetary policy on the $R\&D$ expenditure for the time period 1990Q1-2019Q2 in the different industry groups. Robust standard errors are clustered at firms level, and response functions are smoothed by a centered moving average.

In addition, the analysis suggests that smaller firms are more responsive to contractionary monetary policy shocks. Figure 8 shows the estimation results of a state-dependent local projection as in equation 3, where the state indicator is firms' size before the realization of the shocks. Here firms are classified as small and big firms based on their real sales value. While bigger firms decrease their R&D expenditure by 0.7 percent, smaller firms tend to decrease it for up to 1.7 percent after a contractionary shock. A similar result holds when

[5]The R&D expenditure to the total asset ratio in the primary, secondary, and tertiary industries are 1.9%, 4%, and 4.4%, respectively.

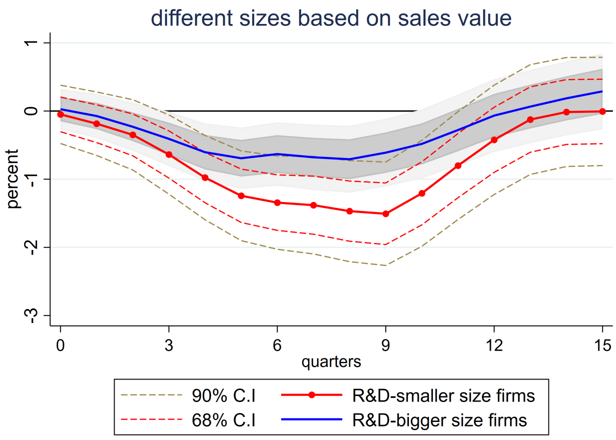
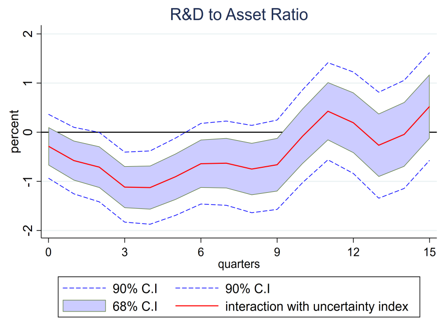


Figure 8: Effect of a one standard deviation shock to the monetary policy on *R&D* expenditure for the time period 1990Q1-2019Q2. The solid blue line shows the effect for bigger size firms, while the dashed red line shows the effect on smaller firms. Firms are classified based on the median value of the real sales in the sample. Robust standard errors are clustered at firms level, and response functions are smoothed by a centered moving average..

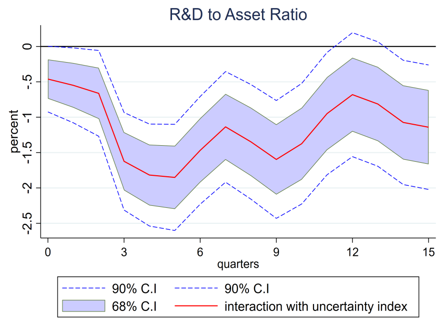
defining firms' size based on their number of employees (see Figure 33 in the Online Appendix). This finding is consistent with the notion that smaller firms are more financially constrained and face limited access to external financing compared to larger firms. As a result, they are more likely to adjust their investment decisions in response to changes in the cost of borrowing imposed by monetary policy shocks.

3.2.1 Nonlinear results based on economic uncertainty

In this section, I investigate how economic uncertainty affects firms' decisions on R&D expenditure after a monetary tightening. Similar to the analysis for the aggregate economy, I follow the same approach as in equation 2 and interact monetary policy with all the control variables and with the economic uncertainty index. To do so, I interact monetary policy shocks with both the three-month ahead economic uncertainty index constructed by Ludvigson et al. (2021) and the VIX financial uncertainty index. Figure 9 shows the estimation result for the interaction parameters, alongside its 68% and 90% confidence intervals.



(a) interaction with macroeconomic uncertainty

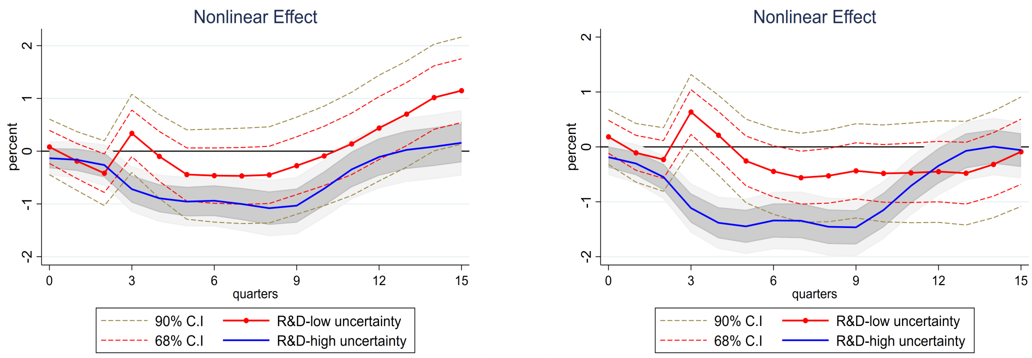


(b) interaction with VIX index

Figure 9: left graph: effect of a one standard deviation contractionary shock to monetary policy on firms R&D expenditure interacted with the economic uncertainty index by Ludvigson et al. (2021). Right graph: effect of a one standard deviation contractionary shock to monetary policy on firms' R&D expenditure interacted with the VIX index for the time period 1990Q1-2019Q2. Robust standard errors are clustered at firms level, and response functions are smoothed by a centered moving average.

A one standard deviation increase in the macroeconomic uncertainty index increases the responsiveness of firms' R&D expenditure to a monetary policy shock after two quarters. The effect peaks at over one percent after a year and fades away after nearly two years (left graph). The right graph in Figure 9 depicts that the effect is more substantial and more significant when interacting monetary policy with the VIX financial uncertainty index. Specifically, higher financial uncertainty raises firms' response to a monetary policy shock for up to four years, with the effect reaching over 1.5 percent of the R&D to asset ratio for a one standard deviation increase in the index. In sum, both analyses confirm that, consistent with the aggregate economy's findings, increased uncertainty leads to greater reductions in firms' R&D expenditure following a monetary contraction.

Figure 10 displays the state-dependent results of a series of regressions similar to equation 3 for each horizon $h \geq 0$. The state of the economy is defined based on the uncertainty measure in the quarter preceding the monetary policy shock. Specifically, any quarter t is considered a high-uncertainty time if the uncertainty measure is higher than the median value over the entire sample. The result for both uncertainty indices, macroeconomic uncertainty (left graph) and VIX index (right graph), is in line with the results for the aggregate economy. Firms are significantly more responsive to a monetary policy shock if the shock hits in a high-uncertainty state of the economy. A similar conclusion holds while comparing the top and lowest 25 percentile of the uncertainty index (see the Online Appendix).



(a) macroeconomic uncertainty index

(b) VIX index

Figure 10: left graph: the state-dependant results based on the macroeconomic uncertainty index. Right graph: the state-dependant results based on the VIX index. The solid blue line shows the effect in high uncertainty quarters, while the dashed red line shows the effect in the low uncertainty period. High uncertainty time is defined as when the uncertainty index is higher than the median value in the sample. Robust standard errors are clustered at firms level, and response functions are smoothed by a centered moving average.

4 A General Equilibrium NK Model with Endogenous Growth

The empirical findings show a negative effect of interest rate hikes on firms R&D expenditure and suggest a stronger effect when economic uncertainty is higher. In this section of the paper, I try to shed more light on the possible mechanisms explaining this state-dependent effect of monetary policy through the lens of a theoretical model. The model is a medium-scale New-Keynesian DSGE model with endogenous output growth through R&D investment and financial frictions in the form of a collateral constraint. The endogenous growth mechanism is defined through vertical innovation in the spirit of Grossman and Helpman (1991), and closely following the model in Bianchi et al. (2019).

Households:

A representative household in this economy receives utility from consuming a final good with an external habit and receives disutility from working. The household maximizes his lifetime utility:

$$E_t \sum_{s=0}^{\infty} \beta^s \left\{ \log\left(C_{i,t+s} - \Phi_C C_{t+s-1}\right) - \frac{L_{t+s}^{1+\sigma}}{1+\sigma} \right\}$$

where β is the discount rate, Φ_c is an external habit parameter, C_t is consumption, L_t denotes the labor supply, and σ is the inverse of the Frisch labor supply elasticity. The household budget constraint is:

$$C_t + \frac{b_{t+1}}{1+r_t} = w_t L_t + \frac{b_t}{\pi_t} + \Pi_t + T_t$$

Where π_t is the inflation rate at time t, w_t is the real wage of L_t, b_t is the real value of the amount of debt issued by firms, Π_t is the net dividend payment by firms to households, and r_t is the nominal interest rate. Finally, T_t is the net transfer from the government.

Final good producer:

A final good producer produces one unit of final good Y_t by aggregating intermediate goods $Y_t(j)$ with a constant elasticity of substitution of intermediate goods ε:

$$Y_t = \left(\int_0^1 Y_t(j)^{\frac{\varepsilon-1}{\varepsilon}} dj \right)^{\frac{\varepsilon}{\varepsilon-1}}$$

As a result of a cost-minimization problem for the final good producer, the demand function for each intermediate good (j) is:

$$Y_t(j) = \left(\frac{P_t(j)}{P_t} \right)^{-\varepsilon} Y_t,$$

where $P_t(j)$ is the price of the intermediate input (j) and the price index P_t is defined as:

$$P_t = \left(\int_0^1 Y_t(i)^{1-\varepsilon} dj \right)^{\frac{1}{1-\varepsilon}}$$

Intermediate goods producers:

Intermediate goods producers, indexed by j, are monopolistically competitive and they produce intermediate goods by using the following Cobb-Douglas technology:

$$Y_t(j) = K_t(j)^{\alpha} \left(Z_t(j) L_t(j) \right)^{1-\alpha} \tag{5}$$

where $K_t(j)$ is physical capital, α is the income share of capital, $Z_t(j)$ is firm level TFP and is defined as:

$$Z_t(j) = A_t N_t(j)^{\eta} N_t^{1-\eta} \tag{6}$$

where $N_t(j)$ is R&D capital for firm j, and $N_t \equiv \int_0^1 N_t(j) dj$ is the aggregate stock of R&D capital. $1-\eta$ captures the spillover effect of R&D capital and A_t is the aggregate productivity shock that follows an AR(1) process.

Intermediate goods producers invest in physical capital $(I_t(j))$ and R&D $(S_t(j))$ and their stock of capital evolves as follows:

$$K_{t+1}(j) = (1-\delta_K)\, K_t(j) + \Lambda_K \left(\frac{I_t(j)}{K_t(j)}\right) K_t(j) \tag{7}$$

$$N_{t+1}(j) = (1-\delta_N)\, N_t(j) + \Lambda_N \left(\frac{S_t(j)}{N_{t(j)}}\right) N_t(j) \tag{8}$$

where δ_K and δ_N denotes the depreciation rate for physical and R&D capital, respectively, $\Lambda(.)$ is a quadratic adjustment cost function where in steady state $\Lambda'_K = \Lambda'_N = 1$, $\Lambda_K = \frac{I}{K}$, and $\Lambda_N = \frac{S}{N}$.

Intermediate firms issue bonds (b_t) with a gross interest rate R_t and use their equity (Π_t) to finance their operation. Following Bianchi et al. (2019), I assume that issuing debt has a tax advantage over using equity. Therefore, the gross rate firms pay is $R_t = 1 + r_t(1-\tau)$, where τ represents the tax benefits of debt. The firms also incur costs if there are any changes in their dividend payment from its steady-state growth $(\Lambda_\Pi(\frac{\Pi_t}{\Pi_{t-1}}))$ that affects the combination of debt and equity financing. Each firm j when updating its price pays a Rotemberg quadratic price adjustment cost and maximizes the lifetime expected value of dividends as follows:

$$\max E_t \sum_{i=0}^{\infty} M_{t,t+i} \Pi_{t+i}(j)$$

where

$$\Pi_t(j) = \frac{P_t(j)}{P_t} Y_t(j) - w_t L_t(j) - I_t(j) - S_t(j) - \frac{\phi_P}{2}\left(\frac{P_t(j)}{\pi P_{t-1}(j)} - 1\right)^2 Y_t - \Lambda_{\Pi,t} + \frac{b_{t+1}(j)}{R_t} - \frac{b_t(j)}{\pi_t}$$

Where $\Lambda_\Pi\left(\tilde{\Pi}_t\right) = \frac{\phi_\Pi}{2}\left(\frac{\Pi_t}{\Pi_{t-1}} - \Delta\Pi\right)^2 Y_t$, ϕ_Π is the dividend adjustment cost parameter and $\Delta\Pi$ denotes the steady state growth of firms dividends. Moreover, following Jermann and Quadrini (2012) and Bianchi et al. (2019), firms use intraperiod debt $(X_t(j))$ with zero interest to cover the cash flow mismatch between the payments made at the beginning of the period and the realization of revenues at the end of the period.

