FINANCIAL HETEROGENEITY AND THE INVESTMENT CHANNEL OF MONETARY POLICY

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ABSTRACT

We study the role of financial frictions and firm heterogeneity in determining the investment channel of monetary policy. Empirically, we find that firms with low default risk – those with low debt burdens, high credit ratings, and large "distance to default" – are the most responsive to monetary shocks. We interpret these findings using a heterogeneous firm New Keynesian model with default risk. In our model, low-risk firms are more responsive to monetary shocks because their marginal cost of financing investment is relatively flat. The aggregate effect of monetary policy therefore depends on the distribution of default risk, which varies over time.

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1 Introduction

Aggregate investment is one of the most responsive components of GDP to monetary shocks. Our goal in this paper is to understand the role of financial frictions in determining this investment channel of monetary policy. Given the rich heterogeneity in financial positions across firms, a key question is: which firms are the most responsive to changes in monetary policy? The answer to this question is theoretically ambiguous. On the one hand, financial frictions generate an upward-sloping marginal cost curve for investment, which dampens the response of investment to monetary policy for firms that are more severely affected by financial frictions. On the other hand, monetary policy may flatten out this marginal cost curve – for example, by increasing cash flows or improving collateral values – which amplifies the response of investment for affected firms. This latter view is the conventional wisdom of the literature, often informed by applying the financial accelerator logic across firms.

We address the question of which firms respond the most to monetary policy using new cross-sectional evidence and a heterogeneous firm New Keynesian model. Our empirical work combines monetary shocks, measured using the high-frequency event-study approach, with quarterly Compustat data. We find that firms with low default risk – those with low debt burdens, high credit ratings, and large "distance to default" – are significantly and robustly more responsive to monetary policy than other firms in our sample. Motivated by this evidence, our model embeds a heterogeneous firm investment model with default risk into the benchmark New Keynesian environment and studies the effect of a monetary shock. Monetary policy stimulates investment by directly increasing the expected return on capital – which drives the response of low-risk firms – and indirectly increasing cash flows and improving collateral values – which drives the response of high-risk firms. In our calibrated model, as in the data, low-risk firms are more responsive to monetary policy, indicating that the direct effects dominate the indirect ones. These heterogeneous responses imply that the aggregate effect of a given monetary shock is smaller when default risk in the economy is high.

Our baseline empirical specification estimates how the semi-elasticity of a firm's investment with respect to a monetary policy shock depends on three measures of the firm's

financial position: leverage, credit rating, and distance to default (which infers the probability of default from the values of equity and liabilities). We control for firm fixed effects to capture permanent differences across firms and sector-by-quarter fixed effects to capture differences in how sectors respond to aggregate shocks. Conditional on our set of controls, leverage is negatively correlated with credit rating and distance to default, and distance to default is positively correlated with credit rating. Therefore, we view low leverage, high credit rating, and large distance to default as proxies for low default risk.

Our main empirical result is that investment by firms with low default risk is significantly and persistently more responsive to monetary policy shocks. Our estimates imply that, one quarter after a monetary shock, a firm with one standard deviation more leverage than the average firm is about one third less responsive than the average firm and a firm with one standard deviation larger distance to default than the average firm is about two thirds more responsive. In addition, highly rated firms – those with a rating above "A" from Standard & Poor's – are more than two times more responsive than other firms. These differences across firms persist up to three years after the shock and imply large differences in accumulated capital over time.

Although we believe that our interpretation of these heterogeneous responses reflecting default risk is natural, we also provide three pieces of evidence that they are not driven by other firm-level characteristics. First, the results are not driven by permanent heterogeneity in financial positions because they hold using only within-firm variation in financial position. Second, our results are not driven by differences in past sales growth, realized future sales growth, size, age, or liquidity. Third, we show that borrowing costs increase and financing flows fall for high-risk firms following a monetary expansion, consistent with what our model will predict.[1]

In order to interpret these empirical results, we embed a model of heterogeneous firms facing default risk into the benchmark New Keynesian framework. There is a group of heterogeneous firms who invest in capital using either internal funds or external borrowing; these firms can default on their debt, leading to an external finance premium. There is also a

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[1]We also argue that other unobservable factors are unlikely to drive our results because we find similar results if we instrument financial position with past financial position (which is likely more weakly correlated with unobservables)

group of "retailer" firms with sticky prices, generating a New Keynesian Phillips curve linking nominal variables to real outcomes. We calibrate the model to match key features of firms' investment, borrowing, and lifecycle dynamics in the micro data. Our model generates realistic behavior along non-targeted dimensions of the data, such as measured investment-cash flow sensitivities. The peak responses of aggregate investment, output, and consumption to a monetary policy shock are in line the peak responses estimated in the data by Christiano, Eichenbaum and Evans (2005).

In our calibrated model, firms with low default risk are more responsive to monetary policy shocks than firms with high default risk, consistent with the data. These heterogeneous responses depend crucially on how monetary policy shifts the marginal cost of capital. On the one hand, firms with high default risk face a steeper marginal cost curve than other firms, which dampens their response to the shock. On the other hand, the marginal cost curve shifts more strongly for high-risk firms due to changes in cash flows and the recovery value of capital, which amplifies their response. This latter force is dominated by the former force in our calibrated model. We estimate our empirical specification on panel data simulated from our model and find that the coefficient capturing heterogeneous responses in our model is within one standard error of its estimate in the data, both upon impact and over time.

Finally, we show that the aggregate effect of a given monetary shock depends on the distribution of default risk across firms. We perform a simple calculation which exogenously varies the initial distribution of firms in the period of the shock. A monetary shock will generate an approximately 40% smaller change in the aggregate capital stock starting from a distribution with 50% less net worth than the steady state distribution. Under the distribution with low average net worth, more firms have a high risk of default and are therefore less responsive to monetary policy. More generally, this calculation suggests a potentially important source of time-variation in monetary transmission: monetary policy is less powerful when more firms have risk of default.

Related Literature   Our paper primarily contributes to five strands of literature. The first studies the transmission of monetary policy to the aggregate economy. Bernanke, Gertler and Gilchrist (1999) embed the financial accelerator in a representative firm New Keynesian

model and find that it amplifies the aggregate response to monetary policy. We build on Bernanke, Gertler and Gilchrist (1999)'s framework to include firm heterogeneity. Consistent with their results, we find that the response of aggregate investment to monetary policy is larger in our model than in a model without financial frictions at all. However, among the 99.4% of firms affected by financial frictions in our model, those with low risk of default are more responsive to monetary policy than those with high risk of default, creating the potential for state dependence.

Second, we contribute to the literature that studies how the effect of monetary policy varies across firms. A number of papers, including Kashyap, Lamont and Stein (1994), Gertler and Gilchrist (1994), and Kashyap and Stein (1995) argue that smaller and presumably more credit constrained firms are more responsive to monetary policy along a number of dimensions. We contribute to this literature by showing that firms with low default risk are also more responsive to monetary policy. In Appendix A.4, we show that our results are robust to controlling for Gertler and Gilchrist (1994)'s measure of firm size. Recent work by Jeenas (2018) and Cloyne et al. (2018) perform similar empirical exercises to our's and argue that there are differential responses by liquidity and age; Appendix A.4 shows that these firm-level characteristics do not drive our results either.[2,3]

Third, we contribute to the literature which studies how incorporating micro-level heterogeneity into the New Keynesian model affects our understanding of monetary transmission. To date, this literature has focused on how household-level heterogeneity affects the consumption channel of monetary policy; see, for example, Auclert (2017); McKay, Nakamura and Steinsson (2015); Wong (2016); or Kaplan, Moll and Violante (2017). We instead explore the role of firm-level heterogeneity in determining the investment channel of monetary policy. In contrast to the heterogeneous-household literature, we find that both direct and

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[2]In a recent paper, Crouzet and Mehrotra (2017) find some evidence of differences in cyclical sensitivity by firm size during extreme business cycle events. Our work is complementary to their's by focusing on the conditional response to a monetary policy shock and using our economic model to draw aggregate implications.

[3]Ippolito, Ozdagli and Perez-Orive (2017) study how the effect of high-frequency shocks on firm-level outcomes depends on firms' bank debt. In order to merge in data on bank debt, Ippolito, Ozdagli and Perez-Orive (2017) must focus on the 2004-2008 time period. Given this small sample, Ippolito, Ozdagli and Perez-Orive (2017) do not consistently find significant differences in investment responses across firms. In addition, Ippolito, Ozdagli and Perez-Orive (2017) use a different empirical specification and focus on stock prices as the main outcome of interest.

indirect effects of monetary policy play a quantitatively important role in driving the invest-ment channel. The direct effect of changes in the real interest rates are larger for firms than for households because firms are more price-sensitive.

Fourth, we contribute to a growing literature which argues that monetary policy is less effective in recessions. Tenreyro and Thwaites (2016) estimate a nonlinear time-series model and find that monetary policy shocks have a smaller impact on real economic activity in re-cessions than in normal times. Vavra (2013) and McKay and Wieland (2019) provide models in which monetary policy is less powerful in recessions due to changes in the distribution of price adjustment and durable expenditures, respectively. We contribute to this literature by suggesting changes in the distribution of default risk are another reason monetary policy may be less effective in recessions.

Finally, we contribute to the literature studying the role of financial heterogeneity in determining the business cycle dynamics of aggregate investment. Our model of firm-level investment builds heavily on Khan, Senga and Thomas (2016), who study the effect of financial shocks in a flexible price model. We contribute to this literature by introducing sticky prices and studying the effect of monetary policy shocks. In addition, we extend Khan, Senga and Thomas (2016)'s model to include capital quality shocks and a time-varying price of capital in order to generate variation in lenders' recovery value of capital, as in the financial accelerator literature. Khan and Thomas (2013) and Gilchrist, Sim and Zakrajsek (2014) study related flexible-price models of investment with financial frictions. Our model is also related to Arellano, Bai and Kehoe (2016), who study the role of financial heterogeneity in determining employment decisions.

Road Map   Our paper is organized as follows. Section 2 provides the empirical evidence that the firm-level response to monetary policy varies with default risk. Section 3 develops our heterogeneous firm New Keynesian model to interpret this evidence. Section 4 provides a theoretical characterization of the channels through which monetary policy drives investment in our model. Section 5 then calibrates the model and verifies that it is consistent with key features of the joint distribution of investment and leverage in the micro data. Section 6 uses the model to study the monetary transmission mechanism. Section 7 concludes.

2 Empirical Results

We document that firms with low default risk – proxied by low debt burdens, high credit ratings, and high measured "distance to default" – are significantly more responsive to changes in monetary policy than are other firms in the economy.

2.1 Data Description

Our sample combines monetary policy shocks with firm-level outcomes from quarterly Compustat data.

Monetary Policy Shocks We measure monetary shocks using the high-frequency, event-study approach pioneered by Cook and Hahn (1989). Following Gurkaynak, Sack and Swanson (2005) and Gorodnichenko and Weber (2016), we construct our shock $\varepsilon_t^{\mathrm{m}}$ as

$$\varepsilon_t^{\mathrm{m}} = \tau(t) \times (\mathtt{ffr}_{t+\Delta_+} - \mathtt{ffr}_{t-\Delta_-}), \tag{1}$$

where t is the time of the monetary announcement, $\mathtt{ffr}_t$ is the implied Fed Funds Rate from a current-month Federal Funds future contract at time t, Δ_+ and Δ_- control the size of the time window around the announcement, and $\tau(t)$ is an adjustment for the timing of the announcement within the month.[4] We focus on a window of $\Delta_- =$ fifteen minutes before the announcement and $\Delta_+ =$ forty five minutes after the announcement. Our shock series begins in January 1990, when the Fed Funds futures market opened, and ends in December 2007, before the financial crisis.[5] During this time there were 164 shocks with a mean of approximately zero and a standard deviation of 9 basis points.[6]

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[4]This adjustment accounts for the fact that Fed Funds Futures pay out based on the average effective rate over the month. It is defined as $\tau(t) \equiv \frac{\tau_m^n(t)}{\tau_m^n(t) - \tau_m^d(t)}$, where $\tau_m^d(t)$ denotes the day of the meeting in the month and $\tau_m^n(t)$ the number of days in the month.

[5]We stop in December 2007 to study a period of conventional monetary policy, which is the focus of our economic model.

[6]In our economic model, we interpret our measured monetary policy shock as an innovation to a Taylor Rule. An alternative interpretation of the shock, however, is that it is driven by the Fed providing information to the private sector. We argue that the information component of Fed announcements does not drive our results in Appendix A by controlling for Greenbook forecast revisions, as in Miranda-Agrippino and Ricco (2018).

TABLE 1
SUMMARY STATISTICS OF MONETARY POLICY SHOCKS

	high frequency	smoothed	sum
mean	-0.0185	-0.0429	-0.0421
median	0	-0.0127	-0.00509
std	0.0855	0.108	0.124
min	-0.463	-0.480	-0.479
max	0.152	0.233	0.261
num	164	71	72

Notes: Summary statistics of monetary policy shocks. "High frequency" shocks are estimated using event study strategy in (1). "Smoothed" shocks are time aggregated to the quarterly frequency using the weighted average (2). "Sum" refers to time aggregating by simply summing all shocks within a quarter.