The intraperiod loan is equal to

$$X_t(j) = w_t L_t(j) + I_t(j) + S_t(j) + \Pi_t(j) + \frac{\phi_P}{2}\left(\frac{P_t(j)}{\pi P_{t-1}(j)} - 1\right)^2 Y_t + \Lambda_{\Pi,t} - \frac{\pi_{t+1}}{R_t} b_{t+1}(j) + b_t(j)$$

where combining with firms budget constraint:

$$X_t(j) = \frac{P_t(j)}{P_t} Y_t(j)$$

Implying that the intraperiod loan is equal to the real revenues. According to the limited enforceability of debt contracts described inJermann and Quadrini (2012), the total debt of firms (which encompasses both intratemporal and intertemporal debt) is limited.

Total debt of the firms (including interatemporal and intertemporal debt) is limited according to the limited enforceability of debt contracts as in Jermann and Quadrini (2012). In case of default, the only asset available for lenders for liquidation is the physical capital $K_{t+1}(j)$ that with probability ζ the lender can recover the full value, but with probability $1-\zeta$ the recovery value is zero. Limited enforceability of debt implies that firms can default after the revenue has been realized but before the intraperiod loan is repaid. According to the contract, in the event of default, the lender will not be able to recover the funds raised by the intraperiod loan. As discussed in more detail in Jermann and Quadrini (2012), the renegotiation process between the firm and lender results in the enforcement constraint for each firm j as:

$$X_t(j) \leq \zeta \left(K_{t+1}(j) - \frac{b_{t+1}(j)}{1+r_t} \right). \tag{9}$$

The dividend maximization problem of firms and the relevant optimization conditions are derived in the Online Appendix section C.1.

Market clearing and monetary authority

The Rotemberg price adjustment cost assumption implies a symmetric equilibrium. Therefore, the optimal decision of all firms is the same. The aggregate resource constraint implies that aggregate output is used for consumption, investment in physical capital and R&D, dividend and price adjustment costs:

$$Y_t = C_t + I_t + S_t + \frac{\phi_P}{2} \left(\frac{\pi_t}{\pi} - 1 \right)^2 Y_t + \Lambda_{\Pi,t} \tag{10}$$

The monetary authority sets the nominal rate R_t following Taylor rule. The nominal policy rate depends on the deviation of the lag policy rate, inflation, and output growth from their steady-state value (R,π, and ΔY). The monetary policy rule is as follows:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_r} \left(\frac{\pi_t}{\pi}\right)^{\rho_\pi} \left(\frac{\Delta Y_t}{\Delta Y}\right)^{\rho_Y} \exp(\sigma_r \varepsilon_{r,t}), \tag{11}$$

The government simply finances the tax shield for firms by using lump-sum taxes T_t:

$$T_t = b_{t+1}\left(\frac{1}{R_t} - \frac{1}{1+r_t}\right) \tag{12}$$

Exogenous processes

Aggregate productivity follow an AR(1) process:

$$\text{Log}(A_t) = (1-\rho_a)\text{Log}(A) + \rho_a \text{Log}(A_{t-1}) + \sigma_{a,t}\varepsilon_{a,t} \tag{13}$$

where A is the steady state value for the aggregate productivity and $\sigma_{a,t}$ is the standard deviation for the productivity shocks. $\sigma_{a,t}$ follows the following AR(1) process with the steady state value of σ_a:

$$Log(\sigma_{a,t}) = (1-\rho_s)\text{Log}(\sigma_a) + \rho_s \text{Log}(\sigma_{a,t-1}) + \varepsilon_{s,t} \tag{14}$$

Solving the model

All the trending variables in the model are divided by the stock of R&D capital (N_t) to induce stationarity. After detrending the equilibrium equations, the nonstochastic steady state is computed. Then, I solve the model using perturbation methods and relying on the third-order approximation of equations around the steady state, which is necessary for analyzing the effects of uncertainty alongside the first moment shocks. More details on the equilibrium conditions and detrending variables are provided in the Online Appendix section C.1.

Calibration

The parameters used in this study have been calibrated through a combination of standard literature values, estimations from other studies, and first-order moment matching. Table 1 summarizes the values of the calibrated parameters. To achieve a quarterly interest rate of 0.4%, the discount factor has been set to 0.997. The inverse Frisch elasticity of labor supply is set to the standard value of 2 in the literature. The elasticity of output to physical capital and elasticity of substitution between goods are standard values in the New-Keynesian models. The price adjustment parameter is set to 60, indicating that firms, on average, adjust their prices every four quarters. The capital depreciation rate has been set to 0.02 to match the average investment-to-output ratio of 0.17 in the data. The depreciation rate of R&D has been set to 0.038, corresponding to an annualized rate of 15%, a standard value assumed by the Bureau of Labour Statistics in the R&D stock calculations. Bonciani and Oh (2022) estimate adjustment cost parameters (τ_K and τ_N) for the US economy matching their estimated VAR impulse responses with IRFs of a medium-scale New Keynesian model with endogenous growth.

The inflation target has been set to 2% annually. Taylor rule coefficients and the parameters for the persistence of the shocks are in a standard range of values in the New Keynesian literature. The steady-state value of productivity A has been calibrated to 0.3 to match the average annual output growth rate of 2%. The remaining parameter values have been taken directly from Bianchi et al. (2019).

Parameter	Description	Value	Source/Target
Households			
β	Discount factor	0.997	quarterly r=0.4
Φ	Habit in consumption	0.9	Bianchi et al. (2019)
σ	Inverse Frisch Elasticity	2	Standard
Firms			
α	Elasticity of output to capital	0.33	Standard
ε	Elasticity of substitution between goods	6	Standard
ϕ_P	Price adjustment cost parameter	60	4Q stickiness
ϕ_Π	dividend adjustment cost parameter	1.2	Bianchi et al. (2019)
η	R&D spillover	0.2	Bianchi et al. (2019)
ζ	Financial Constraint	0.3	Bianchi et al. (2019)
δ_K	Capital depreciation rate	0.03	I/Y=0.17
δ_N	R&D depreciation rate	0.038	annualised rate of 15%
τ_K	Capital adjustment cost parameter	7.5	Bonciani and Oh (2022)
τ_N	R&D adjustment cost parameter	6.2	Bonciani and Oh (2022)
Monetary Policy			
π	Steady-state inflation	1.005	2% annualised inflation rate
ρ_π	Weight on inflation in policy rule	1.5	in standard range
ρ_Y	Weight on output in policy rule	0.5	in standard range
ρ_r	Persistence interest rate	0.9	in standard range
Exogenous Process			
A	Steady-state productivity	0.3	2% annualised growth rate
ρ_a	Persistence of productivity Shock	0.9	in standard range
σ_a	Volatility of productivity shock	0.02	Bianchi et al. (2019)
ρ_s	Persistence of uncertainty Shock	0.9	in standard range

Table 1: Calibration of the parameters

4.1 Simulation Results

In this section, I present the key findings of the model and the mechanisms that underlie them, using impulse response functions. The responses are shown as a percentage deviation from the stochastic steady state. Figure 11 displays the IRFs to a contractionary monetary

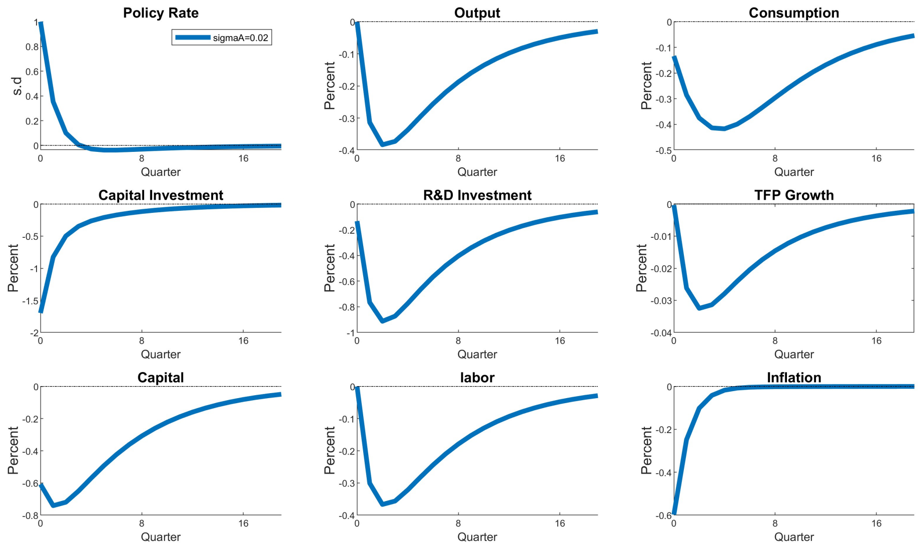


Figure 11: IRFs of a one standard deviation increase in the policy rate

policy shock, i.e., an exogenous one standard deviation increase in the gross interest rate (R_t).

When monetary policy tightens, the gross nominal interest rate increases and the price level falls. As prices are sticky in the economy, aggregate demand falls, and the real rate increases. Due to lower demand, firms decrease their production. This short-term effect of monetary policy on output is vastly discussed and documented in the literature and is compatible with the empirical findings of this study. Moreover, the increase in the real interest rate discourages firms from investing. As a result, both investment in physical capital and R&D decreases. However, since the accumulation of physical capital affects the borrowing constraint, firms recover their physical capital more quickly than their R&D investment. A decline in R&D decreases TFP growth leading to a lower level of aggregate TFP.

To investigate how economic uncertainty can affect the impact of a monetary contraction on the R&D investment, I conduct a similar exercise, but with a higher volatility of TFP shocks, denoted by σ_a. A higher value of σ_a implies more uncertainty since bigger positive or negative shocks are likely to hit the aggregate TFP and affect firms' production. The result of this exercise is illustrated in Figure 12. Higher economic uncertainty amplifies the impact of a monetary contraction. In particular, when firms face a higher uncertainty, they contract their R&D investment even more after an increase in the policy rate. This result aligns with the empirical evidence and with the credit transmission channel theory of the importance of economic uncertainty. Notably, the difference in the reaction of physical

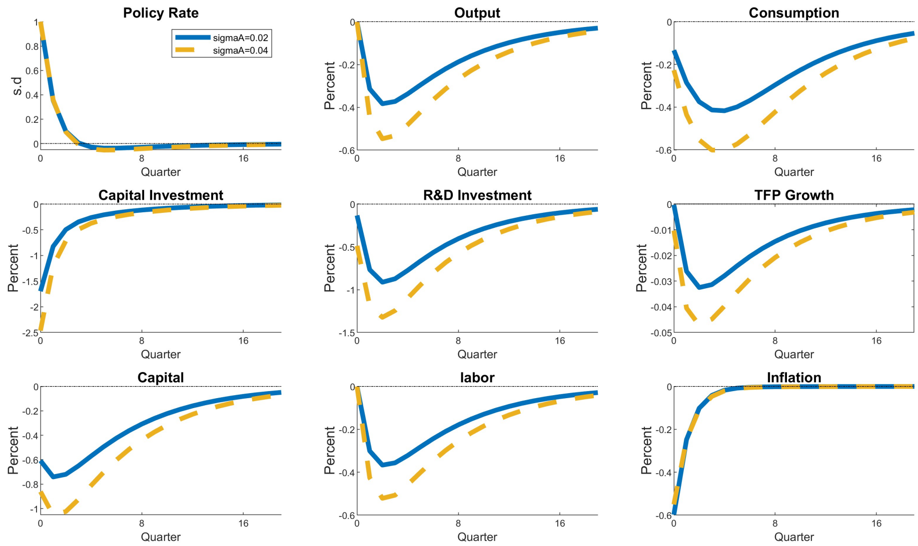


Figure 12: IRFs of a one standard deviation increase in the policy rate (different uncertainty parameters)

capital investment under different economic conditions diminishes faster than that of R&D investment. Figure 38 in the Online Appendix confirms that uncertainty is relatively less important in the monetary policy and physical capital investment nexus. The next section's analysis can provide further insight into the possible mechanisms underlying these results.

4.2 Underlying mechanism

Figure 13 illustrates the steady-state share of physical capital to firm total assets (sum of physical capital, R&D capital, and firm's profit), while the model is simulated under different values of the aggregate TFP uncertainty. In the steady-state of a more uncertain economy, firms tend to hold less physical capital. The working capital constraint that firms face implies that a lower level of capital makes firms more constrained in the financial markets and they keep lower leverage. This result is compatible with the empirical findings as shown in Figure 15. The credit channel theory of the monetary transmission mechanism argues that more constraints in financial markets imply a bigger reaction to monetary shocks. However, as physical capital serves as collateral in financial markets, when firms face a higher uncertainty, they reduce their investment in R&D more strongly and persistently.

To investigate whether financial frictions can explain the higher contractionary impact of monetary policy shocks on R&D expenditure during uncertain times, I perform a counterfactual exercise in an economy without financial constraint. Figure 14 compares the results of a contractionary monetary shock under different levels of economic uncertainty in an

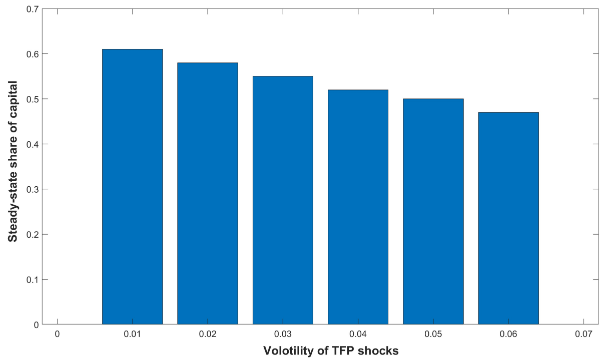


Figure 13: the steady-state level of physical capital under different economic uncertainty states

economy with no financial frictions. First, the result shows that the effect of a monetary contraction is weaker and is almost half of its financially constraint counterpart. Secondly, as economic uncertainty increases (a higher value for the volatility of the exogenous TFP shocks) the effect of a monetary contraction increases slightly, but much less compared to the previous exercise. This result highlights how financial constraint exacerbates the negative effects of monetary policy contractions. Moreover, Figure 39 in the Online Appendix compares the response functions under two different values of the financial constraint parameter in the model (different values for ζ) and shows that a tighter constraint (lower value for ζ) amplifies the impact of a monetary contraction.

To summarize, when economic uncertainty is higher firms keep less collateralizable capital, which implies more restriction in the financial markets and, as a result, more responsiveness of R&D investment to a monetary policy shock. This mechanism is compatible with the data patterns discussed in the previous part of this study. When uncertainty is high financial constraints further deteriorate the response of R&D investment to the monetary policy contraction. This is because higher uncertainty about the realization of the TFP makes the returns to R&D investment more uncertain, while on the other hand, they make the need for capital accumulation more vital when monetary policy contracts. The combination of these two effects with the working capital channel exacerbates the negative effects of a monetary policy contraction in this environment.

5 Discussion

The theoretical findings discussed in the preceding section underscore the importance of the credit channel for altering the effect in the presence of economic uncertainty. This result is compatible with the credit channel theory of monetary transmission. According to this theory, monetary policy is more effective during a crisis and highly uncertain periods since

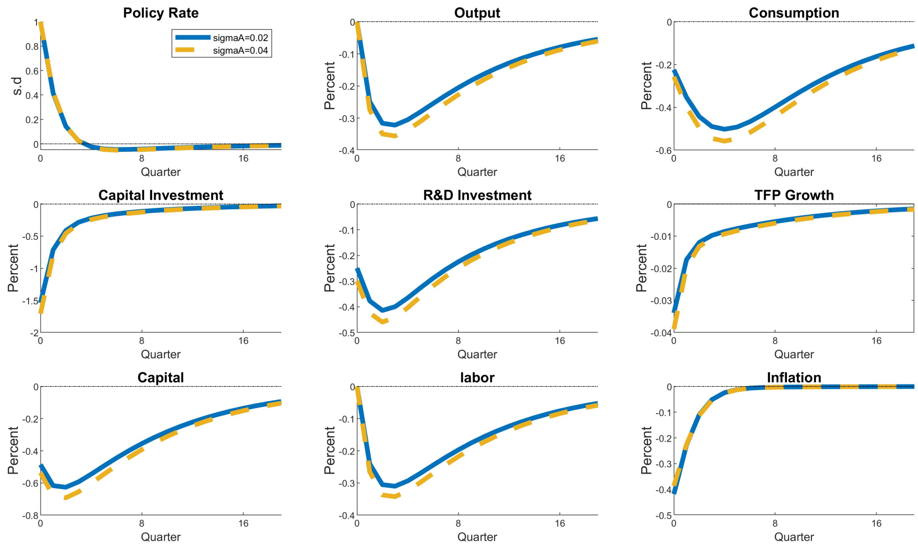


Figure 14: IRFs of a one standard deviation increase in the policy rate (different uncertainty parameters)

firms face more stringent financial constraints due to the rise of external finance premiums and lower net worth value (Bernanke et al. (1999), Brunnermeier and Sannikov (2014), and Burgard and Nockel (2019)). The general equilibrium model discussed in the previous section emphasizes the critical role of financial frictions and firms' collateralizable assets in altering the impact of monetary policy. In this section of the paper, using balance sheet data, I delve into the possibility of such a mechanism's existence in the US firm-level data.

To examine the impact of economic uncertainty on firms financial condition, I use LP as specified in equation 1 substituting monetary policy shocks with macroeconomic uncertainty shocks. Then, I estimate the dynamics of the firms' total debt-to-asset (leverage ratio) and physical tangible capital-to-liquidity ratios in response to an uncertainty shock[6]. As shown in Figure 15, following a one standard deviation increase in the macroeconomic uncertainty index, the debt-to-asset ratio decreases by 0.7 percentage points on impact. The ratio remains lower (although not statistically significant from the third to the seventh horizon of estimation) for up to four years, reaching its maximum drop of 1.2 percentage points ten quarters after the uncertainty shock [7]. Baum et al. (2009) find a similar result for the US firms' short-run leverage between 1993-2003. A lower leverage ratio during uncertain times could result from the endogenous decision of both firms and credit providers. In response to an increase in economic uncertainty, firms tend to invest more in intangible capital, such as R&D investment, rather than tangible physical capital. Figures 34 and 36 in the Online

[6]Uncertainty shock is identified using Blanchard and Perotti (2002) approach by controlling for four lags of unemployment, CPI, and uncertainty index

[7]The average leverage ratio in the sample is 19 percent with the standard deviation of 43 percent.

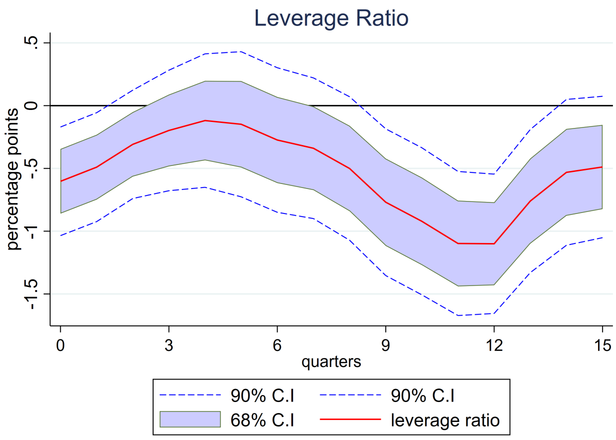
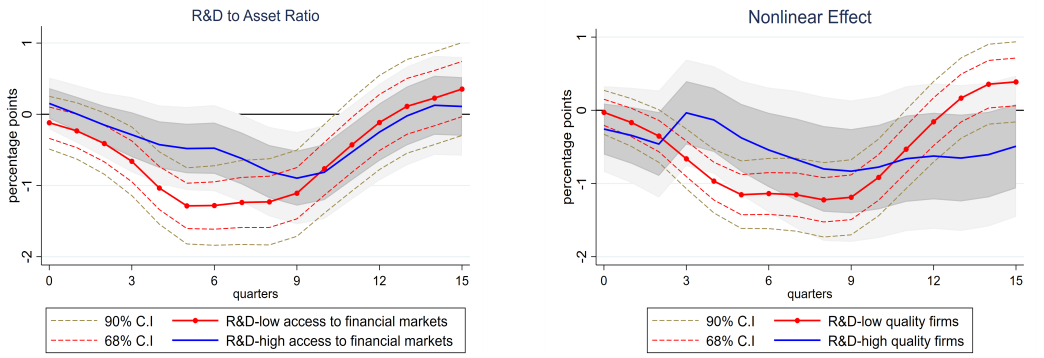


Figure 15: Effect of a one standard deviation shock to the macroeconomic uncertainty index on firms leverage ratio for the time period 1990Q1-2019Q2. Robust standard errors are clustered at firms level, and response functions are smoothed by a centered moving average.

Appendix show that following an uncertainty shock, firms decrease their physical capital investment ratio while increasing their share of R&D spending and liquidity holding. The tangible capital-to-intangible capital ratio is a useful proxy for firms' collateralizable assets ratio. Less collateral can tighten financial constraints for firms. Kara and Yook (2022), on the other hand, using bank mortgage data, show that after an increase in policy uncertainty banks tend to reduce their supply of jumbo mortgage loans.

The results from the previous exercise indicate that firms' leverage ratio as a measure of access to financial markets decreases significantly and persistently after an increase in economic uncertainty. Theoretical models predict that if firms face greater financial constraints, their research and development investment will be more sensitive to monetary policy shocks. o assess whether empirical results support this prediction, I estimate regressions akin to equation 3, where I compare the dynamic response of firms to a monetary contraction based on their access to financial markets before the realization of the shocks. I employ two different commonly used measures for firms' access to financial markets: leverage ratio and firms' S&P500 quality index. The underlying assumption behind this exercise is that firms with a lower leverage ratio and lower quality index have less access to financial markets for borrowing.

Figure 16 illustrates the responsiveness of firms' R&D expenditure bbased on their financial condition prior to the occurrence of monetary policy shocks. As depicted in the left graph, firms with lower access to financial markets (lower debt to asset ratio) decrease their R&D expenditure more than those with higher access. The difference is statistically significant for 4 to 6 quarters after the shock. Consistent with this argument, lower quality firms (based on their S&P quality index) which are more constrained in financial markets,



(a) access to financial market based on leverage ratio

(b) access to financial markets based on firms quality index

Figure 16: left graph: state-dependant results based on the firms' debt to asset ratio, right graph: state-dependant results based on the firms quality ranking. The solid blue line shows the effect for lower financially constrained firms, while the dashed red line shows the effect for the highly constrained firms. Access to the financial market is defined based on the yearly average debt-to-asset ratio. Robust standard errors are clustered at firms level, and response functions are smoothed by a centered moving average.

exhibit a stronger response to a monetary policy shock. Low quality firms decrease their R&D to asset ratio by more than 1.2 percent, while the response of higher quality firms is not statistically different from zero. Therefore, the empirical findings suggest that firms are more financially constrained during uncertain times, and less access to financial markets increases their R&D responsiveness to the contractionary monetary policy shocks. These findings confirm the potential mechanism suggested by the theoretical DSGE model and underscore the significance of financial markets in amplifying the impact of interest rate hikes.

6 Robustness Checks

In this section, I examine the robustness of the main results. For the economy of space, the results of these analyses are presented in the Online Appendix.

I begin by examining the robustness of the empirical results for the aggregate economy. As mentioned in the data section, the monetary shock is a weighted average of monthly shocks identified using high-frequency data in the financial markets. In each quarter, following Ottonello and Winberry (2020), the weights decrease in months, implying that the policy shock needs some time to be effective in the economy. However, figures 20 and 21 in the Online Appendix show that the results are robust to using a simple average of monthly shocks or weighting them by the number of days left to the end of the quarter. Moreover, the main results also survive when focusing only on the pre-recession period and excluding data after 2008 (Figure 18).

Similarly, the result for responsiveness of firms' R&D expenditure to monetary policy shocks is robust to the different weighting schemes for monthly shocks (Figures 27 and 28) and focusing merely on the pre-recession years (Figure 25). To ensure that the results are not depending on the particular identification of monetary policy, I perform the same exercises using two alternatives for policy shocks: first, using Romer and Romer (2004) narrative monetary policy shocks updated until 2007 by Wieland (2021), and second, Blanchard and Perotti (2002) approach in identifying policy shocks by regressing changes in the short-run interest rate on four lags of GDP, consumption, investment, inflation, and its own lags. The residual of this regression identifies the exogenous changes in the interest rate. Using the alternative shocks also confirms the significant effect of monetary policy shocks on the GDP, consumption, private investment, and R&D expenditure in the aggregate analysis (see Figures 22 and 23 in the Online Appendix) and on firms R&D expenditure and physical capital dynamics (Figures 29 and 30 in the Online Appendix).

Benefiting from the panel dimension of the firm-level data, I compare firms' responsiveness to policy shocks in the top and lowest 25 percentiles of the uncertainty index distribution. Figure 37 in the Online Appendix shows that the difference between the two uncertainty states becomes more transparent and more significant. Moreover, I use the high-frequency identified monetary policy as an instrument for changes in the short-run interest rate to address any possible endogeneity issue with the identified shocks. The results of the IV local projection estimation (as shown in Figure 31) are similar to the original results, which is consistent with the findings of Jeenas (2019a).