We time aggregate the high-frequency shocks to the quarterly frequency in order to merge them with our firm-level data. We construct a moving average of the raw shocks weighted by the number of days in the quarter after the shock occurs.[7] Our time aggregation strategy ensures that we weight shocks by the amount of time firms have had to react to them. Table 1 indicates that these "smoothed" shocks have similar features to the original high-frequency shocks. For robustness, we will also use the alternative time aggregation of simply summing all the shocks that occur within the quarter, as in Wong (2016). Table 1 shows that the moments of these alternative shocks do not significantly differ from the moments of the smoothed shocks, and Appendix A.2.1 shows that our main results are robust to using this alternative form of time aggregation.

Firm-Level Variables We draw firm-level variables from quarterly Compustat, a panel of publicly listed U.S. firms. Compustat satisfies three key requirements for our study: it is quarterly, a high enough frequency to study monetary policy; it is a long panel, allowing us to use within-firm variation; and it contains rich balance-sheet information, allowing us

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[7]Formally, the monetary-policy shock in quarter q is defined as

$$\varepsilon_q^m = \sum_{t \in J(q)} \omega^a(t)\varepsilon_t^m + \sum_{t \in J(q-1)} \omega^b(t)\varepsilon_t^m \tag{2}$$

where $\omega^a(t) \equiv \frac{\tau_q^n(t) - \tau_q^d(t)}{\tau_q^n(t)}$, $\omega^b(t) \equiv \frac{\tau_q^d(t)}{\tau_q^n(t)}$, $\tau_q^d(t)$ denotes the day of the monetary-policy announcement in the quarter, $\tau_q^n(t)$ denotes the number of days in the monetary-policy announcement's quarter, and $J(q)$ denote the set periods t contained in quarter q.

to construct our key variables of interest. To our knowledge, Compustat is the only U.S. dataset that satisfies these three requirements. The main disadvantage of Compustat is that it excludes privately held firms which are likely subject to more severe financial frictions.[8] In Section 5, we calibrate our economic model to match a broad sample of firms, not just those in Compustat.

Our main measure of investment is $\Delta \log k_{jt+1}$, where k_{jt+1} is the book value of the firm's tangible capital stock of firm j at the beginning of period $t + 1$. We use this log-difference specification because investment is highly skewed, suggesting a log-linear rather than level-linear regression specification. We use the net change in log capital rather than the log of gross investment because gross investment often takes negative values.

We use three different measures of a firm's financial position to proxy for default risk. First, we measure leverage ℓ_{jt} as the firm's debt-to-asset ratio, where debt is the sum of short term and long term debt and assets is the book value of assets. Second, we measure the firm's credit rating cr_{jt} using S&P's long-term issue rating of the firm. For most of the paper, we will summarize the firm's credit rating using an indicator variable for whether it is at least an A rating, $\mathbb{1}\{\mathrm{cr}_{jt} \geq A\}$. Third, we measure the firm's "distance to default" dd_{jt} following Gilchrist and Zakrajšek (2012). This measure uses the firm's equity value to infer its asset value; given the value of liabilities and assumptions on firm-level shocks, it then backs out the implied probability of default. Distance to default dd_{jt} has been shown by Schaefer and Strebulaev (2008) to account well for variation in corporate bond prices due to default risk and is widely used in the finance industry.

Appendix A.1 provides details of our data construction, which follows standard practice in the investment literature. Panel (a) of Table 2 presents simple summary statistics of the final sample used in our analysis. The mean capital growth rate is roughly 0.5% quarterly with a standard deviation of 9.3%. The mean leverage ratio is approximately 27% with a cross-sectional standard deviation of 36%. The mean distance to default implies a six standard

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TABLE 2

SUMMARY STATISTICS OF FIRM-LEVEL VARIABLES

(a) Marginal Distributions

Statistic	$\Delta \log k_{jt+1}$	ℓ_{jt}	$\mathbb{1}\{\mathrm{cr}_{jt} \geq A\}$	dd_{jt}
Mean	0.005	0.267	0.024	5.744
Median	-0.004	0.204	0.000	4.704
S.D.	0.093	0.361	0.154	5.032
95th Percentile	0.132	0.725	0.000	14.952

(b) Correlation Matrix (raw variables)

	ℓ_{jt}	$\mathbb{1}\{\mathrm{cr}_{jt} \geq A\}$	dd_{jt}
ℓ_{jt}	1.00		
(p-value)			
$\mathbb{1}\{\mathrm{cr}_{jt} \geq A\}$	-0.02	1.00	
	(0.00)		
dd_{jt}	-0.46	0.21	1.00
	(0.00)	(0.00)	

(c) Correlation matrix (residualized)

	ℓ_{jt}	$\mathbb{1}\{\mathrm{cr}_{jt} \geq A\}$	dd_{jt}
ℓ_{jt}	1.00		
(p-value)			
$\mathbb{1}\{\mathrm{cr}_{jt} \geq A\}$	-0.02	1.00	
	(0.00)		
dd_{jt}	-0.38	0.05	1.00
	(0.00)	(0.00)	

Notes: summary statistics of firm-level outcome variables. $\Delta \log k_{jt+1}$ is the change in the capital stock. ℓ_{jt} is the ratio of total debt to total assets. $\mathbb{1}\{\mathrm{cr}_{jt} \geq A\}$ is an indicator variable for whether the firm's credit rating is above an A. dd_{jt} is the firm's "distance to default," constructed following Gilchrist and Zakrajšek (2012). Panel (a) computes the mean, median, standard deviation, and 95th percentile of each of these variables in our un-winsorized sample. Panel (b) computes the pairwise correlations between the measures of financial position ℓ_{jt}, $\mathbb{1}\{\mathrm{cr}_{jt} \geq A\}$, and dd_{jt}. Panel (c) computes the pairwise correlations of the residuals from the regression

$$x_{jt} = \alpha_j + \alpha_{st} + \mathbf{\Gamma}_1' Z_{jt-1} + e_{jt},$$

where $x_{jt} \in \{\ell_{jt}, \mathbb{1}\{\mathrm{cr}_{jt} \geq A\}, \mathrm{dd}_{jt}\}$, where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, and Z_{jt-1} is a vector of firm-level controls containing sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter.

deviation shock drives the average firm to default, in line with Gilchrist and Zakrajšek (2012). We winsorize our sample at the top and bottom 0.5% of observations of investment, leverage, and distance to default in order to ensure our results are not driven by outliers.

Panel (b) of Table 2 shows the cross-correlation structure of leverage, credit rating, and distance to default. Higher leverage is positively correlated with lower credit ratings and a smaller distance to default, indicating that higher debt burdens are associated with higher default risk. Firms with higher distance to default also have higher credit ratings, consistent with the idea that credit ratings partly proxy for default risk. Panel (c) of Table 2 shows

that these results are all also true conditional on the controls in our baseline regression specification (3) below.

2.2 Heterogeneous Responses to Monetary Policy

We estimate variants of the baseline empirical specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta x_{jt-1}\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt}, \tag{3}$$

where α_j is a firm j fixed effect, α_{st} is a sector s by quarter t fixed effect, $\varepsilon_t^{\mathrm{m}}$ is the monetary policy shock, $x_{jt} \in \{\ell_{jt}, \mathbb{1}\{\mathrm{cr}_{jt} \geq A\}, \mathrm{dd}_{jt}\}$ is the firm's leverage ratio, credit rating, or distance to default, Z_{jt} is a vector of firm-level controls, and e_{jt} is a residual.[9] Our main coefficient of interest is β, which measures how the semi-elasticity of investment $\Delta \log k_{jt+1}$ with respect to monetary shocks $\varepsilon_t^{\mathrm{m}}$ depends on the firm's financial position x_{jt}.[10] This coefficient estimate is conditional on a number of controls that may simultaneously affect investment and leverage, but which are outside the scope of our economic model in Section 3. First, firm fixed effects α_j capture permanent differences in investment behavior across firms. Second, sector-by-quarter fixed effects α_{st} capture differences in how broad sectors are exposed to aggregate shocks. Finally, the firm-level controls Z_{jt} include the level of the financial position variable x_{jt-1}, total assets, sales growth, current assets as a share of total assets, and a fiscal quarter dummy. We cluster standard errors two ways in order to account for correlation within firms and within quarters. This clustering strategy is conservative, effectively leaving 71 time-series observations.

Table 3 reports the results from estimating the baseline specification (3). We perform two normalizations to make the estimated coefficient β easily interpretable. First, we standardize the firm's leverage ℓ_{jt} and distance to default dd_{jt} over the entire sample, so their units are standard deviations relative to their mean value in our sample. Second, we normalize the

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[9]The sectors s we consider are: agriculture, forestry, and fishing; mining; construction; manufacturing; transportation communications, electric, gas, and sanitary services; wholesale trade; retail trade; and services. We do not include finance, insurance, and real estate or public administration.

[10]We lag both financial position x_{jt-1} and the controls Z_{jt-1} to ensure they are predetermined at the time of the monetary shock. Note that both k_{jt+1} and x_{jt} measure end-of-period values. We denote the end-of-period capital stock with k_{jt+1} rather than k_{jt} to be consistent with the standard notation in our economic model in Section 3.

TABLE 3

HETEROGENEOUS RESPONSES TO MONETARY POLICY

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
leverage $\times$ ffr shock	-0.66**	-0.52**			-0.50*	-0.47	-0.24
	(0.27)	(0.25)			(0.25)	(0.39)	(0.38)
$\mathbb{1}\{cr_{jt} \geq A\} \times$ ffr shock			2.69**		2.41**		
			(1.16)		(1.19)		
dd $\times$ ffr shock				1.06**		0.70	1.07**
				(0.45)		(0.44)	(0.52)
ffr shock							1.63**
							(0.72)
Observations	239259	239259	239259	151433	239259	151433	151433
R^2	0.108	0.119	0.116	0.137	0.119	0.139	0.126
Firm controls	no	yes	yes	yes	yes	yes	yes
Time sector FE	yes	yes	yes	yes	yes	yes	no
Time clustering	yes	yes	yes	yes	yes	yes	yes

Notes: results from estimating variants of the baseline specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta x_{jt-1}\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathbb{1}\{cr_{jt} \geq A\}, dd_{jt}\}$ is either the firm's leverage ratio, credit rating, or distance to default, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} and distance to default dd_{jt} over the entire sample, so their units are in standard deviations relative to the mean.

sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive value corresponds to a cut in interest rates.

The first four columns in Table 3 show that firms with lower proxies for default risk – lower leverage, better credit ratings, and higher distance to default – are more responsive to the monetary shocks $\varepsilon_t^{\mathrm{m}}$. Column (1) reports the coefficient on leverage without the firm-level controls Z_{jt-1} and implies that a firm with one standard deviation more leverage than the average firm has approximately a 0.65 units lower semi-elasticity of investment to monetary policy. Adding firm-level controls Z_{jt-1} in Column (2) does not significantly change this point estimate, suggesting our results are not driven by unobserved heterogeneity that is correlated with our controls. Therefore, we focus on specifications with firm-level controls Z_{jt-1} for the remainder of the paper. Column (3) shows that a firm with a credit rating greater than A has a more than 2.5 units greater semi-elasticity. Finally, Column (4) shows that a firm with one standard deviation higher distance to default has an approximately 1

unit higher semi-elasticity.[11]

Columns (5) and (6) in Table 3 show that these conclusions hold conditional on various combinations of financial position, but statistical power falls due to the correlated nature of the variables. Column (5) shows that jointly including leverage and credit rating only slightly changes their interaction coefficients, consistent with their low correlation in Table 2. In contrast, Column (6) shows that the coefficients on both leverage and distance to default become marginally insignificant once we jointly include both include leverage and distance to default, consistent with their strong correlation in Table 2.

A natural way to assess the economic significance of our estimated interaction coefficients β is to compare them to the average effect of a monetary policy shock. However, in our baseline specification (3), the average effect is absorbed by the sector-by-quarter fixed effect α_{st}. We relax this restriction by estimating

$$\Delta \log k_{jt+1} = \alpha_j + \gamma \varepsilon_t^{\mathrm{m}} + \beta x_{jt-1} \varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}'_1 Z_{jt-1} + \mathbf{\Gamma}'_2 Y_{t-1} + \varepsilon_{jt}, \tag{4}$$

where Y_t is a vector of aggregate controls for GDP growth, the inflation rate, and the unemployment rate. Column (7) of Table 3 shows that the average investment semi-elasticity is roughly 1.6.[12] Hence, our interaction coefficients in the previous columns imply an economically meaningful degree of heterogeneity.

Within-Firm Variation In the economic model that we develop in Section 3, firms are ex-ante homogeneous and heterogeneity in default risk is generated ex-post due to lifecycle dynamics and idiosyncratic shocks. However, it is possible that the empirical results presented in Table 3 are instead driven by permanent heterogeneity in how firms respond to monetary policy according to their financial position x_{jt}, breaking the tight link between default risk and shock responsiveness in our model. In order to ensure our results are not driven by

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[11]A simple back of the envelope calculation using these estimates implies that monetary policy may become substantially less effective in recessions. For example, average distance to default fell by 1.65 standard deviations between 2007q2 and 2009q2; according to the estimates in Table 3, this change would decrease the responsiveness of investment by 1.75 (holding all other covariates fixed).

[12]Assuming an annual depreciation rate of $\delta = 0.1$, this estimated coefficient implies that a one percentage point cut in the interest rate increases annualized investment by 16%, in line with the upper end of estimated user-cost elasticities in the literature, for example, Zwick and Mahon (2017).