7 Conclusion

This paper studies the impact of monetary policy on firms' R&D expenditure in the US economy and its dependence on the level of aggregate economy uncertainty. By using both aggregate quarterly national account data and firm-level balance sheet data, the study finds that a one standard deviation increase in the interest rate results in a significant and persistent decrease in R&D expenditure up to four years after the shock. The effect on R&D expenditure reaches its maximum of a one percent decrease in the R&D to asset ratio for firms around two years after the monetary policy shock. Interest rate hikes tend to have a stronger effect than interest rate cuts, implying that monetary policy negatively affects R&D investment in the long run. Additionally, firms tend to react more strongly to a policy shock when the economy is uncertain. The main mechanism for this state-dependency works through credit transmission channel theory. When facing higher economic uncertainty in the future, firms maintain a lower leverage ratio and are more constrained in the financial market due to a lower level of tangible capital. Thus, financial constraints further deteriorate the response of R&D investment to a monetary contraction.

Finally, I employ a medium-scale DSGE model with endogenous output growth and financial frictions to interpret the empirical results and to highlight the importance of the credit channel for altering the effects of monetary policy on firms' investment in R&D in the presence of economic uncertainty. The model features sticky prices and endogenous growth through investment in R&D and financial frictions in the form of a borrowing constraint on production costs. When the nominal interest rate increases in this model, as prices are sticky in the economy, aggregate demand falls, and the real rate rises. Due to lower demand, firms decrease their production and are discouraged from investing. As a result, both investment in physical capital and R&D decreases.

When economic uncertainty increases, the theoretical model suggests that firms tend to hold less collateralizable capital, which implies more restrictions in the financial markets and, consequently, a greater responsiveness of R&D investment to a monetary policy shock. This mechanism aligns with the data patterns analyzed in this study. The higher uncertainty about the realization of the TFP makes the returns to R&D investment more uncertain. On the other hand, they make the need for capital accumulation more vital when monetary policy contracts. The combination of these two effects with the working capital channel exacerbates the negative effects of a monetary policy contraction in this environment. The results of this paper imply that central banks need to consider the long-run TFP and economic hysteresis in their policy rule, especially during highly uncertain times. A detailed analysis of optimal monetary policy in this environment and conditional on aggregate uncertainty is an essential direction for future research.

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Online Appendix (not intended for publication)

A Aggregate Results

A.1 Summary Statistics of the Aggregate Indicators

Table 2 presents a summary of the key aggregate indicators for the US economy during the period of 1990Q1-2019Q2. The data sources used in this study include the National Income and Product Accounts (NIPA) provided by The U.S. Bureau of Economic Analysis (BEA) for real GDP, private consumption, private investment, and R&D expenditure. CPI, interest rates, and unemployment rate data were obtained from the Federal Reserve Economic Data (FRED). The R&D expenditure includes total real investment by the private sector in research and development, including expenditures for software. The monetary policy shock used in this study is standardized genuine shocks identified in Jarociński and Karadi (2020). To measure macroeconomic uncertainty, I use the standardized measure constructed in Ludvigson et al. (2021), while the volatility index (VIX) is the measure created by the Chicago Board Options Exchange (CBOE), which captures the 30-day expected volatility of the S&P 500 index.

Variables	N	mean	s.d	min	max
Real GDP (billion dollars)	118	14,032	2,851	9,271	19,028
Real Consumption (billion dollars)	118	9,376	2,073	5,950	12,932
Real Investment (billion dollars)	118	2,433	536.1	1,412	3,387
CPI	118	81.21	15.75	54	108
Real R&D (million dollars)	118	393.0	96.24	259.7	598.8
Unemployment Rate	118	5.88	1.6	3.6	9.9
MP Shocks	118	5.76e-10	1.000	-4.837	2.888
Macroeconomic Uncertainty	118	-1.06e-09	1.000	-1.148	5.166
Financial Uncertainty (VIX)	118	0	1.000	-1.249	5.513

Table 2: Summary Statistics for the aggregate macroeconomic indicators for the sample period 1990-Q1-2019Q2.

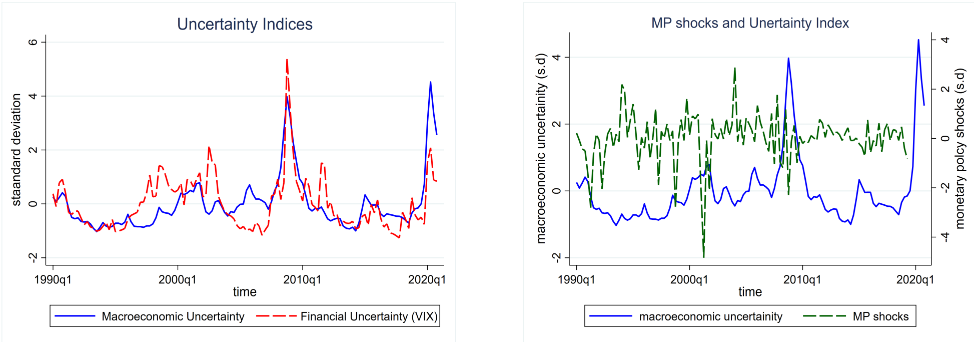


Figure 17: left graph: comparing two alternative uncertainty indices; right graph: macroeconomic uncertainty index vs monetary policy shocks. Quarterly uncertainty indices are the simple average of monthly indices.

A.2 Different Samples

Local projection estimation of the equation 1 for the sub-sample 1990Q1-2007Q4, for pre-recession period.

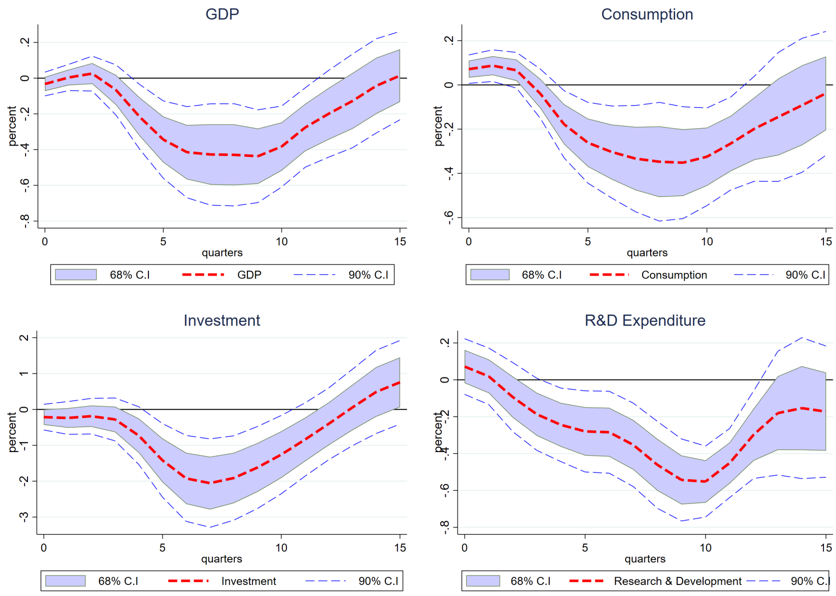


Figure 18: Effect of a one standard deviation contractionary monetary policy shock on real GDP, private consumption, private investment, and *R&D* expenditure for the period 1990Q1-2007Q4 using LP in the equation 1. Robust standard errors are corrected for serial correlation, and response functions are smoothed by centered moving average.

A.3 Different Monetary Policy Shocks

Using a simple average of the monetary policy shocks, instead of monthly-averaged shock used in the paper:

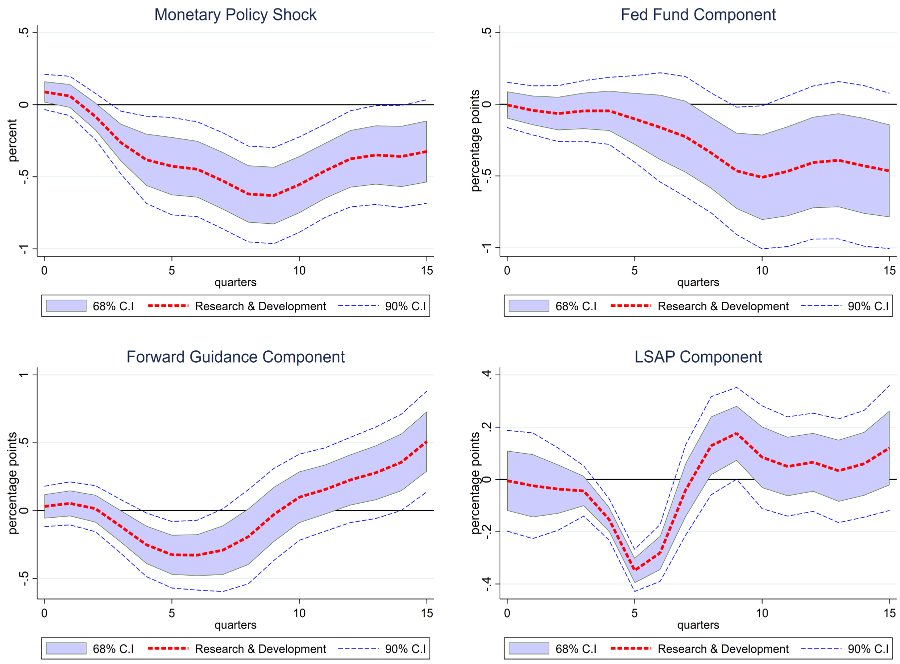


Figure 19: left graph: effect of a one standard deviation contractionary shock to the different components of monetary policy shock on R&D expenditure for the sample period 1900Q1-2019Q2 (the sample for LSAP shocks only includes after financial crisis period). Robust standard errors are corrected for heteroskedasticity, and serial correlation and response functions are smoothed by centered moving average.

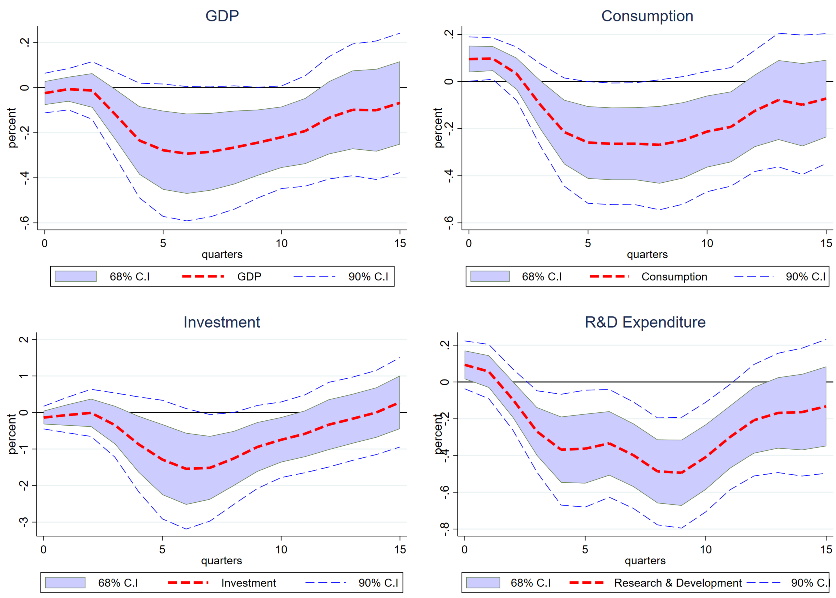


Figure 20: Effect of a one standard deviation contractionary monetary policy shock on real GDP, private consumption, private investment, and $R\&D$ expenditure for the period 1990Q1-2019Q2 using LP in the equation 1. Quarterly shock is a simple average of monthly shocks. Robust standard errors are corrected for serial correlation, and response functions are smoothed by centered moving average.

Using a different scheme of averaging the monetary policy shocks, where weights are the number of days left to the end of the quarter:

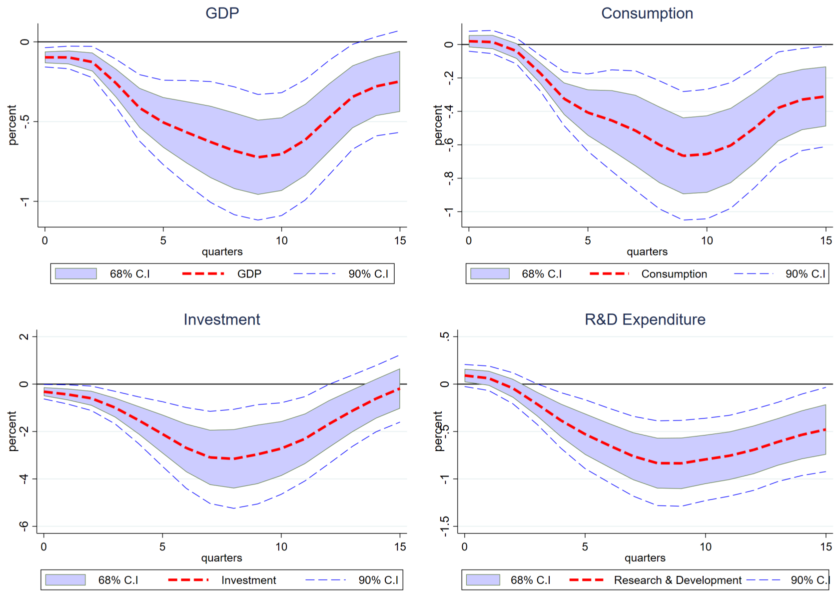


Figure 21: Effect of a one standard deviation contractionary monetary policy shock on real GDP, private consumption, private investment, and $R\&D$ expenditure for the period 1990Q1-2019Q2 using LP in the equation 1. Quarterly shock is a weighted average of monthly shocks, where weights are the number of days left to the end of the quarter. Robust standard errors are corrected for serial correlation, and response functions are smoothed by centered moving average.

Using Romer and Romer (2004) narrative shocks updated updated until 2007 by Wieland (2021) as an alternative monetary policy shock:

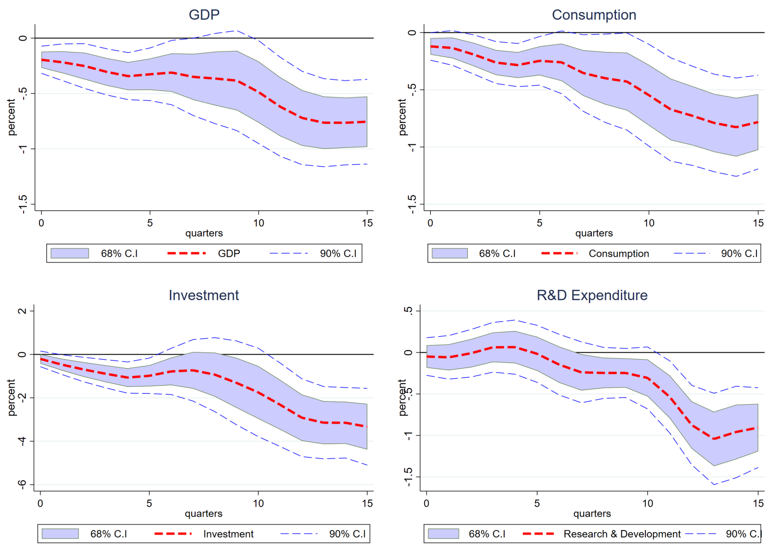


Figure 22: Effect of a one standard deviation contractionary monetary policy shock on real GDP, private consumption, private investment, and $R\&D$ expenditure for the period 1990Q1-2019Q2 using LP in the equation 1. Monetary policy shocks are replaced by Romer & Romer shocks. Robust standard errors are corrected for serial correlation, and response functions are smoothed by centered moving average.

Identifying monetary policy shocks using changes in the interest rate with Blanchard-Perotti method:

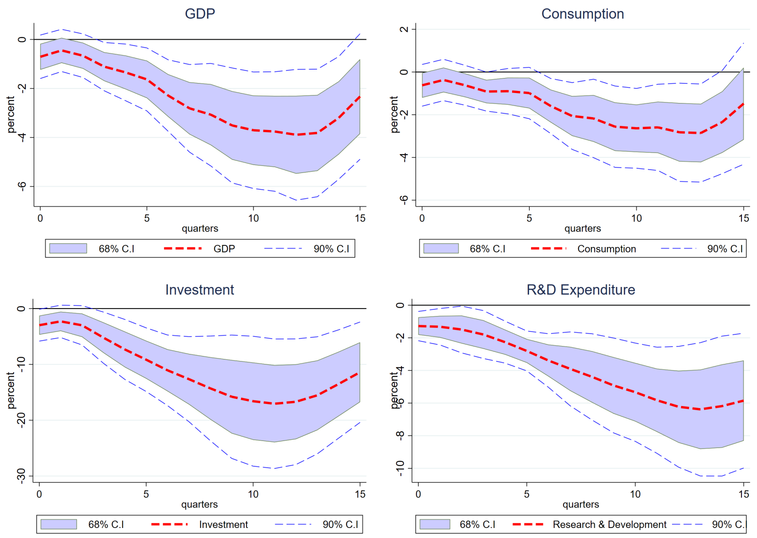


Figure 23: Effect of a one standard deviation contractionary monetary policy shock on real GDP, private consumption, private investment, and $R\&D$ expenditure for the period 1990Q1-2019Q2 using LP in the equation 1. Monetary policy shocks are replaced by Blanchard-Perotti shocks. Robust standard errors are corrected for serial correlation, and response functions are smoothed by centered moving average.

A.4 Nonlinear Results

Interaction term estimation and state-dependant results in the aggregate economy, using financial uncertainty (VIX) index as a measure for the aggregate uncertainty:

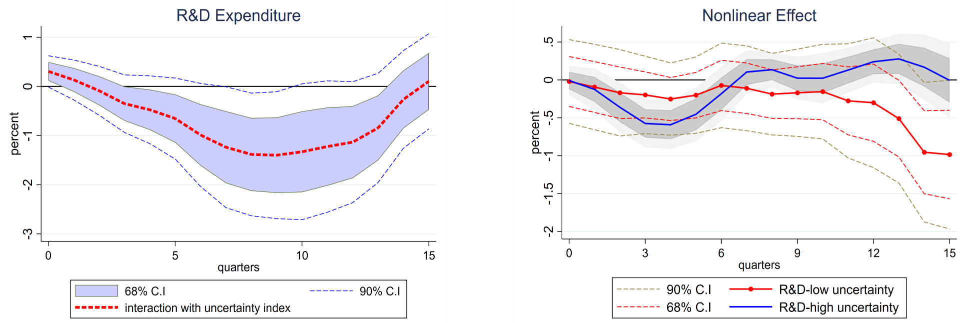


Figure 24: left graph: effect of a one standard deviation contractionary shock to the policy interacted with the uncertainty index on the aggregate R&D expenditure for the time period 1990Q1-2019Q2 using LP in equation 2. Right graph: the state-dependant results. The solid blue line shows the effect in high uncertainty quarters, while the dashed red line shows the effect in the low uncertainty period. High uncertainty time is defined when the VIX uncertainty index is higher than the median value in the sample. Robust standard errors are corrected for heteroskedasticity, and serial correlation and response functions are smoothed by centered moving average.

B Firm-level Results

B.1 Summary Statistics of firm-level data

Definition of the variables: R&D: represents the company's total expenditure on research and development of new or improved product lines and methods of production (denoted XRDQ in the Compustat dataset). Asset: book value of total assets (ATQ). Capital: Following Ottonello and Winberry (2020), the first value of capital for firms is the level of gross plant, property, and equipment (PPEGTQ) of the first reported value in Compustat. The evolution of capital in successive periods is computed using the changes of net plant, property, and equipment (PPENTQ), as a measure for net investment. Real Sales: total sales reported by firms in each quarter (SALEQ) deflated by the GDP deflator. Liquidity: sum of cash and short-term investments (CHEQ) as a share of total assets. Leverage Ratio: the ratio of the sum of short-term debt (DLCQ) and long-term debt (DLTTQ) to total assets. All extreme observations are excluded from the sample (closely following Ottonello and Winberry (2020).

Variables	N	mean	sd	min	max
R&D to asset ratio	95,370	0.0391	0.0597	0.000181	4.623
R&D growth	103,839	0.00969	0.379	-5.372	6.015
Capital to asset ratio	94,970	0.27	0.38	0	25
Capital growth	105,333	0.00619	0.174	-15.32	16.97
Real sales growth	106,122	0.0170	0.243	-1.000	1.000
Liquidity to asset ratio	95,370	0.328	0.516	-9.984	0.997
Leverage ratio	100,982	0.194	0.435	0	22.58
Capital to liquidity ratio	94,965	0.900	48.21	-3,610	6,123

Table 3: Summary Statistics for the firm-level data for the sample period 1990-Q1-2019Q2.

B.2 Estimation for pre-recession period:

Local projection estimation of the equation 4 for the sub-sample 1990Q1-2007Q4 (pre- recession period):

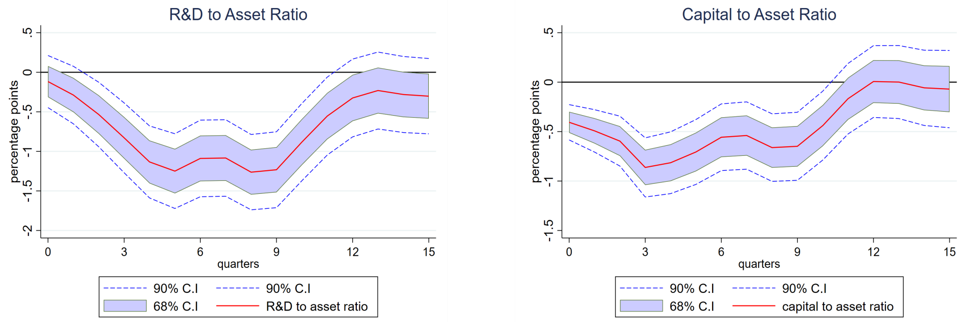


Figure 25: Effect of a one standard deviation shock to the monetary policy on the cumulative growth of *R&D* expenditure to total asset ratio (left graph) and capital to total asset ratio (right graph) for the time period 1990Q1-2008Q4. Robust standard errors are clustered in firms level and response functions are smoothed by centered moving average.

B.3 Effect of an Information shock on firms R&D expenditure

The effect of an information shock identified as the positive co-movement of interest rates and stock prices in a narrow window around the policy announcement (identified in Jarociński and Karadi (2020)):

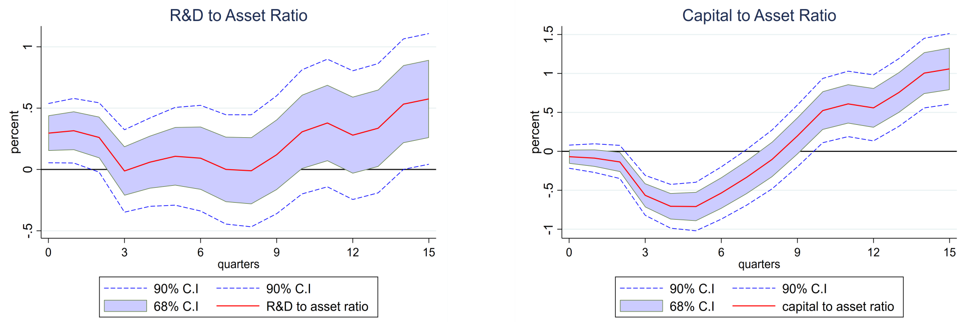


Figure 26: Effect of a one standard deviation information shock on the *R&D* expenditure to total asset ratio (left graph) and capital to total asset ratio (right graph) for the time period 1990Q1-2019Q2. Robust standard errors are clustered in firms level and response functions are smoothed by centered moving average.

B.4 Different Monetary Policy Shocks

Using a simple average of the monetary policy shocks, instead of monthly-averaged shock used in the paper:

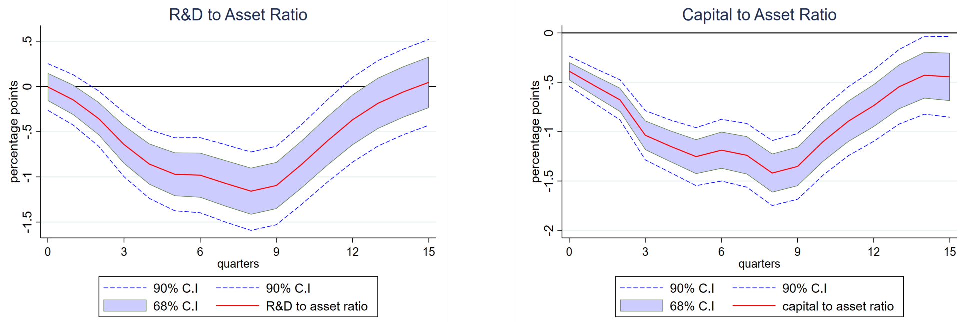


Figure 27: Effect of a one standard deviation shock to the monetary policy on the cumulative growth of *R&D* expenditure to total asset ratio (left graph) and capital to total asset ratio (right graph) for the time period 1990Q1-2019Q2. Quarterly shock is a weighted average of monthly shocks, where weights are the number of days left to the end of the quarter. Robust standard errors are clustered in firms level and response functions are smoothed by centered moving average.

Using a different scheme of averaging the monetary policy shocks, where weights are the number of days left to the end of the quarter:

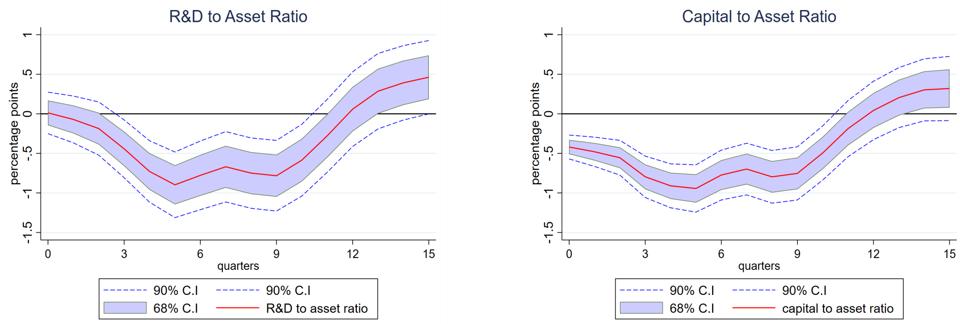


Figure 28: Effect of a one standard deviation shock to the monetary policy on the cumulative growth of *R&D* expenditure to total asset ratio (left graph) and capital to total asset ratio (right graph) for the time period 1990Q1-2019Q2. Quarterly shock is a simple average of monthly shocks. Robust standard errors are clustered in firms level and response functions are smoothed by centered moving average.