TABLE 4

HETEROGENEOUS RESPONSES ESTIMATED USING WITHIN-FIRM VARIATION

	(1)	(2)	(3)	(4)	(5)
leverage × ffr shock	-0.81**	-0.68**		-0.33	-0.21
	(0.31)	(0.28)		(0.37)	(0.38)
dd × ffr shock			1.10***	0.89**	1.12**
			(0.39)	(0.38)	(0.47)
ffr shock					1.64**
					(0.77)
Observations	219702	219702	151433	151433	151433
R^2	0.113	0.124	0.137	0.139	0.126
Firm controls	no	yes	yes	yes	yes
Time sector FE	yes	yes	yes	yes	no
Time clustering	yes	yes	yes	yes	yes

Notes: results from estimating

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^m + \beta_2(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + \mathbf{\Gamma}'Z_{jt-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is leverage or distance to default, $\mathbb{E}_j[x_{jt}]$ is the average of x_{jt} for firm j in the sample, ε_t^m is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and quarter. We have normalized the sign of the monetary shock ε_t^m so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized within-firm leverage $(\ell_{jt} - \mathbb{E}[\ell_{jt}])$ and within-firm distance to default $(\mathrm{dd}_{jt} - \mathbb{E}[\mathrm{dd}_{jt}])$ over the entire sample, so their units are in standard deviations relative to the mean.

permanent heterogeneity, we estimate the specification:

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^m + \mathbf{\Gamma}_1'Z_{jt-1} + \mathbf{\Gamma}_2'(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + e_{jt}, \quad (5)$$

where $\mathbb{E}_j[x_{jt}]$ is the average value of financial position x_{jt} of firm j in our sample and Y_{t-1} is lagged GDP growth.[13] Permanent heterogeneity in financial position is differenced out of the interaction $(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^m$ and the heterogeneous responses are identified from temporary variation in financial position within a firm.[14]

Table 4 shows that the heterogeneous responses become stronger when using within-

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[13]Our sample selection focuses on firms with at least forty quarters of data in order to precisely estimate the within-firm mean $\mathbb{E}_j[x_{jt}]$.

[14]We add the interaction of $(x_{jt-1} - \mathbb{E}_j[x_{jt}])$ with lagged GDP growth Y_{t-1} in order to control for differences in cyclical sensitivities across firms. While this control is unimportant for the impact effect of the shock, we show below that there are significant differences in cyclical sensitivities at longer horizons. Not controlling for these interactions does not significantly affect the point estimates of the dynamics but leads to wider standard errors. See Appendix A.3 for details.

firm variation in financial position. We estimate the specification (5) only for leverage ℓ_{jt} and distance to default dd_{jt} because the within-firm variation in credit rating is small. We standardize the demeaned variables $(x_{jt} - \mathbb{E}[x_{jt}])$ so that their units are comparable to the previous specification (3). Column (2) shows that a firm with a one standard deviation within-firm increase in leverage has a 0.68 units lower semi-elasticity, compared to 0.52 in the baseline specification (3). Column (3) shows that a firm with a one standard deviation within-firm increase in distance to default has a 1.1 units higher semi-elasticity, compared to 1.06 in the previous specification. Furthermore, Column (4) shows that controlling for distance to default renders the coefficient on leverage insignificant. This result indicates that the heterogeneous responses within-firm are primarily driven by distance to default, which we view as our most direct measure of default risk.

Dynamics In order to estimate the dynamics of these differential responses across firms, we run the Jorda (2005)-style local projection of specification (5):

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_h(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \boldsymbol{\Gamma}'_{1h}Z_{jt-1} + \boldsymbol{\Gamma}'_{2h}(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + \varepsilon_{jth},$$

(6)

where $h \geq 1$ indexes the forecast horizon. The coefficient β_h measures how the cumulative response of investment in quarter $t + h$ to a monetary policy shock in quarter t depends on the firm's financial position x_{jt} in quarter $t - 1$. We estimate the local projection (6) separately for demeaned leverage ℓ_{jt} and demeaned distance to default dd_{jt}.

Figure 1 shows that firms with low leverage and high distance to default are consistently more responsive to the shock up to three years after the shock. Panel (a) shows that the peak of the differences by leverage occurs after four quarters and the differences disappear after twelve quarters. Panel (b) shows that the differences by distance to default are larger and significantly more persistent than for leverage. However, in both cases the long-run differences are imprecisely estimated with large standard errors. We focus on the impact effect of the shock for the rest of the paper because it is precisely estimated and is robust to a broader set of modeling choices than are the dynamics.

Recent work by Jeenas (2018) performs a similar empirical exercise and argues that low-leverage firms become significantly *less* responsive to monetary policy over time, in con-

FIGURE 1: Dynamics of Differential Response to Monetary Shocks

(a) Leverage

(b) Distance to Default

Notes: dynamics of the interaction coefficient between financial position and monetary shocks and between distance to default and monetary shocks over time. Reports the coefficient β_h over quarters h from

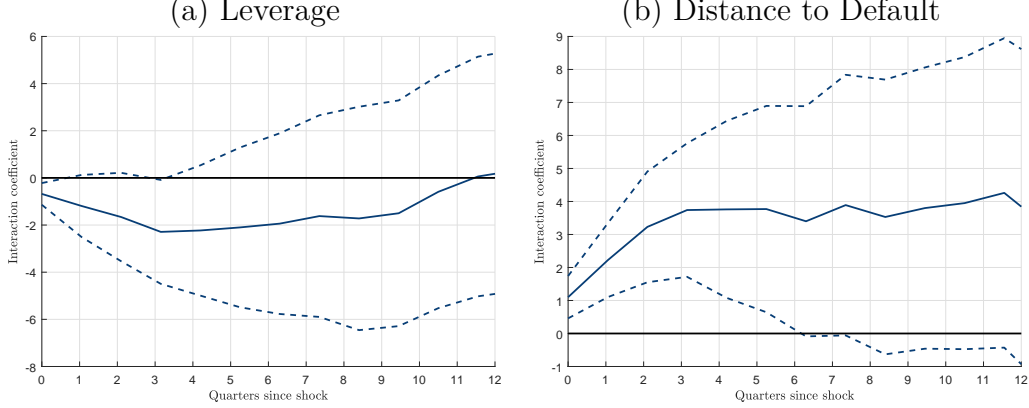$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_h(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_h' Z_{jt-1} + \mathbf{\Gamma}_{2h}'(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + e_{jt},$$

where α_{jh} is a firm fixed effect, α_{sth} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is either the firm's leverage ratio or distance to default, $\mathbb{E}_j[x_{jt}]$ is the average of x_{jt} for firm j in the sample, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter, and Y_{t-1} is GDP growth. Standard errors are two-way clustered by firms and time. Dashed lines report 90% error bands. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized within-firm leverage ($\ell_{jt} - \mathbb{E}[\ell_{jt}]$) and within-firm distance to default ($\mathrm{dd}_{jt} - \mathbb{E}[\mathrm{dd}_{jt}]$) over the entire sample, so their units are in standard deviations relative to the mean.

trast with the insignificant dynamics in Figure 1. Appendix A.4.4 replicates the spirit of his result and argues that the difference between our results is accounted for by permanent heterogeneity in responsiveness across firms. Jeenas (2018) sorts firms based on their average leverage over the past year, which averages over high-frequency variation in leverage and implies that the estimated high-order dynamics are largely driven by permanent heterogeneity. While such permanent heterogeneity in responsiveness is certainly interesting to study, it is outside the scope of the economic model in this paper. Ultimately, we focus most of our analysis on the heterogeneous responses upon impact, which are robustly estimated in both our specification and Jeenas (2018).

Additional Empirical Results Appendix A contains three sets of additional empirical results. The first set of additional results contains a number of robustness checks of our main results. First, we perform robustness checks with respect to our monetary shock, including

but not limited to: controlling for the information channel of monetary policy using Green-book forecast revisions (following Miranda-Agrippino and Ricco (2018)); using raw changes in the Fed Funds rate rather than the shocks; and showing our results hold in the post-1994 sample. Second, we perform robustness checks regarding firm-level heterogeneity, including: controlling for lagged investment; controlling for interactions of the monetary shock with other firm-level covariates such as sales growth, future sales growth, size, or liquidity; and investigating other indices of financial constraints.

The second set of results includes some additional analysis of the data. First, we show that high-risk firms see a relative increase in their borrowing cost and a relative decrease in their financing flows in response to a monetary expansion, consistent with our model. Second, we show that the heterogeneous responses to monetary policy are primarily driven by expansionary shocks. Third, we show that our results hold if we measure leverage using only short term debt, only long term debt, other liabilities, or leverage net of liquid assets.

The third set of additional results relates our work to various strands of the existing literature. First, we show that small firms, measured using Gertler and Gilchrist (1994)'s methodology, are more responsive to monetary shocks in our sample; our results are robust to controlling for this effect. Second, we show that older firms are slightly less responsive to monetary shocks, consistent with recent work by Cloyne et al. (2018); again, our results are robust to controlling for this effect. Third, we reconcile our results with recent work by Jeenas (2018), as discussed above. We also show that our results are not driven by heterogeneity in liquidity across firms; in fact, once we control for distance to default, we find that there are no significant differences by liquidity in our specification (although statistical tests are weak given the two variables are positively correlated).

3 Model

We now develop a heterogeneous firm New Keynesian model in order to interpret the cross-sectional evidence in Section 2 and study aggregate implications. We describe the model in three blocks: an investment block, which captures heterogeneous responses to monetary policy; a New Keynesian block, which generates a Phillips curve; and a representative household,

which closes the model.

3.1 Investment Block

The investment block contains a fixed mass of heterogeneous firms that invest in capital subject to financial frictions. It builds heavily on the flexible-price model developed in Khan, Senga and Thomas (2016). Besides incorporating sticky prices, we extend Khan, Senga and Thomas (2016)'s framework in three additional ways. First, we add idiosyncratic capital quality shocks, which help us match observed default rates in the data. Second, we incorporate aggregate adjustment costs in order to generate time-variation in the relative price of capital, as in the financial accelerator literature (e.g., Bernanke, Gertler and Gilchrist (1999)). Third, we assume that new entrants have lower initial productivity than incumbents, which helps us match lifecycle dynamics.

Production firms Time is discrete and infinite. There is no aggregate uncertainty; in Sections 4 and 6 below, we study the transition path in response to an unexpected monetary shock. Each period, there is a fixed mass 1 of production firms.[15] Each firm $j \in [0, 1]$ produces an undifferentiated good y_{jt} using the production function

$$y_{jt} = z_{jt}(\omega_{jt}k_{jt})^\theta l_{jt}^\nu, \tag{7}$$

where z_{jt} is an idiosyncratic total factor productivity shock, ω_{jt} is an idiosyncratic capital quality shock, k_{jt} is the firm's capital stock, l_{jt} is the firm's labor input, and $\theta + \nu < 1$. The idiosyncratic TFP shock follows an log-AR(1) process

$$\log z_{jt+1} = \rho z_{jt} + \varepsilon_{jt+1}, \text{ where } \varepsilon_{jt+1} \sim N(0, \sigma^2). \tag{8}$$

The capital quality shock is i.i.d. across firms and time and follows a truncated log-normal process with support $[-4\sigma_\omega, 0]$, where σ_ω is the standard deviation of the underlying normal distribution. This process implies that with some probability p_ω, no capital quality shock is realized $\log \omega_{jt} = 0$ and with probability p_ω is drawn from the region of a normal distribution

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[15]We describe the entry and exit process below, which keeps the total mass of firms fixed.

within $[-4\sigma_\omega, 0]$. The capital quality shock also affects the value of the firm's undepreciated capital at the end of the period, $(1-\delta)\omega_{jt}k_{jt}$. We view the capital quality shocks as capturing unmodeled forces which reduce the value of the firm's capital, such as frictions in the resale market, breakdown of machinery, or obsolescence of capital.[16,17]

The timing of events within period is as follows.

(i) Idiosyncratic shocks to TFP and capital quality are realized.

(ii) With probability π_d the firm receives an i.i.d. exit shock and must exit the economy after producing. Firms that do not receive the exit shock will be allowed to continue into the next period.

(iii) The firm decides whether or not to default. If the firm defaults it immediately and permanently exits the economy. In the event of default, lenders recover a fraction of the firm's capital stock (described in more detail below) and the remaining capital is transferred lump-sum to the household. In order to continue, the firm must pay back the face value of its outstanding debt, b_{jt}, and pay a fixed operating cost ξ in units of the final good.

(iv) Continuing firms produce using the production function (7). In order to produce, firms hire labor l_{jt} from a competitive labor market with real wage w_t. Firms sell their output to retailers (described below) in a competitive market at relative price p_t. At this point, firms that received the i.i.d. exit shock sell their undepreciated capital and exit the economy.

(v) Continuing firms purchase new capital k_{jt+1} at relative price q_t. Firms have two sources of investment finance, each of which is subject to a friction. First, firms can issue new nominal debt with real face value $b_{jt+1} = \frac{B_{jt+1}}{\Pi_{t+1}}$, where B_{jt+1} is the nominal face value and Π_{t+1} is realized inflation on the final good (which is our numeraire, described

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[16]Mechanically, the capital quality shocks allow the model to generate positive default risk for a large cross-section of firms. In our model, the value of a firm is dominated by the value of its undepreciated capital stock; without risk to this stock, our model would have the counterfactual prediction that only firms with very low net worth would have positive probability of default.