Using Romer and Romer (2004) narrative shocks updated updated until 2007 by Wieland (2021) as an alternative monetary policy shock:

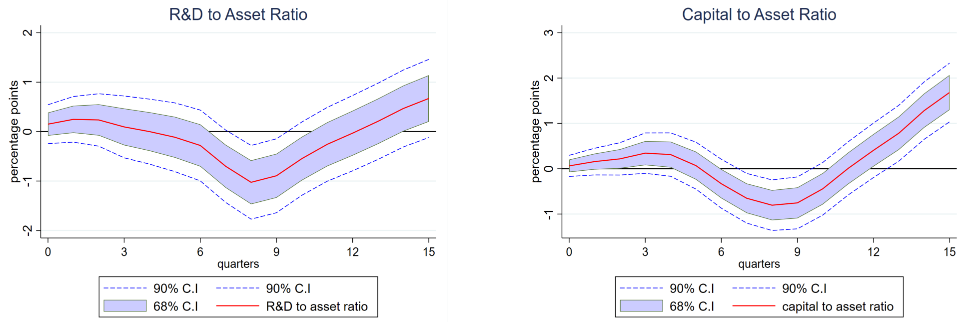


Figure 29: Effect of a one standard deviation shock to the monetary policy on the cumulative growth of $R\&D$ expenditure to total asset ratio (left graph) and capital to total asset ratio (right graph) for the time period 1990Q1-2019Q2. Monetary policy shocks are replaced by Romer and Romer (2004) shocks. Robust standard errors are clustered in firms level and response functions are smoothed by centered moving average.

Identifying monetary policy shocks using changes in the interest rate with Blanchard-Perotti method:

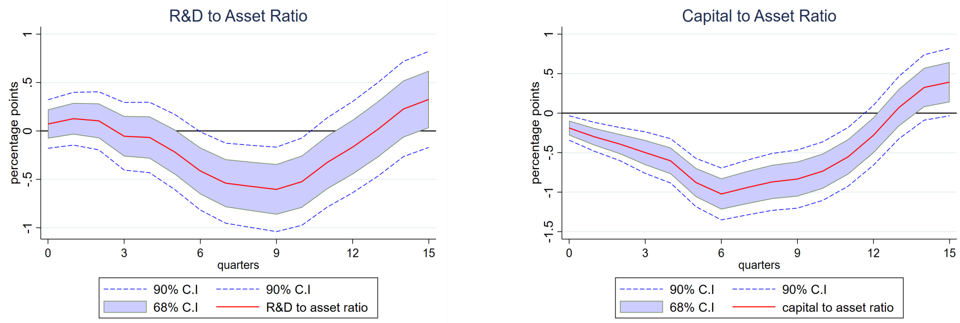


Figure 30: Effect of a one standard deviation shock to the monetary policy on the cumulative growth of $R\&D$ expenditure to total asset ratio (left graph) and capital to total asset ratio (right graph) for the time period 1990Q1-2019Q2. Monetary policy shocks are replaced by Blanchard-Perotti shocks. Robust standard errors are clustered in firms level and response functions are smoothed by centered moving average.

Result of an IV regression for the firm-level data. Here the changes in the policy rate is instrumented by the monetary policy shocks identified by high-frequency movement in the financial market as in Jarociński and Karadi (2020).

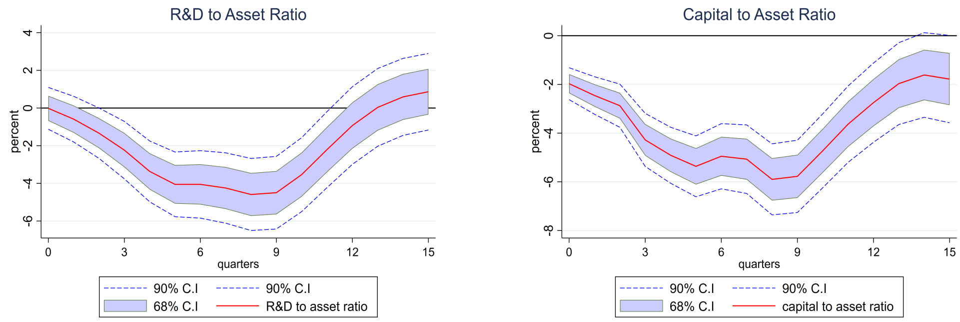
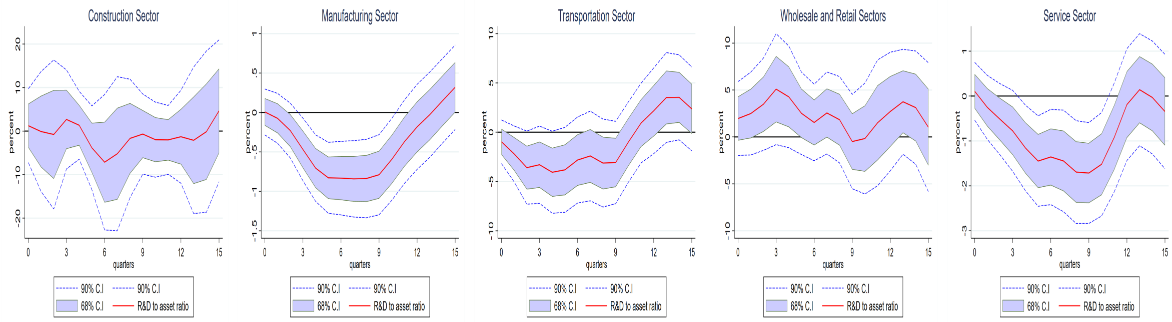


Figure 31: Effect of a one standard deviation shock to the policy rate instrumented by the monetary policy shock, on the cumulative growth of $R\&D$ expenditure to total asset ratio (left graph) and capital to total asset ratio (right graph) for the time period 1990Q1-2019Q2. Robust standard errors are clustered in firms level and response functions are smoothed by centered moving average.

B.5 Different Industries



(a) Construction **(b)** Manufacture **(c)** Transport **(d)** Sales **(e)** Services

Figure 32: Effect of a one standard deviation shock to the monetary policy on the cumulative growth of normalized $R\&D$ expenditure for the time period 1990Q1-2019Q2 in different industries. Robust standard errors are clustered at firms level, and response functions are smoothed by a centered moving average.

B.6 Different Sizes

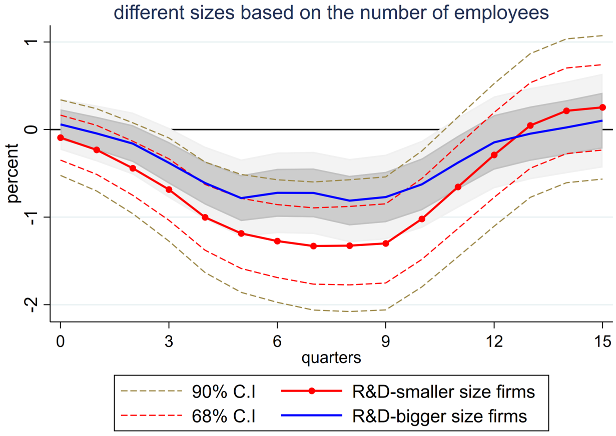
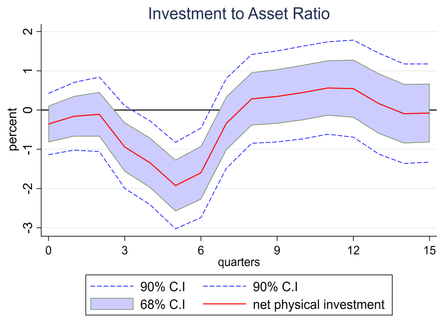


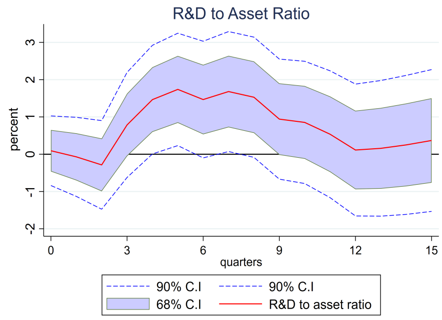
Figure 33: Effect of a one standard deviation shock to the monetary policy on the cumulative growth of normalized *R&D* expenditure for the time period 1990Q1-2019Q2. The solid blue line shows the effect for bigger size firms, while the dashed red line shows the effect on smaller firms. Firms are classified based on the median value of their number of employees in the sample. Robust standard errors are clustered at firms level, and response functions are smoothed by a centered moving average..

C Uncertainty and Collateralizable Assets

How higher uncertainty can tighten firms financial constrain? This section investigates the dynamics of firms tangible capital in response to an exogenous uncertainty shock, and assess if change in tangible capital ratio can affect monetary policy-R&D expenditure nexus.

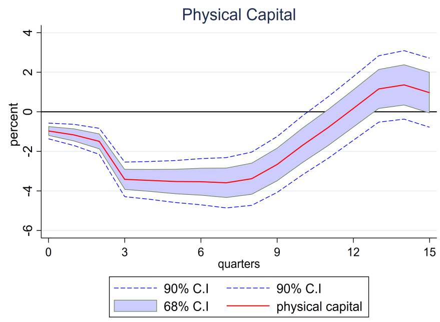


(a) net physical capital investment

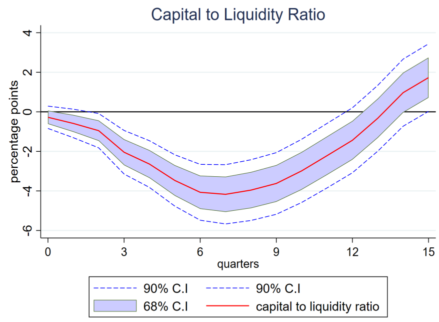


(b) R&D expenditure

Figure 34: Effect of a one standard deviation shock to the macroeconomic uncertainty index on firms net physical investment (left graph) and on R&D (right graph) both as a share of total assets, for the time period 1990Q1-2019Q2. Robust standard errors are clustered in firms level, and response functions are smoothed by centered moving average.



(a) physical capital



(b) tangible capital to liquidity

Figure 35: Effect of a one standard deviation shock to the macroeconomic uncertainty index on firms investment in tangible capital (left graph) and on the tangible capital to liquidity ratio (right graph) for the time period 1990Q1-2019Q2. Robust standard errors are clustered in firms level, and response functions are smoothed by centered moving average.

The left graph in Figure 36 presents the interaction effect of capital to liquidity ratio and monetary policy shocks on firms' R&D expenditure. A one unit increase in the ratio decreases the responsiveness of firms to a contractionary policy shock by 0.04 percentage points after two years. The effect turns significant with 6 quarter lags but remains up to three years after the shock. This result is in accordance with the prediction of the partial equilibrium, approving that when firms decrease their capital to liquidity ratio, it makes them more responsive to policy shocks due to the frictions in financial markets.

The right graph in Figure 36 shows the state-dependant results. The dashed red lines show the response function for firms in a low capital to liquidity state before the aggregate shock happens. Due to the results, firms with low collateralizable assets are more responsive to a policy shock. Lower tangible capital and keeping more liquid assets make firms more constrained in the financial market. If a contraction in their credit line occurs, they decide to decrease their long-run investment since they may not be able to cover the short-run risks that the project faces.

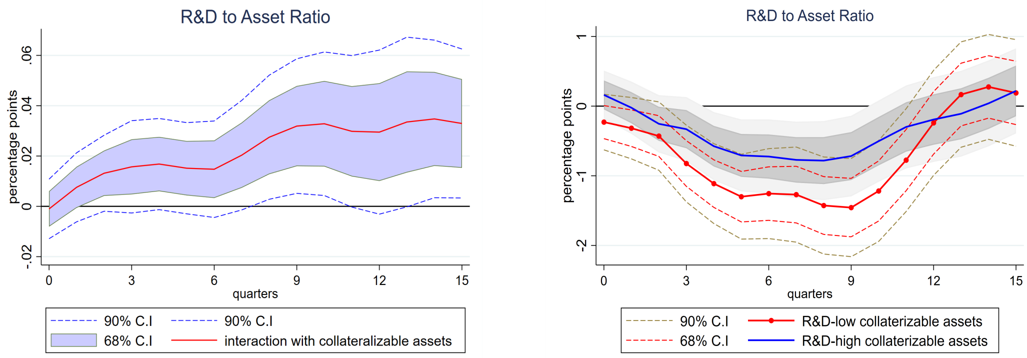


Figure 36: left graph: the dynamic effect of interacting monetary policy with capital to liquidity ratio on forms R&D expenditure, right graph: the state-dependant results based on the firms' collateralizable assets. The solid blue line shows the effect for high collateral firms-quarters, while the dashed red line shows the effect for the low collateral firms-quarters. High collateral observations are defined based on the tangible capital to liquidity ratio. Robust standard errors are clustered in firms level, and response functions are smoothed by a centered moving average.