[17]Note that firms in our model face aggregate capital adjustment costs but not firm-level adjustment costs. We discuss the role of this assumption in determining our results in Footnote 27.

below).[18] Lenders offer a price schedule $\mathcal{Q}_t(z_{jt}, k_{jt+1}, b_{jt+1})$. The price schedule is decreasing in the amount of borrowing b_{jt+1} because firms may default on this borrowing (we derive this price schedule below). Second, firms can use internal finance by lowering dividend payments d_{jt} but cannot issue new equity, which bounds dividend payments $d_{jt} \geq 0$.[19]

We write the firm's optimization problem recursively. The individual state variables of a firm are its total factor productivity z and its net worth

$$n = \max_l p_t z(\omega k)^\theta l^\nu - w_t l + q_t(1 - \delta)\omega k - b - \xi.$$

Net worth n is the total amount of resources available to the firm other than additional borrowing. Conditional on continuing, the real equity value $v_t(z, n)$ solves the Bellman equation[20]

$$v_t(z, n) = \max_{k', b'} n - q_t k' + \mathcal{Q}_t(z, k', b')b' + \mathbb{E}_t \left[\Lambda_{t,t+1} \left(\pi_d \chi^1(n')n' + (1 - \pi_d)\chi^2_{t+1}(z', n')v_{t+1}(z', n') \} \right) \right]$$

$$\text{such that } n - q_t k' + \mathcal{Q}_t(z, k', b')b' \geq 0 \tag{9}$$

$$n' = \max_{l'} p_{t+1} z'(\omega' k')^\theta (l')^\nu - w_{t+1} l' + q_{t+1}(1 - \delta)\omega' k' - \frac{b'}{\Pi_{t+1}} - \xi,$$

where $\chi^1(n)$ and $\chi^2_t(z, n)$ are indicator variables for default conditional on the realization of the exit shock.

Proposition 1. *Consider a firm at time t that is eligible to continue into the next period, has idiosyncratic productivity z, and has net worth n. The firm's optimal decision is characterized*

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[18]Note that all borrowing is short-term in our model; Footnote 26 argues that our main results are likely to be robust to incorporating long-term debt.

[19]The non-negative dividend constraint captures two key facts about external equity documented in the corporate finance literature. First, firms face significant costs of issue new equity, both direct flotation costs (see, for example, Smith (1977)) and indirect costs (for example, Asquith and Mullins (1986)). Second, firms issue external equity very infrequently (DeAngelo, DeAngelo and Stulz (2010)). The specific form of the non-negativity constraint is widely used in the macro literature because it allows for efficient computation of the model in general equilibrium. Other potential assumptions include proportional costs of equity issues (e.g., Gomes, 2001; Cooley and Quadrini, 2001; Hennessy and Whited, 2005; Gilchrist, Sim and Zakrajsek, 2014) and quadratic costs (e.g., Hennessy and Whited, 2007).

[20]Firms which receive the exogenous exit shock have simple decision rules. Those that do not default simply sell their undepreciated capital after production. Since these firms cannot borrow, they default whenever net worth $n < 0$.

by one of the following three cases.

(i) **Default**: *there exists a threshold $\underline{n}_t(z)$ such that the firm defaults if $n < \underline{n}_t(z)$.*

(ii) **Unconstrained**: *there exists a threshold $\overline{n}_t(z)$ such that the firm is **financially unconstrained** if $n > \overline{n}_t(z)$. Unconstrained firms follow the "frictionless" capital accumulation policy $k'_t(z,n) = k^*_t(z)$. Unconstrained firms are indifferent over any combination of b' and d such that they remain unconstrained for every period with probability one.*

(iii) **Constrained**: *firms with $n \in [\underline{n}_t(z), \overline{n}_t(z)]$ are **financially constrained**. Constrained firms' optimal investment $k'_t(z,n)$ and borrowing $b'_t(z,n)$ decisions solve the Bellman equation* (9). *Constrained firms also pay zero dividends, which implies*

$$q_t k' = n + \mathcal{Q}_t(z, k', b')b'.$$

Proof. See Appendix B.1. ■

Proposition 1 characterizes the decision rules which solve this Bellman equation. Firms with low net worth $n < \underline{n}_t(z)$ default because they cannot satisfy the non-negativity constraint on dividends $d \geq 0$. Firms with high net worth $n > \overline{n}_t(z)$ are *financially unconstrained* in the sense that they have no probability of default, which implies that any combination of external financing b' and internal financing d which leaves them unconstrained is optimal. Finally, firms with net worth $n \in [\underline{n}_t(z), \overline{n}_t(z)]$ are *financially constrained* in the sense that they affected by default risk. These firms set $d = 0$ because the value of resources inside the firm, used to lower borrowing costs, is higher than the value of resources outside the firm. Over 99.4% of firms in our calibrated steady state are affected by default risk in this way. Below, we focus our analysis on how these firms respond to monetary policy, since the analysis of the unconstrained firms is fairly standard. It is important to note that these constrained firms can be either *risky constrained* – have a positive probability of default in the next period – or *risk-free constrained* – have no probability of default in the next period yet not be financially unconstrained.

Lenders   There is a representative financial intermediary that lends resources from the representative household to firms at the firm-specific price schedule $\mathcal{Q}_t(z, k', b')$. If the firm defaults on the loan in the following period, the lender recovers a fraction α of the market value of the firm's capital stock $q_{t+1}\omega'k'$. The price schedule prices this default risk competitively:

$$\mathcal{Q}_t(z, k', b') = \mathbb{E}_t \left[\Lambda_{t+1} \left(\frac{1}{\Pi_{t+1}} - \left(\pi_d \chi^1(n') + (1 - \pi_d)\chi^2_{t+1}(z', n') \right) \left(\frac{1}{\Pi_{t+1}} - \min\{ \frac{\alpha q_{t+1}(1 - \delta)\omega'k'}{b'/\Pi_{t+1}}, 1\} \right) \right) \right],$$
(10)

where $n' = \max_{l'} p_{t+1} z(\omega'k')^\theta (l')^\nu - w_t l' + q_{t+1}(1 - \delta)\omega'k' - b' - \xi$ is the net worth implied by k', b', and the realization of z'. The debt price schedule does not depend on the capital quality shock ω_{jt} since capital quality is i.i.d.

Entry   Each period, a mass $\overline{\mu}_t$ of new firms enter the economy. We assume that the mass of new entrants is equal to the mass of firms that exit the economy so that the total mass of production firms is fixed in each period t. Each of these new entrants $j \in [0, \overline{\mu}_t]$ draws a idiosyncratic productivity z_{jt} from the time-invariant distribution

$$\mu^{\mathrm{ent}}(z) \sim \log N \left(-m \frac{\sigma}{\sqrt{(1 - \rho^2)}}, \frac{\sigma}{\sqrt{(1 - \rho^2)}} \right),$$

where $m \geq 0$ is a parameter. We calibrate m to match the average size and growth rates of new entrants, motivated by the evidence in Foster, Haltiwanger and Syverson (2016) that young firms have persistently low levels of measured productivity.[21] New entrants also draw capital quality from its ergodic distribution, are endowed with k_0 units of capital from the household, and have zero units of debt. They then proceed as incumbent firms.

3.2   New Keynesian Block

The New Keynesian block of the model is designed to parsimoniously generate a New Keynesian Phillips curve relating nominal variables to the real economy. Following Bernanke,

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[21]Foster, Haltiwanger and Syverson (2016) argue that these low levels of measured productivity among young firms demand across firms rather than physical productivity. We remain agnostic about the interpretation of TFP in our model. Without the assumption that entrants have lower average productivity than existing firms, default risk would be disproportionately concentrated in a small group of young firms.

[Gertler and Gilchrist](#) (1999), we keep the nominal rigidities separate from the investment block of the model.

Retailers and Final Good Producer   There is a fixed mass of retailers $i \in [0, 1]$. Each retailer producers a differentiated variety $\widetilde{y}_{it}$ using the heterogeneous production firms' good as its only input:

$$\widetilde{y}_{it} = y_{it},$$

where y_{it} is the amount of the undifferentiated good demanded by retailer i. Retailers set a relative price for their variety $\widetilde{p}_{it}$ but must pay a quadratic price adjustment cost $\frac{\varphi}{2} \left(\frac{\widetilde{p}_{it}}{\widetilde{p}_{it-1}} - 1 \right)^2 Y_t$, where Y_t is the final good. The retailers' demand curve is generated by the representative final good producer, who has production function

$$Y_t = \left(\int \widetilde{y}_{it}^{\frac{\gamma-1}{\gamma}} \, \mathrm{d}i \right)^{\frac{\gamma}{\gamma-1}},$$

where γ is the elasticity of substitution over intermediate goods. The final good is the numeraire.

The retailers and final good producers aggregate into the familiar New Keynesian Phillips Curve:

$$\log \Pi_t = \frac{\gamma - 1}{\varphi} \log \frac{p_t}{p^*} + \beta \mathbb{E}_t \log \Pi_{t+1}, \tag{11}$$

where Π_t is gross inflation of the final good and $p^* = \frac{\gamma-1}{\gamma}$ is the steady state relative price of the heterogeneous production firm output.[22] The Phillips Curve links the New Keynesian block to the investment block through the relative price p_t. When aggregate demand for the final good Y_t increases, retailers must increase production of their differentiated goods because of the nominal rigidities; this force increases demand for the heterogeneous firms' good y_{it}, which increases its relative price p_t and generates inflation through the Phillips Curve (11).

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[22]We focus directly on the linearized formulation for computational simplicity.

Capital Good Producer There is a representative capital good producer who produces aggregate capital K_{t+1} using the technology

$$K_{t+1} = \Phi(\frac{I_t}{K_t})K_t + (1-\delta)K_t, \tag{12}$$

where $\Phi(\frac{I_t}{K_t}) = \frac{\delta^{1/\phi}}{1-1/\phi}\left(\frac{I_t}{K_t}\right)^{1-1/\phi} - \frac{\delta}{\phi-1}$ and I_t are units of the final good used to produce capital.[23] Profit maximization pins down the relative price of capital as

$$q_t = \frac{1}{\Phi'(\frac{I_t}{K_t})} = \left(\frac{I_t/K_t}{\delta}\right)^{1/\phi}. \tag{13}$$

Monetary Authority The monetary authority sets the nominal risk-free interest rate R_t^{nom} according to the Taylor rule

$$\log R_t^{\mathrm{nom}} = \log\frac{1}{\beta} + \varphi_\pi \log \Pi_t + \varepsilon_t^{\mathrm{m}}, \text{ where } \varepsilon_t^m \sim N(0,\sigma_m^2),$$

where φ_π is the weight on inflation in the reaction function, and $\varepsilon_t^{\mathrm{m}}$ is the monetary policy shock.

3.3 Representative Household and Equilibrium

There is a representative household with preferences over consumption C_t and labor supply L_t represented by the expected utility function

$$\mathbb{E}_0 \sum_t^\infty \beta^t \left(\log C_t - \Psi L_t\right),$$

where β is the discount factor and Ψ controls the disutility of labor supply. The household owns all firms in the economy. The stochastic discount factor and nominal interest rate are linked through the Euler equation for bonds, $\Lambda_{t+1} = \frac{1}{R_t^{\mathrm{nom}}/\Pi_{t+1}}$.

An equilibrium involves a set of value functions $v_t(z,n)$; decision rules $k_t'(z,n)$, $b_t'(z,n)$,

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[23]We use external adjustment costs rather than internal adjustment costs for two reasons. First, external adjustment costs generate time-variation in the price of capital, which allows us to study changes in the recovery value of capital. Second, because capital is liquid at the firm level, we can reduce the number of individual state variables, which is useful in the computation of the model.

$l_t(z,n)$; measure of firms $\mu_t(z,\omega,k,b)$; debt price schedule $\mathcal{Q}_t(z,k',b')$; and prices w_t, q_t, p_t, Π_t, $\Lambda_{t,t+1}$ such that (i) all firms optimize, (ii) lenders price default risk competitively, (iii) the household optimizes, (iii) the distribution of firms is consistent with decision rules, and (iv) all markets clear. Appendix B.2 precisely defines an equilibrium of our model.

4 Channels of Monetary Transmission

Before performing the quantitative analysis, we theoretically characterize the channels through which monetary policy affects investment in our model. This exercise identifies the key sources of heterogeneous responses across firms, which motivates our calibration in Section 5.

Monetary policy experiment We study the effect an unexpected innovation to the Taylor rule $\varepsilon_t^{\mathrm{m}}$ followed by a perfect foresight transition back to steady state. This approach allows for clean analytical results because there is no distinction between ex-ante expected real interest rates and ex-post realized real interest rates. We focus on financially constrained firms as defined in Proposition 1, which make up more than 99.4% of the firms in our calibration.