C.1 State-dependent Results

In this exercises, I compare the response of R&D expenditure to a contactionary monetary policy shock, under different uncertainty states. Uncertainty states are defined based on the top and lowest 25% of the two different uncertainty indices over the sample period.

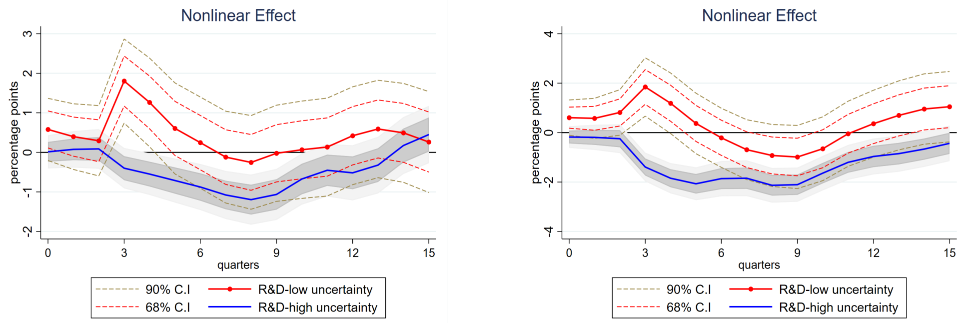
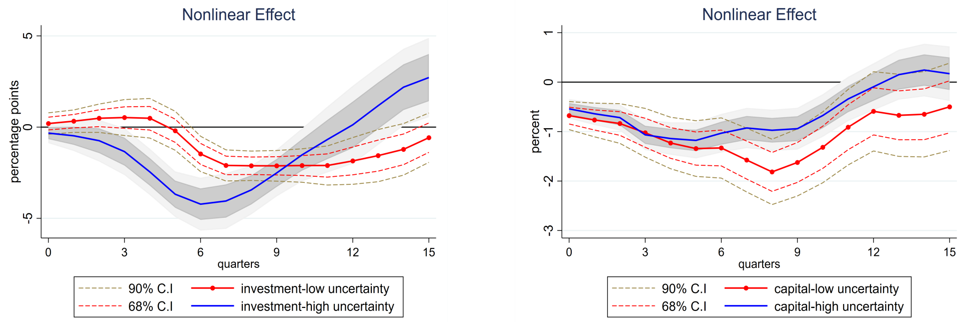


Figure 37: left graph: the state-dependant results based on the macroeconomic uncertainty index. right graph: the state-dependant results based on the VIX index. The solid blue line shows the effect in high uncertainty quarters, while the dashed red line shows the effect in the low uncertainty period. High uncertainty time is defined when the uncertainty index is higher than the 75th percentile of the index value in the sample. Low-uncertainty is defined as values less than 25th percentile. Robust standard errors are clustered in firms level, and response functions are smoothed by centered moving average.



(a) aggregate economy

(b) firm-level data

Figure 38: left graph: the state-dependant results based on the macroeconomic uncertainty index for the aggregate capital investment. right graph: the state-dependant results based on the macroeconomic uncertainty index for firms' capital to asset ratio. The solid blue line shows the effect in high uncertainty quarters, while the dashed red line shows the effect in the low uncertainty period. High uncertainty time is defined when the uncertainty index is higher than the median of the index value in the sample. Robust standard errors are clustered in firms level, and response functions are smoothed by centered moving average.

D Equilibrium Conditions of the DSGE model

Households Problem

$$max_{C_t,L_t,b_{t+1}} E_t \sum_{s=0}^{\infty} \beta^s \big\{ \log(C_{t+s} - \Phi C_{t+s-1}) - \chi L_{t+s}^{1+\sigma}/(1+\sigma) \big\},$$

subject to:

$$C_t + \frac{b_{t+1}}{1+r_t} = w_t L_t + \frac{b_t}{\pi_t} + \Pi_t + T_t$$

and $\lambda_{1,t}$ is the Lagrange multipliers of the budget constraints, respectively.

FOCs:

$$\frac{\partial}{\partial C_t} = U'(C_t) = \frac{1}{C_t - \Phi C_{t-1}} - \frac{\beta \Phi}{C_{t+1} - \Phi C_t} - \lambda_{1,t} = 0$$

$$\Rightarrow U'(C_t) = \lambda_{1,t}$$

$$\frac{\partial}{\partial L_t} = -\chi L_t^{\sigma} + \lambda_{1,t} w_t = 0$$

$$\Rightarrow L_t = \left(\frac{U'(C_t) w_t}{\chi}\right)^{\frac{1}{\sigma}} \tag{15}$$

$$\frac{\partial}{\partial b_{t+1}} = -\frac{\lambda_{1,t}}{1+r_t} + \frac{\lambda_{1,t+1}}{\pi_{t+1}} = 0$$

$$\Rightarrow \frac{\pi_{t+1}}{1+r_t} = \frac{\lambda_{1,t+1}}{\lambda_{1,t}} = \frac{\beta U'(C_{t+1})}{U'(C_t)} \tag{16}$$

Intermediate good producers:

$$\max_{P_{t,j}, L_{t,j}, I_{t,j}, S_{t,j}, Z_{t,j}, Y_{t,j}, K_{t+1,j}, N_{t+1,j}, b_{t+1,j}, \Pi_t} E_t \sum_{j=0}^{\infty} M_{t,t+j} \Pi_{t+j}(j)$$

where

$$\Pi_t(j) = \frac{P_t(j)}{P_t} Y_t(j) - w_t L_t(j) - I_t(j) - S_t(j) - \frac{\phi_P}{2}\left(\frac{P_t(j)}{\pi P_{t-1}(j)} - 1\right)^2 Y_t - \Lambda_{\Pi,t} + \frac{b_{t+1}}{R_t} - \frac{b_t}{\pi_t} \tag{17}$$

subject to the following constraints:

$$Y_t(j) = K_t(j)^{\alpha} \left(Z_t(j) L_t(j)\right)^{1-\alpha} \tag{18}$$

$$Z_t(j) = A_t N_t(j)^{\eta} N_t^{1-\eta} \tag{19}$$

$$Y_t(j) = \left(\frac{P_t(j)}{P_t}\right)^{-\varepsilon} Y_t$$

$$\frac{P_t(j)}{P_t} Y_t(j) \leq \zeta (K_{t+1}(j) - \frac{b_{t+1}}{1+r_t}) \tag{20}$$

$$K_{t+1} = (1-\delta_K) K_t + \Lambda_K \left(\frac{I_t}{K_t}\right) K_t \tag{21}$$

$$N_{t+1} = (1-\delta_N) N_t + \Lambda_N \left(\frac{S_t}{N_t}\right) N_t \tag{22}$$

$$\Lambda_{\Pi}\left(\tilde{\Pi}_t\right) = \frac{\phi_{\Pi}}{2}\left(\frac{\Pi_t}{\Pi_{t-1}} - \Delta\Pi\right)^2 Y_t$$

with $\gamma_{i,t}, i = 0, 1, 2, 3, 4, 5, 6$ being their corresponding Lagrange multipliers.

FOCs:

$$\frac{\partial}{\partial P_{t,j}} = \gamma_{0,t} \frac{Y_t(j)}{P_t} - \gamma_{0,t} \phi_P \frac{1}{\pi P_{t-1}(j)} \left(\frac{P_t(i)}{\pi P_{t-1}(j)} - 1\right) Y_t + \gamma_{0,t+1} M_{t,t+1} \phi_P \frac{P_{t+1}(j)}{\pi P_t^2(j)} \left(\frac{P_{t+1}(j)}{\pi P_t(j)} - 1\right) Y_{t+1} -$$

$\varepsilon\gamma_{3,t}\frac{1}{P_t}\left(\frac{P_t(j)}{P_t}\right)^{-\varepsilon-1}Y_t - \gamma_{4,t}\frac{1}{P_t}Y_t(j) = 0$

or

$$\gamma_{0,t}(1-\phi_P\frac{\pi_t}{\pi}\left(\frac{\pi_t}{\pi}-1\right)) + \gamma_{0,t+1}M_{t,t+1}\phi_P\frac{\pi_{t+1}}{\pi}\left(\frac{\pi_{t+1}}{\pi}-1\right)\frac{Y_{t+1}}{Y_t} - \varepsilon\gamma_{3,t} - \gamma_{4,t} = 0$$

$$\gamma_{0,t}(1-\phi_P\frac{\pi_t}{\pi}\left(\frac{\pi_t}{\pi}-1\right))+\gamma_{0,t+1}M_{t,t+1}\phi_P\frac{\pi_{t+1}}{\pi}\left(\frac{\pi_{t+1}}{\pi}-1\right)\frac{Y_{t+1}}{Y_t}-\varepsilon\gamma_{0,t}-(1-\varepsilon)\gamma_{4,t}+\varepsilon\gamma_{1,t} = 0 \tag{23}$$

$$\frac{\partial}{\partial L_{t,j}} = -\gamma_{0,t}w_t + \gamma_{1,t}(1-\alpha)K_t(j)^{\alpha}Z_t(j)^{1-\alpha}L_t(j)^{-\alpha} = 0$$

$$w_t = \frac{\gamma_{1,t}}{\gamma_{0,t}}(1-\alpha)\frac{Y_{j,t}}{L_{j,t}} \tag{24}$$

$$\frac{\partial}{\partial K_{t+1,j}} = \gamma_{1,t+1}\alpha\frac{Y_{j,t+1}}{K_{j,t+1}}+\gamma_{4,t}\zeta-\gamma_{5,t}+\gamma_{5,t+1}\left(1-\delta_K+\Lambda_K\left(\frac{I_{t+1}}{K_{t+1}}\right)-\frac{I_{t+1}}{K_{t+1}}\Lambda_K'\left(\frac{I_{t+1}}{K_{t+1}}\right)\right) = 0$$

$$\Rightarrow \gamma_{1,t+1}\alpha\frac{Y_{j,t+1}}{K_{j,t+1}}+\gamma_{4,t}\zeta = \frac{\gamma_{0,t}}{\Lambda_K'(\frac{I_t}{K_t})}-\frac{\gamma_{0,t+1}}{\Lambda_K'(\frac{I_{t+1}}{K_{t+1}})}\left(1-\delta_K+\Lambda_K\left(\frac{I_{t+1}}{K_{t+1}}\right)-\frac{I_{t+1}}{K_{t+1}}\Lambda_K'\left(\frac{I_{t+1}}{K_{t+1}}\right)\right) \tag{25}$$

$$\frac{\partial}{\partial N_{t+1,j}} = \gamma_{2,t+1}\eta\frac{Z_{j,t+1}}{N_{j,t+1}} - \gamma_{6,t} + \gamma_{6,t+1}\left(1-\delta_N+\Lambda_N\left(\frac{S_{t+1}}{N_{t+1}}\right)-\frac{S_{t+1}}{N_{t+1}}\Lambda_N'\left(\frac{S_{t+1}}{N_{t+1}}\right)\right) = 0$$

$$\Rightarrow \gamma_{1,t+1}(1-\alpha)\eta\frac{Y_{j,t+1}}{N_{j,t+1}} = \frac{\gamma_{0,t}}{\Lambda_N'(\frac{S_t}{N_t})}-\frac{\gamma_{0,t+1}}{\Lambda_N'(\frac{S_{t+1}}{N_{t+1}})}\left(1-\delta_N+\Lambda_N\left(\frac{S_{t+1}}{N_{t+1}}\right)-\frac{S_{t+1}}{N_{t+1}}\Lambda_N'\left(\frac{S_{t+1}}{N_{t+1}}\right)\right) \tag{26}$$

$$\frac{\partial}{\partial Z_t(j)} = \gamma_{1,t}(1-\alpha)\left(K_t(j)\right)^{\alpha}Z_t(j)^{-\alpha}L_t(j)^{1-\alpha} - \gamma_{2,t} = 0$$

$$\gamma_{2,t} = \gamma_{1,t}(1-\alpha)\frac{Y_{j,t}}{Z_{j,t}}$$

$$\frac{\partial}{\partial Y_t(j)} = \gamma_{0,t}\frac{P_t(j)}{P_t} - \gamma_{1,t} - \gamma_{3,t} - \frac{P_t(j)}{P_t}\gamma_{4,t} = 0$$

$$\gamma_{1,t} + \gamma_{3,t} + \gamma_{4,t} = \gamma_{0,t}$$

$$\frac{\partial}{\partial b_{t+1}} = \gamma_{0,t}\frac{1}{R_t} - \gamma_{0,t+1}\frac{M_{t,t+1}}{\pi_{t+1}} - \gamma_{4,t}\zeta\frac{1}{1+r_t} = 0$$

$$\gamma_{0,t}\frac{\pi_{t+1}}{R_t} - \gamma_{4,t}\zeta\frac{\pi_{t+1}}{1+r_t} = \gamma_{0,t+1}M_{t,t+1} \tag{27}$$

$$\frac{\partial}{\partial I_t} = -\gamma_{0,t} + \gamma_{5,t}\Lambda'_K(\frac{I_t}{K_t}) = 0$$

$$\Rightarrow \gamma_{5,t} = \frac{\gamma_{0,t}}{\Lambda'_K(\frac{I_t}{K_t})}$$

$$\frac{\partial}{\partial S_t} = -\gamma_{0,t} + \gamma_{6,t}\Lambda'_N(\frac{S_t}{N_t}) = 0$$

$$\Rightarrow \gamma_{6,t} = \frac{\gamma_{0,t}}{\Lambda'_N(\frac{S_t}{N_t})}$$

$$\frac{\partial}{\partial \Pi_t} = 1 - \gamma_{0,t} - \gamma_{0,t}\Lambda'_{\Pi,t} - \gamma_{0,t+1}M_{t,t+1}\Lambda'_{\Pi,t+1} = 0$$

$$\Rightarrow \gamma_{0,t}(1+\Lambda'_{\Pi,t}) + \gamma_{0,t+1}M_{t,t+1}\Lambda'_{\Pi,t+1} = 1 \tag{28}$$

Market clearing conditions

Goods market:

$$Y_t = C_t + I_t + S_t + \frac{\phi_P}{2}\left(\frac{\pi_t}{\pi} - 1\right)^2 Y_t + \Lambda_{\Pi,t} \tag{29}$$

definition:

$$R_t = 1 + (1-\tau)r_t \tag{30}$$

monetary policy:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_r} \left(\frac{\pi_t}{\pi}\right)^{\rho_\pi} \left(\frac{\Delta Y_t}{\Delta Y}\right)^{\rho_Y} \exp(\sigma_r \varepsilon_{r,t}), \tag{31}$$

aggregate productivity:

$$\mathrm{Log}(A_t) = (1-\rho_a)\mathrm{Log}(A) + \rho_a \mathrm{Log}(A_{t-1}) + \sigma_a \varepsilon_{a,t} \tag{32}$$

government budget balance:

$$T_t = b_{t+1}\left(\frac{1}{R_t} - \frac{1}{1+r_t}\right) \tag{33}$$

D.1 All De-trended Equations

I define $\tilde{X}_t = \frac{X_t}{N_t}$ and also $g_{N,t} = \frac{N_t}{N_{t-1}}$.

Set of endogenous variables:

$$\left\{ \mathrm{L}_t, \tilde{C}_t, \tilde{I}_t, \tilde{S}_t, \tilde{K}_{t+1}, g_{N,t+1}, \tilde{Y}_t, \pi_t, \tilde{Z}_t, b_{t+1}, \tilde{w}_t, R_t, r_t, \tilde{T}_t, \gamma_{0,t}, \gamma_{1,t}, \gamma_{4,t}, A_t, \tilde{\Pi}_t \right\}$$

$$g_{N,t+1}\widetilde{K_{t+1}} = (1-\delta_K)\,\tilde{K}_t + \Lambda_K\left(\frac{\tilde{I}_t}{\tilde{K}_t}\right)\tilde{K}_t \tag{1}$$

$$g_{N,t+1} = (1-\delta_N) + \Lambda_N\left(\tilde{S}_t\right) \tag{2}$$

$$U'(\tilde{C}_t) = \frac{1}{\tilde{C}_t - \Phi\frac{\widetilde{C_{t-1}}}{g_{N,t}}} - \frac{\beta\Phi}{g_{N,t+1}\widetilde{C_{t+1}} - \Phi\tilde{C}_t}$$

$$U'(\widetilde{C_{t+1}}) = \frac{1}{g_{N,t+1}\widetilde{C_{t+1}} - \Phi\tilde{C}_t} - \frac{\beta\Phi}{(g_{N,t+2}\times g_{N,t+1})\widetilde{C_{t+2}} - \Phi g_{N,t+1}\widetilde{C_{t+1}}}$$

$$\widetilde{M_{t,t+1}} = \frac{\beta U'(\widetilde{C_{t+1}})}{U'(\tilde{C_t})}$$

$$\frac{\pi_{t+1}}{1+r_t} = \widetilde{M_{t,t+1}} \tag{3}$$

$$L_t = \left(\frac{U'(\tilde{C}_t)\tilde{w}_t}{\chi}\right)^{\frac{1}{\sigma}} \tag{4}$$

$$\gamma_{1,t+1}\alpha\frac{\widetilde{Y_{j,t+1}}}{\widetilde{K_{j,t+1}}} + \gamma_{4,t}\zeta = \frac{\gamma_{0,t}}{\Lambda_K'(\frac{\tilde{I}_t}{\tilde{K}_t})} - \frac{\gamma_{0,t+1}}{\Lambda_K'(\frac{\tilde{I}_{t+1}}{\tilde{K}_t1})}\left(1-\delta_K+\Lambda_K\left(\frac{\tilde{I}_{t+1}}{\tilde{K}_{t+1}}\right) - \frac{\tilde{I}_{t+1}}{\tilde{K}_{t+1}}\Lambda_K'\left(\frac{\tilde{I}_{t+1}}{\tilde{K}_{t+1}}\right)\right) \tag{5}$$

$$\gamma_{1,t+1}(1-\alpha)\eta\widetilde{Y_{j,t+1}} = \frac{\gamma_{0,t}}{\Lambda_N'(\tilde{S}_t)} - \frac{\gamma_{0,t+1}}{\Lambda_N'(\widetilde{S_{t+1}})}\left(1-\delta_N+\Lambda_N\left(\widetilde{S_{t+1}}\right) - \widetilde{S_{t+1}}\Lambda_N'\left(\widetilde{S_{t+1}}\right)\right) \tag{6}$$

$$\Lambda_K\left(\frac{\tilde{I}_t}{\tilde{K}_t}\right)=a_{K,1}+\frac{a_{K,2}}{1-\frac{1}{\tau_K}}\left(\frac{\tilde{I}_t}{\tilde{K}_t}\right)^{1-\frac{1}{\tau_K}}$$

$$\Lambda'_{K,t}=a_{K,2}\left(\frac{\tilde{I}_t}{\tilde{K}_t}\right)^{-\frac{1}{\tau_K}}$$

$$\Lambda_N\left(\tilde{S}_t\right)=a_{N,1}+\frac{a_{N,2}}{1-\frac{1}{\tau_N}}\tilde{S}_t^{1-\frac{1}{\tau_N}}$$

$$\Lambda'_{N,t}=a_{N,2}\tilde{S}_t^{-\frac{1}{\tau_N}}$$

$$\Lambda_\Pi\left(\tilde{\Pi}_t\right)=\frac{\phi_\Pi}{2}\left(\frac{\tilde{\Pi}_t}{\tilde{\Pi}_{t-1}}g_t-\bar{g}\right)^2\tilde{Y}_t$$

$$\Lambda'_\Pi\left(\tilde{\Pi}_t\right)=\frac{\phi_\Pi g_t}{\Pi_{t-1}}\left(\frac{\Pi_t}{\Pi_{t-1}}g_t-\bar{g}\right)\tilde{Y}_t$$

$$\Lambda'_\Pi\left(\tilde{\Pi}_{t+1}\right)=-\frac{\phi_\Pi g_{t+1}\Pi_{t+1}}{\Pi_t^2}\left(\frac{\Pi_{t+1}}{\Pi_t}g_{t+1}-\bar{g}\right)\tilde{Y}_{t+1}$$

$$\tilde{w}_t=\frac{\gamma_{1,t}}{\gamma_{0,t}}(1-\alpha)\frac{\tilde{Y}_t}{L_t}\tag{7}$$

$$\tilde{Y}_t=\tilde{K}_t^\alpha\left(\tilde{Z}_tL_t\right)^{1-\alpha}\tag{8}$$

$$\tilde{Z}_t=A_t\tag{9}$$

$$\gamma_{0,t}(1-\phi_P\frac{\pi_t}{\pi}\left(\frac{\pi_t}{\pi}-1\right))+\gamma_{0,t+1}\tilde{M}_{t,t+1}\phi_P\frac{\pi_{t+1}}{\pi}\left(\frac{\pi_{t+1}}{\pi}-1\right)\frac{g_{N,t+1}\tilde{Y}_{t+1}}{\tilde{Y}_t}-\gamma_{0,t}\varepsilon-(1-\varepsilon)\gamma_{4,t}+\varepsilon\gamma_{1,t}=0\tag{10}$$

$$\tilde{Y}_t=\zeta\left(\tilde{K}_{t+1}-\frac{b_{t+1}}{1+r_t}\right)\tag{11}$$

$$\tilde{Y}_t = \tilde{C}_t + \tilde{I}_t + \tilde{S}_t + \frac{\phi_P}{2}\left(\frac{\pi_t}{\pi} - 1\right)^2 \tilde{Y}_t + \Lambda_{\Pi,t} \tag{12}$$

$$\gamma_{0,t}\frac{\pi_{t+1}}{R_t} - \gamma_{4,t}\zeta\frac{\pi_{t+1}}{1+r_t} = \gamma_{0,t+1}M_{t,t+1} \tag{13}$$

$$R_t = 1 + (1-\tau)r_t \tag{14}$$

$$\tilde{T}_t = b_{t+1}\left(\frac{1}{R_t} - \frac{1}{1+r_t}\right) \tag{15}$$

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_r}\left(\frac{\pi_t}{\pi}\right)^{\rho_\pi}\left(\frac{\tilde{Y}_t}{\tilde{Y}_{t-1}}\frac{\tilde{g}_t}{\bar{g}}\right)^{\rho_Y}\exp(\sigma_r\varepsilon_{r,t}), \tag{16}$$

$$\text{Log}(A_t) = (1-\rho_a)\text{Log}(A) + \rho_a\text{Log}(A_{t-1}) + \sigma_a\varepsilon_{a,t} \tag{17}$$

$$\tilde{\Pi}_t = \tilde{Y}_t - \tilde{w}_t L_t - \tilde{I}_t - \tilde{S}_t - \frac{\phi_P}{2}\left(\frac{\pi_t}{\pi} - 1\right)^2 Y_t - \Lambda_{\Pi,t} + \frac{b_{t+1}}{R_t} - \frac{b_t}{\pi_t} \tag{18}$$

$$\gamma_{0,t}(1 + \Lambda'_{\Pi,t}) + \gamma_{0,t+1}M_{t,t+1}\Lambda'_{\Pi,t+1} = 1 \tag{19}$$

D.2 More theoretical results

This section provides some extra exercises for the theoretical DSGE model. The details of the model construction and each counterfactual exercises is provided in the paper. Figure 39 compares the impact of a contractionary monetary policy shock under different value for financial constraint.

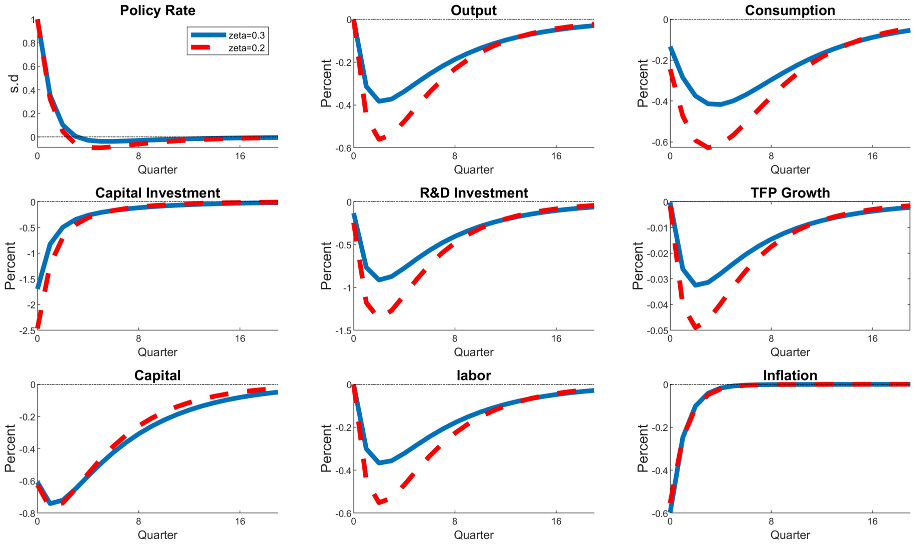


Figure 39: IRFs of a one standard deviation increase in the policy rate (different financial constraint parameters)