Impact on decision rules The optimal choice of investment k' and borrowing b' satisfy the following two conditions:

$$q_t k' = n + \frac{1}{R_t(z,k',b')}b' \tag{14}$$

$$
\left(q_t - \varepsilon_{R,k'}(z,k',b')\frac{b'}{k'} \right) \frac{R_t^{\mathrm{sp}}(z,k',b')}{1 - \varepsilon_{R,b'}(z,k',b')} = \frac{1}{R_t}\mathbb{E}_t\left[\mathrm{MRPK}_{t+1}(z',k')\right] \tag{15}
$$
$$
+ \frac{1}{R_t}\frac{\mathbb{C}ov_t(\mathrm{MRPK}_{t+1}(z',\omega'k'), 1 + \lambda_{t+1}(z',\omega'k',b'))}{\mathbb{E}_t[1 + \lambda_{t+1}(z',\omega'k',b')]}
$$
$$
+ \frac{1}{R_t}\mathbb{E}_{\omega'}\left[v_t^0(\underline{z}_{t+1}(\omega'k',b'))g(\underline{z}(\omega'k',b'))\left(\frac{\partial\underline{z}_{t+1}(\omega'k',b')}{\partial k'} - \frac{\partial\underline{z}_{t+1}(\omega'k',b')}{\partial b'} \right) \right],
$$

where R_t is the risk-free rate between t and $t+1$, $R_t(z,k',b') = \frac{1}{\mathcal{Q}_t(z,k',b')}$ is the firm's implied interest rate schedule, $\varepsilon_{Rk'}(z,k',b')$ is the elasticity of the interest rate schedule

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with respect to investment k', $R_t^{\mathrm{sp}}(z, k', b') = R_t(z, k', b')/R_t$ is a measure of the borrowing spread, $\varepsilon_{Rb'}(z, k', b')$ is the elasticity of the debt price schedule with respect to borrowing, $\mathrm{MRPK}_{t+1}(z, k') = \mathbb{E}_{\omega'}[\frac{\partial}{\partial k'}(\max_{l'} p_{t+1} z'(\omega' k')^{\theta}(l')^{\nu} - w_{t+1}l' + q_{t+1}(1 - \delta)\omega' k')]$ is the return on capital to the firm, $\lambda_t(z, \omega k, b)$ is the Lagrange multiplier on the non-negativity constraint on dividends, (reflecting the shadow value of funds inside the firm relative to funds outside the firm) and $\underline{z}_t(\omega k, b)$ is the default threshold in terms of productivity (which inverts the net worth threshold defined in Proposition 1). Condition (14) is the non-negativity constraint on dividends, which implies that capital expenditures $q_t k'$ must be financed either by internal resources n or new borrowing $\frac{1}{R_t(z, k', b')} b'$. Condition (15) is the intertemporal Euler equation, which equates the marginal cost of new capital k' on the left-hand side with the marginal benefit on on the right-hand side. The expectation and covariances in this expression are only taken over the states in which the firm does not default.

The marginal cost of capital is the product of two terms. The first term, $q_t - \varepsilon_{R,k'}(z, k', b')\frac{b'}{k'}$, is the relative price of new investment q_t net of the interest savings due to higher capital, $\varepsilon_{R,k'}(z, k', b')\frac{b'}{k'}$. The interest savings result from the fact that, all else equal, higher capital decreases expected losses due to default to the lenders. The second term in the marginal cost of capital is related to borrowing costs, $\frac{R_t^{\mathrm{sp}}(z, k', b')}{1 - \varepsilon_{R,b'}(z, k', b')}$. Borrowing costs enter the marginal cost of capital because borrowing is the marginal source of investment finance for these constrained firms. A higher interest rate spread or a higher slope of that spread result in higher borrowing costs.

The marginal benefit of capital is the sum of three terms. The first term, $\frac{1}{R_t}\mathbb{E}_t[\mathrm{MRPK}_{t+1}(z', k')]$, is the expected return on capital discounted by the real interest rate.[24] The second term, $\frac{1}{R_t}\frac{\mathbb{C}ov_t(\mathrm{MRPK}_{t+1}(z', \omega' k'), 1 + \lambda_{t+1}(z', \omega' k', b'))}{\mathbb{E}_t[1 + \lambda_{t+1}(z', \omega' k', b')]}$, captures the covariance of the return on capital with the firm's shadow value of resources; capital is more valuable to the firm if it pays a high return when the firm values additional resources. The third term captures how the additional investment affects the firm's default probabilities and, therefore, the value of the firm. In our calibration, this term is negligible because the value of the firm close to the default threshold, $v_t^0(\underline{z}_{t+1}(\omega' k', b'))$, is essentially zero.

Figure 2 plots the marginal benefit and marginal cost schedules as a function of capital

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[24]Firms discount using the risk-free rate because there is no aggregate risk.

FIGURE 2: Response to Monetary Policy for Risk-Free and Risky Firms

(a) Risk-Free Firm

(b) Risky Firm
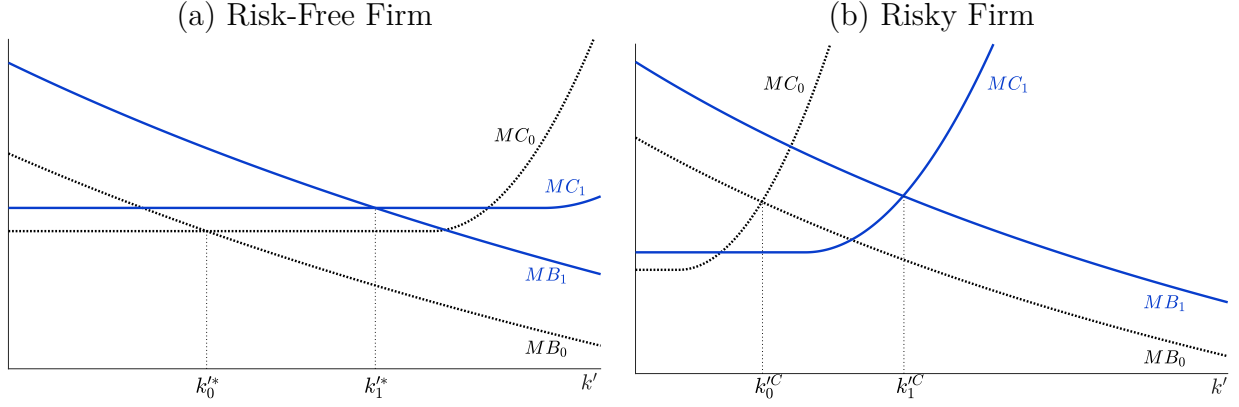
Notes: Marginal benefit and cost curves as a function of capital investment k' for firms with same productivity. Left panel is for a firm with high initial net worth and right panel is for a firm with low initial net worth. Marginal cost curve is the left-hand side of (15) and marginal benefit left-hand side of (15). Dashed black lines plot the curves before the expansionary monetary policy shock, and solid blue lines plot the curves after the shock.

accumulation k'. In order to illustrate the key economic mechanisms, we compare how these curves shift following an expansionary monetary policy shock for two polar examples of firms. These firms share the same level of productivity but differ in their initial net worth; the first firm has high net worth and is currently risk-free (though it is still constrained in the sense of Proposition 1), while the second has low net worth and is risky constrained.

Risk-Free Firm The left panel of Figure 2 plots the two schedules for the risk-free firm. The marginal cost curve is flat when capital accumulation k' can be financed without incurring default risk, but becomes upward sloping when the required creates default risk and therefore a credit spread. The marginal benefit curve is downward sloping due to diminishing returns of capital. In the initial equilibrium, the firm is risk-free because the two curves intersect in the flat region of the marginal cost curve.

The expansionary monetary shock shifts both the marginal benefit and marginal cost curves. The marginal benefit curves shifts out for two reasons. First, the shock decreases the real interest rate, which decreases the firm's discount rate R_t and therefore increases the discounted return on capital. Second, the shock also changes the relative price of output p_{t+1}, the real wage w_{t+1}, and the relative price of undepreciated capital q_{t+1} due to general

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equilibrium. In our calibration, these changes increase the return on capital $\mathrm{MRPK}_{t+1}(z, k')$ and therefore further shift out the marginal benefit curve. The shock also affects the covariance term and the change in default threshold, which further shift out the marginal benefit curve.

The marginal cost curve shifts up because the increase in aggregate investment demand increases the relative price of capital q_t. In the new equilibrium, the firm has increased its investment and remains risk-free because the marginal benefit and marginal cost curves still intersect along the flat region of marginal cost.

Risky Firm　The right panel of Figure 2 plot how the marginal benefit and marginal cost schedules shift for the risky firm. Because this firm has low initial net worth n, it needs to borrow more than the risk-free firm to achieve the same level of investment. Hence, its marginal cost curve is upward-sloping over a larger region of the state space.

The key difference between the risky and the risk-free firm is how monetary policy shifts the marginal cost curve. As for the risk-free firm, the curve shifts up because the relative price of capital q_t increases, but there are now two additional effects. First, monetary policy increases net worth n, which decreases the amount the firm needs to borrow to finance any level of investment and therefore extends the flat region of the marginal cost curve. The increase in net worth can be decomposed according to:

$$\frac{\partial \log n}{\partial \varepsilon_t^{\mathrm{m}}} = \frac{1}{1 - \nu - \theta} \left(\frac{\partial \log p_t}{\partial \varepsilon_t^{\mathrm{m}}} - \nu \frac{\partial \log w_t}{\partial \varepsilon_t^{\mathrm{m}}} \right) \frac{\iota_t(z, \omega k)}{n} + \frac{\partial \log q_t}{\partial \varepsilon_t^{\mathrm{m}}} \frac{q_t(1 - \delta)\omega k}{n} + \frac{\partial \log \Pi_t}{\partial \varepsilon_t^{\mathrm{m}}} \frac{b/\Pi_t}{n},$$

(16)

where $\iota_t(z, \omega k) = \max_l p_t z(\omega k)^\theta l^\nu - w_t l$. This expression (16) contains three ways that monetary policy affects cash flows. First, monetary policy affects current revenues by changing the relative price of output p_t net of real labor costs νw_t. Second, monetary policy affects the value of firms' undepreciated capital stock by changing the relative price of capital q_t. Finally, monetary policy changes the real value of outstanding nominal debt through inflation Π_t.

The second key difference in how monetary policy affects the risky firm's marginal cost curve is that it flattens the upward-sloping region, reflecting reduced credit spreads. Credit

spreads fall because the expansionary shock decreases the expected losses from default to the lender. Recall that, in the event of default, lenders recover $\alpha q_{t+1} \omega_{jt+1} k_{jt+1}$ per unit of debt; since the shock increases the relative price of capital q_{t+1}, it also increases the recovery rate. This channel is reminiscent of the "financial accelerator" in Bernanke, Gertler and Gilchrist (1999). In addition, monetary policy also decreases the probability of default, although this effect is quantitatively small in our calibration.

Whether the risky firm is more or less responsive than the risk-free firm depends crucially on the size of these two shifts in the marginal cost curve. Theoretically, they may or may not be large enough to induce the risky firm to be more responsive to monetary policy than the risk-free firm. The goal of our calibration is to quantitatively discipline these shifts using our model.[25,26,27]

Relationship to other papers The simple framework in Figure 2 provides a powerful tool to organize various results in the existing literature.

(i) For example, Bernanke, Gertler and Gilchrist (1999) develop a model in which firms' production functions are constant returns to scale, which results in a horizontal marginal benefit curve for investment. The level of investment is determined by the point at which this curve intersects the upward-sloping region of the marginal cost curve. Therefore, monetary transmission is determined by how much the marginal cost curve re-

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[25]Appendix A.3.2 shows that the heterogeneous responses to monetary policy we find in the data are primarily driven by expansionary shocks. While we do not emphasize that result in our model analysis due to its wide standard errors, it is potentially consistent with the analysis in Figure 2. Suppose that high-risk firms tend to position themselves at the point where their marginal cost curve just begins to be upward sloping. Then an expansionary shock will move these firms forward along the upward-sloping part – dampening their response relative to low-risk firms – while a contractionary shock will move them backward along the flat part – not dampening their response.

[26]This analysis also suggests that our results are robust to incorporating long-term debt. In our model, high-risk firms are less responsive to monetary policy because they face an upward-sloping marginal cost curve for investment. This upward slope reflects the fact that the probability of default is increasing in the amount of borrowing the firm does. If we were to increase the maturity of debt but hold all other parameter values fixed, then we would of course decrease default probabilities (since firms will have to roll over less debt each period) and potentially flatten out the marginal cost curve. However, we would also need to recalibrate the parameters in order to match the same average probability of default as in the current model. We expect that this recalibration would also imply a similar slope of the default probabilities with respect to borrowing and, therefore, a similar slope for the marginal cost curve.

[27]This analysis can be extended to incorporate convex firm-level adjustment costs. These costs would induce an upward-sloping marginal cost curve uniformly across firms, but risky firms would still face a steeper marginal cost curve due to their higher borrowing costs.

sponds to a monetary shock, which is primarily shifted due to the "financial accelerator" channel described above.

(ii) Jeenas (2018) develops a model in which firms face a fixed cost of issuing debt but can accumulate liquid financial assets. In response to a monetary shock, many firms do not find it worthwhile to issue new debt, so their marginal source of investment finance is liquid assets. This model implies a kinked marginal cost curve, which is flat over the region that firms use their liquid assets but then vertical when the firm would need to issue debt. Firms that have more liquid assets have a larger flat region of their marginal cost curve and are therefore more responsive to monetary policy.

(iii) Cloyne et al. (2018) argue that young firms are more responsive to monetary shocks in the U.S. and the U.K. While we show in Appendix A.4.2 that age does not drive our empirical results, one can nevertheless interpret their findings through the lens of our model. One possible interpretation is that young firms face a steeper marginal cost curve than old firms, but young firms' marginal cost curve is also more sensitive to monetary policy. Another interpretation is that the young firms' marginal benefit curve is itself more responsive to monetary policy, for example if their product demand is more cyclically sensitive.

5 Parameterization

We now calibrate the model and verify that its steady state behavior is consistent with key features of the micro data. In Section 6, we use the calibrated model to quantitatively study the effect of a monetary policy shock $\varepsilon_t^{\mathrm{m}}$.

5.1 Calibration

We calibrate the model in two steps. First, we exogenously fix a subset of parameters. Second, we choose the remaining parameters in order to match moments in the data.

TABLE 5
FIXED PARAMETERS

Parameter	Description	Value
Household		
β	Discount factor	0.99
Firms		
ν	Labor coefficient	0.64
θ	Capital coefficient	0.21
δ	Depreciation	0.025
New Keynesian Block		
ϕ	Aggregate capital AC	4
γ	Demand elasticity	10
φ_π	Taylor rule coefficient	1.25
φ	Price adjustment cost	90

Notes: Parameters exogenously fixed in the calibration.

Fixed Parameters   Table 5 lists the parameters that we fix. The model period is one quarter, so we set the discount factor $\beta = 0.99$. We set the coefficient on labor $\nu = 0.64$. We choose the coefficient on capital $\theta = 0.21$ to imply a total returns to scale of 85%. Capital depreciates at rate $\delta = 0.025$ quarterly. We choose the elasticity of substitution in final goods production $\gamma = 10$, implying a steady state markup of 11%. This choice implies that the steady state labor share is $\frac{\gamma-1}{\gamma}\nu \approx 58\%$, close to the current U.S. labor share reported in Karabarbounis and Neiman (2013). We choose the coefficient on inflation in the Taylor rule $\varphi_\pi = 1.25$, in the middle of the range commonly considered in the literature. We set the price adjustment cost parameter $\varphi = 90$ to generate the slope of the Phillips Curve equal to 0.1, as in Kaplan, Moll and Violante (2017). Finally, we set the curvature of the aggregate adjustment costs $\varphi = 2.5$ in order to roughly match the peak response of investment relative to the peak response of output estimated in Christiano, Eichenbaum and Evans (2005).

Fitted Parameters   We choose the parameters listed in Table 6 to match the empirical moments reported in Table 7.[28] The first set of parameters govern the idiosyncratic shocks: ρ and σ control the AR(1) process for TFP and σ_ω controls the i.i.d. process for capital quality.

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[28]We exogenously fix the persistence of productivity shocks to $\rho = 0.9$ due to Clementi and Palazzo (2015)'s result that the persistence and volatility of an AR(1) is hard to separately identify from investment data.

TABLE 6
FITTED PARAMETERS

Parameter	Description	Value
Idiosyncratic shock processes		
ρ	Persistence of TFP (fixed)	0.90
σ	SD of innovations to TFP	0.03
σ_ω	SD of capital quality	0.035
Financial frictions		
ξ	Operating cost	0.03
α	Loan recovery rate	0.45
Firm lifecycle		
m	Mean shift of entrants' prod.	3.00
k_0	Initial capital	0.22
π_d	Exogenous exit rate	0.02

Notes: Parameters chosen to match the moments in Table 7.

The second set of parameters govern the frictions to external finance: the fixed operating cost ξ controls how often firms default and the recovery rate α controls the credit spread conditional on default. The final set of parameters govern the firm lifecycle: the m controls the productivity distribution of new entrants, k_0 controls the initial capital stock of new entrants, and π_d is the probability of receiving an exogenous exit shock.

We target four key sets of statistics in our calibration.[29] Importantly, none of these statistics is drawn from Compustat; later on, when we compare our model to the empirical results from Section 2, we will explicitly mirror the selection of firms into Compustat.

First, we target the dispersion of plant-level investment rates in Census micro data reported by Cooper and Haltiwanger (2006).[30] The dispersion of investment rates places discipline on the degree of idiosyncratic risk faced by firms. Cooper and Haltiwanger (2006)'s sample is a balanced panel of plants that have survived at least sixteen years; to mirror this sample selection in the model, we condition on firms that have survived for twenty years, and our calibration results are robust to different choices of this cutoff.

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[29]At each step of this moment-matching process, we choose the disutility of labor supply Ψ to generate a steady state employment rate of 60%.

[30]An issue with this empirical target is that production units in our model correspond more closely to firms than to plants. We prefer to use the plant-level data from Cooper and Haltiwanger (2006) because it carefully constructs measures of retirement and sales of capital to measure negative investment, which is important in our model because capital is liquid.

TABLE 7
CALIBRATION TARGETS AND MODEL FIT

Moment	Description	Data	Model
Investment behavior (annual)			
$\sigma\left(\frac{i}{k}\right)$	SD investment rate	33.7%	35.2%
Financial behavior (annual)			
$\mathbb{E}\left[\text{default rate}\right]$	Mean default rate	3.00%	3.05%
$\mathbb{E}\left[\text{credit spread}\right]$	Mean credit spread	2.35%	0.70%
$\mathbb{E}\left[\frac{b}{k}\right]$	Mean gross leverage ratio	34.4%	41.3%
Firm Growth (annual)			
N_1/N	Share of employment in age ≤ 1	2.6%	2.8%
N_{1-10}/N	Share of employment in age $\in (1,10)$	21%	36%
N_{11+}/N	Share of employment in age ≥ 10	76%	61%
Firm Exit (annual)			
$\mathbb{E}\left[\text{exit rate}\right]$	Mean exit rate	8.7%	8.92%
M_1/M	Share of firms at age 1	10.5%	7.8%
M_2/M	Share of firms at age 2	8.1%	6.0%

Notes: Empirical moments targeted in the calibration. Investment behavior drawn from the distribution of plant-level investment rates in Census microdata, 1972-1988, reported in Cooper and Haltiwanger (2006). These investment moments are drawn from a balanced panel; we mirror this sample selection in the model by computing investment moments for firms who have survived at least twenty years. The mean default rate is from Dun and Bradstreet survey, as reported by Bernanke, Gertler and Gilchrist (1999). The average firm-level gross leverage ratio is taken from the micro data underlying the Quarterly Financial Reports, and is reported in Crouzet and Mehrotra (2017). The average credit spread is measured as the yield on BAA rated corporate bonds relative to a ten-year Treasury bond. The mean exit rate, share of employment by age groups, and share of firms by age groups are from the Business Dynamics Statistics (BDS).

The second set of moments we target are related to firms' use of external finance. Following Bernanke, Gertler and Gilchrist (1999), we target a mean default rate of 3% as estimated in a survey of businesses by Dun and Bradstreet. We target an average annual credit spread implied by BAA rated corporate bond yields to the ten-year Treasury yield.[31] We target the average firm-level gross leverage ratio of 34.4% from the microdata underlying the Quarterly Financial Reports, as reported in Crouzet and Mehrotra (2017).

The final two sets of moments are informative about firm lifecycle dynamics. We target the share of employment in firms of age less than one year, between one and ten years,

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[31]We target credit spreads because the debt price schedule is central to the economic mechanisms in our model. To the extent that observed credit spreads are driven by risk premia rather than risk-neutral pricing of default risk, we may overstate the importance of default risk in our calibration. Consistent with this idea, our calibrated model does not succeed in matching the overall level of spreads.

and over ten years. The share of employment in one year old firms is informative about the relative size of new entrants, and the share of employment in other age groups are informative about how quickly young firms grow. We also target the average exit rate and the share of firms in the economy at age one and two. The difference in shares of age one and two firms is informative about the exit rate of young firms. All of these statistics are computed from the Business Dynamics Statistics (BDS), the public-release sample of statistics aggregated from the Census' Longitudinal Business Database (LBD).

Table 7 shows that our model matches the targeted moments reasonably well. The model closely matches the dispersion of investment rates, which captures the degree of idiosyncratic risk faced by firms. The model also matches the average default rate and average gross leverage, but under predicts the average credit spread, consistent with the idea that empirical spreads also reflect unmodeled risk premia. Our model matches the share of employment in young firms, but somewhat over predicts the share of employment in 1-10 year old firms. We show below that our model matches standard statistics describing the firm lifecycle fairly well. In our calibration, 53.5% of firms are risky constrained, 45.8% of firms are risk-free constrained, and 0.6% of firms are unconstrained.

The calibrated parameters in Table 6 are broadly comparable to existing estimates in the literature. Idiosyncratic TFP shocks are less persistent and more volatile than aggregate productivity shocks, consistent with direct measurements of plant- or firm-level productivity. The calibrated loan recovery rate is 45%, as in Khan, Senga and Thomas (2016). New entrants start with significantly lower productivity and capital than the average firm. The capital quality shock process implies that there is a $p_\omega = 0.59$ probability of receiving a zero shock $\log \omega_{jt} = 0$.

Appendix B.3 contains a formal discussion of identification using the local elasticities of moments with respect to parameters as well as the elasticities of estimated parameters with respect to moments (computed using the tools from Andrews, Gentzkow and Shapiro (2017)).

FIGURE 3: Firm Lifecycle Dynamics, Model vs. Data

(a) Distribution of firm growth rates
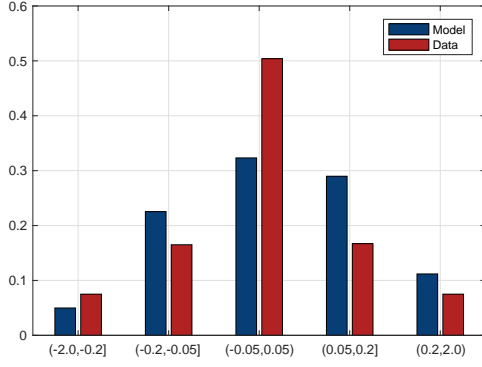
(b) Age-growth profile
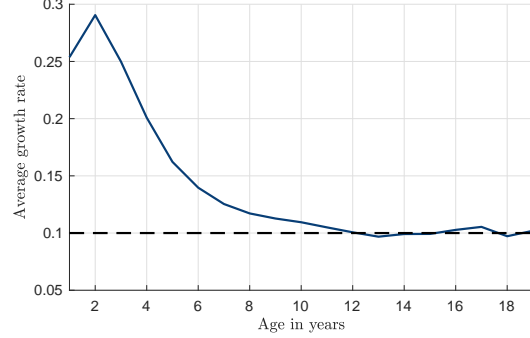
Notes: Panel (a) plots a histogram of the distribution of quarterly growth rates in the model vs. the data. In the model, we measure the firm's growth rate as $\frac{n_{jt+1}-n_{jt}}{0.5(n_{jt+1}+n_{jt})}$. "Data" is the empirical distribution of quarterly establishment growth rates in the Business Employment Dynamics (BED) data, reported in Davis et al. (2010). Panel (b) plots the average firm-level growth rate as a function of age in steady state. We add 0.1 to the model's growth profile to account for the fact that our model does not feature trend growth. We exclude the first year of growth since firms in our model are born significantly below optimal scale; Appendix B.3 shows the growth rate in year 1 is nearly 1.

5.2 Financial Heterogeneity in the Model and the Data

Appendix B.3 analyzes firms' decision rules in steady state and identifies two key sources of financial heterogeneity across firms. The first source is lifecycle dynamics; firms are born below their optimal scale, i.e. $k_0 < k^*(z)$, and need to grow their capital stock. These young firms initially borrow in order to accumulate capital, increasing their risk of default and therefore borrowing costs. The second source of financial heterogeneity is TFP shocks z; a positive shock increases the firm's optimal scale $k^*(z)$, which again induces debt-financed capital accumulation. We show that firms more affected by these financial frictions have a positive "marginal propensity to invest" out of net worth; on average, the marginal propensity to invest is 0.17, and there is substantial variation across firms.

The lifecycle dynamics of firms in our model are in line with the key features of the data emphasized by the firm dynamics literature. Panel (a) in Figure 3 compares the distribution of firm growth rates in steady state to the establishment-level data from the Business Employment Dynamics (BED) data, reported in Davis et al. (2010). The model matches the empirical distribution of growth rates fairly well except for the large mass of growth rates

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within $(-0.05, 0.05)$ in the data. This discrepancy is driven by the fact that 15% of firms have exactly zero growth rates in the data; these observations likely correspond to small, non-growing establishments, which are outside our model. Panel (b) in Figure 3 shows that the model produces a negative correlation of age and growth, as in the data (and comparable to the model in Clementi and Palazzo (2015)).[32]

Appendix B.3 further analyzes the behavior of the model in steady state and compares it to the data. First, we further analyze the lifecycle dynamics of firms. Second, we show that the joint distribution of investment and leverage rates in our model is comparable to Census and Compustat data. Third, we show that measured investment-cash flow sensitivities in our model are roughly in line with the data. Finally, we compare our model's sample of public vs. private firms (used to replicate the empirical results in Section 6) to the data.

6 Quantitative Monetary Policy Analysis

We now quantitatively analyze the effect of a monetary policy shock $\varepsilon_t^{\mathrm{m}}$. Section 6.1 begins the analysis by computing the aggregate impulse responses to an expansionary shock in our calibrated model. Section 6.2 then studies the heterogeneous effects of monetary policy across firms and shows that, consistent with the empirical results from Section 2, firms with high default risk are less responsive to monetary policy. Finally, Section 6.3 shows that the aggregate effect of monetary policy depends on the distribution of default risk across firms.

The economy is initially in steady state and unexpectedly receives a $\varepsilon_0^{\mathrm{m}} = -0.0025$ innovation to the Taylor rule which reverts to 0 according to $\varepsilon_{t+1}^{\mathrm{m}} = \rho_m \varepsilon_t^{\mathrm{m}}$ with $\rho_m = 0.5$. We compute the perfect foresight transition path of the economy as it converges back to steady state.[33]

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[32]We exclude the growth of firms less than one year old from this comparison because their growth rate is dominated by the fact that all firms start with low initial capital k_0; the average growth rate of these firms is nearly 1. We exclude them from the figure since they account for a small share of economic activity but would dominate the scaling.

[33]Allowing for persistence in the monetary policy shocks themselves is a simple way to create inertia in response to a monetary shock; in the representative firm version of the model, the response is very similar to a version of the model in which the innovations are transitory but the Taylor rule includes interest rate smoothing.

FIGURE 4: Aggregate Responses to Expansionary Monetary Shock
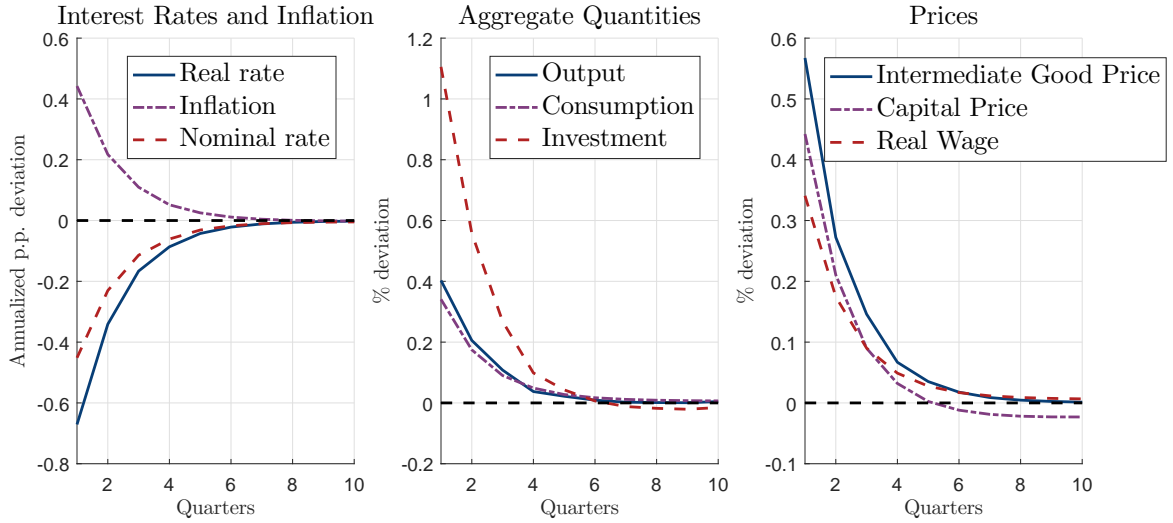
Notes: Aggregate impulse responses to a $\varepsilon_0^{\mathrm{m}} = -0.0025$ innovation to the Taylor rule which decays at rate $\rho_m = 0.5$. Computed as the perfect foresight transition in response to a series of unexpected innovations starting from steady state.

6.1 Aggregate Response to Monetary Policy

Figure 4 plots the responses of key aggregate variables to this expansionary shock. The shock lowers the nominal interest rate and, because prices are sticky, also lowers the real interest rate. The lower real interest rate stimulates investment demand by shifting out the marginal benefit of investment, as discussed in Section 4. It also stimulates consumption demand from the household due to the standard intertemporal substitution. The higher aggregate demand for goods changes other prices in the economy, further shifting the marginal benefit and marginal costs curves for investment. Overall, investment increases by approximately 1.1%, consumption increases by 0.35%, and output increases by 0.4%. These magnitudes are broadly in line with the peak effect of monetary policy estimated in Christiano, Eichenbaum and Evans (2005).[34]

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[34]Our model does not generate the hump-shaped aggregate responses emphasized by Christiano, Eichenbaum and Evans (2005). We could do so by incorporating adjustment costs to investment rather than capital. However, in order to be consistent with the hump-shaped responses of consumption and employment, we would also need to add habit formation and potentially labor adjustment costs. While interesting, this extension is outside the scope of this paper, whose goal is to focus on the role of financial heterogeneity in monetary transmission using an otherwise basic New Keynesian model.

6.2 Heterogeneous Responses to Monetary Policy

We now study the heterogeneous responses to monetary policy across firms in our model and show that they are consistent with the data. We also decomposes the various channels through which monetary policy affects investment.

Model-Implied Regression Coefficients   In order to directly compare our model to the data, we simulate a panel of firms in response to a monetary shock and estimate our empirical specification (5) on the simulated data:[35]

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \boldsymbol{\Gamma}_1' Z_{jt-1} + \boldsymbol{\Gamma}_2'(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + e_{jt}.$$

We mirror the sample selection into Compustat by conditioning on firms that have survived at least ten years, which is on the upper end of time to IPO reported in Wilmer et al. (2017). Appendix B.3 shows that the behavior of the model's public firms vs. private firms compares fairly well to the data along certain dimensions. We assume that the high-frequency shocks $\varepsilon_t^{\mathrm{m}}$ we measure in the data are the innovations to the Taylor rule in the model.[36] We estimate the regressions using data from one year before the shock to ten quarters after the shock.

We estimate the specification (5) using leverage ℓ_{jt} as the measure of financial position x_{jt}. We use leverage ℓ_{jt} for two reasons. First, it is not obvious how to compute our other measures of financial position in the model; in the data, credit ratings are constructed by ratings agencies – which do not exist in our model – and distance to default is based on the volatility of firms' equity values – which are partially determined by aggregate shocks. Second, there is a tight relationship between leverage and default risk in the model. This relationship occurs because there is a monotonic relationship between leverage and net worth (shown in Figure 24 in Appendix B.3), and firms only default when net worth falls below

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[35]In the model, we use time fixed effects rather than sector-time fixed effects. In addition, we do include the subset of the controls in Z_{jt} which are not in our model.

[36]In our model, the change in the nominal interest rate is smaller than the innovation to the Taylor rule because the monetary authority responds to the resulting inflation. This fact may lead to an inconsistency between the monetary shocks in the model and the measured shocks in the data, which are based on changes in expected nominal rates. Our implicit assumption is that the feedback effect through the Taylor rule takes sufficient time that it is not incorporated into the measure of the high-frequency shocks. Because we use the one-month futures, our assumption requires that the monetary authority respond to inflation with at most a one month lag.

TABLE 8

EMPIRICAL RESULTS, MODEL VS. DATA

	LHS: $\Delta \log k_{jt}$		**LHS:** Δr_{jt}	
	Data	Model	Data	Model
	(1)	(2)	(3)	(4)
demeaned leverage $\times$ ffr shock	-0.68^{**}	-0.59	0.17^{**}	0.26
	(0.28)		(0.06)	
Firm controls	yes	yes	yes	yes
Time FE	yes	yes	yes	yes
R^2	0.12	0.58	0.55	0.99

Notes: Results from running the specification $\Delta \log k_{jt} = \alpha_j + \alpha_t + \beta(\ell_{jt-1} - \mathbb{E}_j[\ell_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}'Z_{jt-1} + e_{jt}$ on model-simulated data, where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is the firm's leverage, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Z_{jt-1} is a vector of firm-level controls containing leverage, cash flow, and size, and $\mathbb{E}_j[\ell_{jt}]$ is the average leverage of firm j in our sample. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} or demeaned leverage $\ell_{jt} - \mathbb{E}_j[\ell_{jt}]$ over the entire sample, so its units are in standard deviations relative to the mean. In the model, the sample period is four quarters before the monetary shock through ten quarters after the shock. To mirror the sample selection into Compustat, we condition on firms that have survived at least ten years. Columns (3) and (4) replace the left-hand side variable with Δr_{jt}. In the model, Δr_{jt} is the change in the firm's interest rate $1/\mathcal{Q}_{jt}$. In the data, Δr_{jt} is the change in the firm's total interest payments over twelve quarters divided by total liabilities. We compute the change over twelve quarters because the data's interest rate measures average costs over all borrowing, and the average maturity of corporate debt is roughly three years. See Appendix A.3.1 for the full dynamics.

the default threshold $\underline{n}(z)$.

Table 8 shows that high-leverage firms are less responsive to monetary policy in the model, as in the data. In the data, a firm with one standard deviation more leverage than the average firm has an investment semi-elasticity that is approximately -0.7 percentage points lower than the average firm; in the model, that firm is has an approximately -0.6 lower semi-elasticity, which is well within one standard error of the data. The R^2 of the regression is higher in the data than in the model, indicating that the data contain more unexplained variation in investment.

Figure 5 shows that the dynamics of the differential responses of investment are are persistent in the model, consistent with the data. In this figure, we estimate the local projection (6) on our model-simulated data. Quantitatively, the model's differences stay within the data's 90% confidence interval up to eight quarters after the shock.

These heterogeneous responses indicate that high-leverage firms are positioned on the

FIGURE 5: Dynamics of differential responses, model vs. data

Notes: dynamics of the interaction coefficient between leverage and monetary shocks and between distance to default and monetary shocks over time. Reports the coefficient β_h over quarters h from

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_h(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_h' Z_{jt-1} + \mathbf{\Gamma}_{2h}'(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is the firm's leverage, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Z_{jt-1} is a vector of firm-level controls containing leverage, cash flow, and size, and $\mathbb{E}_j[\ell_{jt}]$ is the average leverage of firm j in our sample. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} or demeaned leverage $\ell_{jt} - \mathbb{E}_j[\ell_{jt}]$ over the entire sample, so its units are in standard deviations relative to the mean. In the model, the sample period is four quarters before the monetary shock through ten quarters after the shock. To mirror the sample selection into Compustat, we condition on firms that have survived at least ten years.

upward-sloping part of their marginal cost curve from Figure 2, and that the shifts in that curve are quantitatively dominated by the shift out in the marginal benefit curve. An implication of this mechanism is that firms with high leverage should see a larger increase in their interest rate $1/\mathcal{Q}_{jt}$ in response to the monetary shock. Columns (3) and (4) in Table 8 show that this implication holds true in both the model and in the data. In these columns, we replace the left-hand side of the empirical specification (5) with the change in the firm's interest rate and find that it increases more for high-leverage firms. Appendix A.3 further studies heterogeneous responses of firm-level interest rates in the data.[37]

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[37]We do not study the response of interest rates in Section 2 because our measure of interest rates is total interest payments divided by total liabilities. This variable is a noisy measure of the firm's interest rate on a marginal unit of borrowing, so the results are subject to large standard errors.

FIGURE 6: Decomposition of Semi-Elasticity of Capital to Monetary Policy Shock

Average Semi-Elasticity w.r.t. Monetary Shock
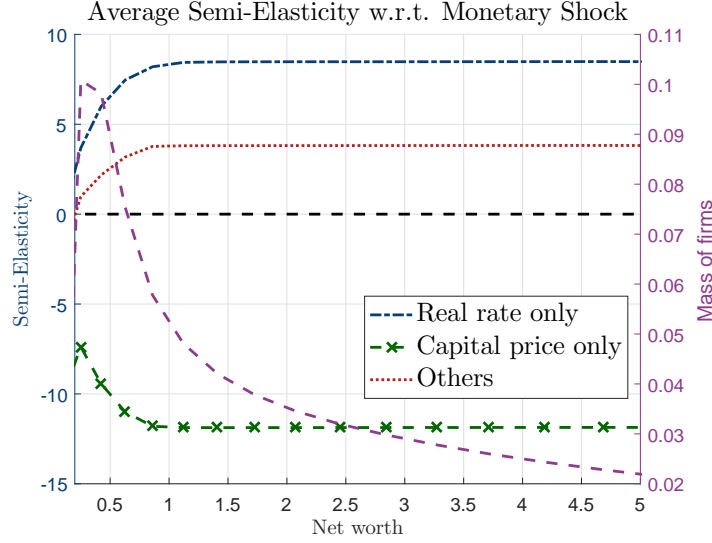
Notes: Semi-elasticity of capital in response to monetary shock and the initial distribution of firms. "Real rate only" refers to feeding in the path of the real interest rate R_t but keeping all other prices fixed at steady state. "Capital price only" refers to feeding in the path of the relative price of capital q_t but keeping all other prices fixed at steady state. "Others" refers to feeding in all other prices but keeping the real rate and capital price fixed at steady state. Dashed purple line is the initial distribution of firms. Idiosyncratic productivity shocks z have been averaged over using their ergodic distribution.

Decomposition of Channels Driving Heterogeneous Responses   In order to better understand the sources of these heterogeneous responses across firms, we now decompose the channels through which monetary policy affects firms' investment intro three different channels. First, we compute the "direct effect" of monetary policy by feeding in the path of the real interest rate R_t and hold all other prices fixed at steady state. Second, we feed in the series of the relative price of capital q_t but keep all other prices fixed. Finally, we feed in all other prices in the model – the relative price of output p_t, the real wage w_t, and inflation Π_t – but keep the real interest rate R_t and relative price of capital q_t fixed. Figure 6 plots the semi-elasticity of investment to each of these series in the initial period of the shock.

The results in Figure 6 also indicate that the heterogeneous responses in our model are driven by the fact that firms with high default risk face a steeper marginal cost curve for financing investment. The decrease in the real interest rate shifts out the marginal benefit curve in Figure 2; firms with higher default risk – which, in Figure 6, have low net worth – are less responsive to this change because they have a steeper marginal cost curve. The

increase in the relative price of capital has two offsetting effects. On the one hand, it makes new capital more expensive and therefore shifts the marginal cost curve up for all firms; on the other hand, it increases the recovery rate of lenders in the event of default, which flattens out the marginal cost curve for firms with low net worth. On net, the former force outweighs the latter, but firms with low net worth are more strongly affected by the latter. Finally, the increase in all other prices also shifts out the marginal benefit curve by increasing the revenue product of capital; once again, this effect is offset for low net worth firms by their steeper marginal cost curve.[38]

The fact that both the direct and indirect effects play a quantitatively important role in driving the investment channel of monetary policy contrasts with Auclert (2017)'s and Kaplan, Moll and Violante (2017)'s decomposition of the consumption channel. In the context of a household's consumption-savings problem, they find that the contribution of the direct effect of lower real interest rates is small relative to the indirect general equilibrium effects of higher labor income. In our model, direct interest rate effects are stronger because firms are more price-sensitive than households. In fact, without any financial frictions at all, the partial equilibrium elasticity of investment with respect to interest rates would be nearly infinite (see Koby and Wolf (2019) for a discussion of the role of interest-elasticities in heterogeneous firm macro models). In contrast, households are less price sensitive because of consumption-smoothing motives, so these direct effects are less important.

6.3 Aggregate Implications of Financial Heterogeneity

In this subsection, we illustrate two ways in which financial heterogeneity matters for understanding the aggregate transmission mechanism. We first show that the aggregate effect of a given monetary shock is smaller when the initial distribution of firms features higher default risk. Nevertheless, we show find that the aggregate effect of monetary policy is *larger* in our model than in a comparable version of the model without financial frictions (which collapses to a representative firm). The reason is that all constrained firms in our model – either the risky or risk-free constrained – are more responsive to a monetary shock than to

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[38]The changes in these other prices also increase net worth by increasing cash flow and increasing the relative value of undepreciated capital, which moves firms along the x-axis of Figure 6.

a completely unconstrained firm.

State Dependence of Aggregate Transmission   In order to illustrate the quantitative scope for state dependence, we perform a simple back-of-the-envelope calculation: we fix the semi-elasticity of capital respect to monetary policy as a function of firms' state variables and vary the initial distribution of firms.[39] We vary the initial distribution of firms $\mu(z, n)$ by taking the weighted average of two reference distributions. The first reference distribution is the steady-state distribution $\mu^*(z, n)$. The second reference distribution $\widetilde{\mu}(z, n)$ assumes that the conditional distribution of net worth for every level of productivity is equal to the distribution of net worth conditional on the lowest realization of productivity in steady state.[40] We then compute the initial distribution as a weighted average of these two reference distributions, $\mu(z, n) = \hat{\omega}\widetilde{\mu}(z, n) + (1 - \hat{\omega})\mu^*(z, n)$. We vary $\hat{\omega} \in [0, 1]$ to trace out linear combinations of distributions between the steady state ($\hat{\omega} = 0$) and the low net worth ($\hat{\omega} = 1$) distributions.

The left panel of Figure 7 shows that the change in the aggregate capital stock is 60% smaller starting from the low-net worth distribution $\widetilde{\mu}(z, n)$ than starting from the steady state distribution $\mu^*(z, n)$. Average net worth is 70% lower and there are 50% more risky constrained firms in the low-net worth distribution than in the steady state distribution. The right panel of Figure 7 shows that this effect is due to the fact that the low-net worth distribution $\widetilde{\mu}(z, n)$ places more mass in the region of the state space where the elasticity of capital with respect to the monetary policy shock is low.

These results suggests a potentially powerful source of time-variation in the aggregate transmission mechanism: monetary policy is less powerful when net worth is low and default

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[39]This exercise does not allow for prices to vary with the initial distribution. However, it is a nevertheless an important necessary condition for the general equilibrium model to generate state dependence. We perform this simple exercise of fixing the elasticities and varying the distribution for two reasons. First, since we do not have to re-compute the equilibrium transition path for each initial distribution, we can investigate state dependence with respect to a large number of initial distributions. Second, it clearly isolates the impact of varying the initial distribution from the additional changes to firms' policy rules arising from changes in prices.

In this exercise, markets do not clear for a given initial distribution of cash-on-hand. We use the elasticities from the representative firm prices so that markets do not clear for any initial distribution. If we had used the equilibrium elasticities, markets would clear for some initial distributions and not others, potentially biasing our interpretation of the results.

[40]We normalize the second reference distribution so that the marginal distribution of productivity is the same as in the steady state distribution.

FIGURE 7: Aggregate Response Depends on Initial Distribution
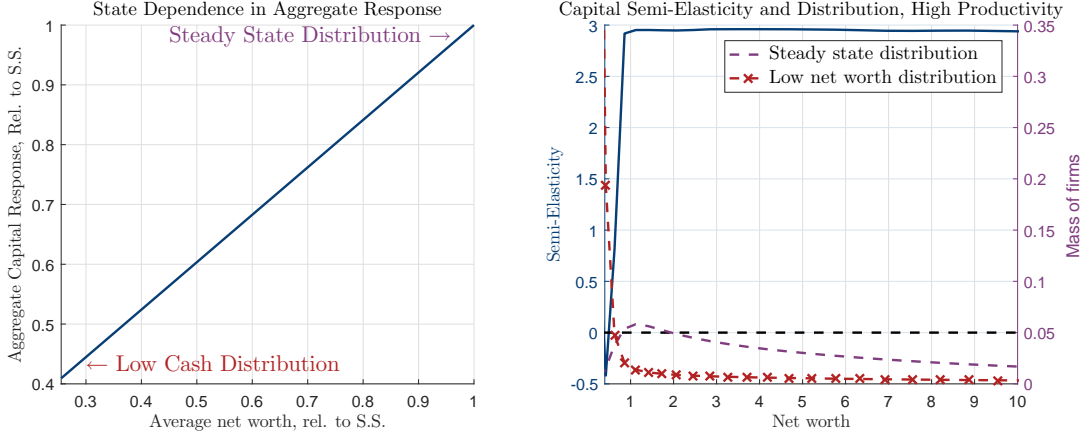
Notes: Dependence of aggregate response on initial distribution. We compute the change in aggregate capital for different initial distributions using the response to monetary policy computed under the price path from the representative firm model. We vary the initial distribution of firms in production $\hat{\mu}(z,n)$ by taking the weighted average of two reference distributions; see main text for details.

FIGURE 8: Aggregate Impulse Responses in Full Model vs. Rep Firm Model
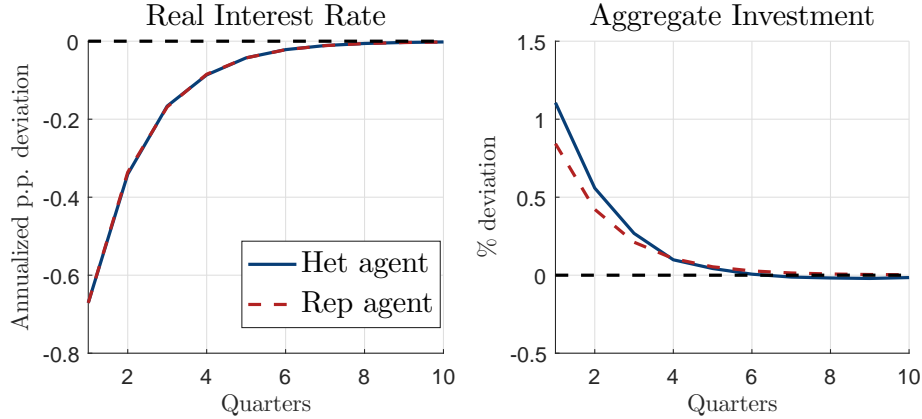
Notes: Aggregate impulse responses to a $\varepsilon_0^m = -0.0025$ innovation to the Taylor rule which decays at rate $\rho_m = 0.5$. Computed as the perfect foresight transition in response to a series of unexpected innovations starting from steady state. "Het agent" refers to calibrated heterogeneous firm model from the main text. "Rep agent" refers to a version of the model in which the heterogeneous production sector is replaced by a representative firm with the same production function and no financial frictions.

risk is high. Of course, a limitation of this analysis is that we have varied the initial distribution exogenously. The natural next step in this analysis is to incorporate various business cycle shocks into our model and study the shapes of the distributions that actually arise in equilibrium.

Comparison to Frictionless Model We now compare our full model to a model in which we eliminate financial frictions. We do so by removing the non-negativity constraint on dividends; in this case, the investment block of the model collapses to a financially unconstrained representative firm (see Khan and Thomas (2008) Appendix B). Figure 8 shows that the impact effect of monetary policy on investment is 25% larger in our full model than in the representative firm benchmark. Hence, despite the fact that risky constrained firms are less responsive than risk-free constrained firms, both types of constrained firms are more responsive than completely unconstrained firms (which, by construction, are the same as the representative firm in the frictionless benchmark). This occurs because the constrained firms' marginal value of net worth is strictly larger than for the unconstrained firms. Their higher investment demand puts additional upward pressure on the relative price of capital q_t in our full model, which then induces unconstrained firms to disinvest.

7 Conclusion

In this paper, we have argued that financial frictions dampen the response of investment for firms with high default risk. Our argument had two main components. First, we showed in the micro data that firms with high leverage or low credit ratings invest significantly less than other firms following a monetary policy shock. Second, we built a heterogeneous firm New Keynesian model with default risk that is quantitatively consistent with these empirical results. In the model, monetary policy stimulates investment through a combination of direct and indirect effects. High-risk firms are less responsive to these changes because their marginal cost of investment finance is higher than for low-risk firms. The aggregate effect of monetary policy is primarily driven by these low-risk firms, which suggests a novel form of state dependence: monetary policy is less powerful when default risk in the economy is greater.

Our results may be of independent interest to policymakers who are concerned about the distributional implications of monetary policy across firms. An often-discussed goal of monetary policy is to provide resources to viable but credit constrained firms. Many policymakers' conventional wisdom, built on the financial accelerator mechanism, suggests that

constrained firms will significantly increase their capital investment in response to expansionary monetary policy. Our results imply that, instead, expansionary policy will stimulate the less risky firms in the economy.

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Appendix (For Online Publication Only)

A   Empirical Appendix

This appendix contains additional results related to the empirical work in Section 2. Appendix A.1 describes the construction and cleaning of our dataset. Appendix A.2 shows that our main empirical results are robust along a number of dimensions. Appendix A.3 contains additional empirical results referenced in the main text. Finally, Appendix A.4 compares our results to others in the literature, such as Gertler and Gilchrist (1994), Cloyne et al. (2018), and Jeenas (2018).

A.1   Data Construction

This subsection describes the firm-level variables used in the empirical analysis of the paper, based on quarterly Compustat data. The definition of the variables and sample selection follow standard practices in the literature (see, for example, Whited, 1992; Gomes, 2001; Eisfeldt and Rampini, 2006; Clementi and Palazzo, 2015).

Variables

1. *Investment, intensive margin* (baseline measure): defined as $\Delta \log(k_{jt+1})$, where k_{jt+1} denotes the capital stock of firm j at the end of period t. For each firm, we set the first value of k_{jt+1} to the level of gross plant, property, and equipment (`ppegtq`, item 118) in the first period in which this variable is reported in Compustat. From this period onwards, we compute the evolution of k_{jt+1} using the changes of net plant, property, and equipment (`ppentq`, item 42), which is a measure net investment with significantly more observations than `ppegtq` (net of depreciation). If a firm has a missing observation of `ppentq` located between two periods with nonmissing observations we estimate its value using a linear interpolation with the values of `ppentq` right before and after the missing observation; if two or more consecutive observations are missing we do not do any imputation. We only consider investment spells with 40 quarters or more in order to precisely estimate fixed effects.

2. *Leverage*: defined as the ratio of total debt (sum of `dlcq` and `dlttq`, items 45 and 71) to total assets (`atq`, item 44).

3. *Net leverage*: defined as the ratio of total debt minus net current assets (`actq`, item 40, minus `lctq`, item 49) to total assets.

4. *Distance to default*: Following Merton (1974) and Gilchrist and Zakrajšek (2012), we define this variable as $dd \equiv \frac{\log(V/D)+(\mu_V-0.5\sigma_V^2)}{\sigma_V}$, where V denotes the total value of the firm, μ_V the expected return on V, σ_V the volatility of the firm's value, and D firm's debt.[41] To estimate the firm's value V, we follow an iterative procedure, based on Gilchrist and Zakrajšek (2012) and Blanco and Navarro (2016):

   i. Set an initial value for the firm value equal to the sum of firm debt and equity, $V = E + D$, where E is measured as the firm's stock price times the number of shares (data source: `CRSP`).

   ii. Estimate the mean and variance of return on firm value over a 250-day moving window. The return on firm value is measured as the daily log return on assets, $\Delta \log V$.

   iii. Obtain a new estimate of V for every day of the 250-day moving window from the Black-Scholes-Merton option-pricing framework $E = V\Phi(\delta_1) - e^{-rT}D\Phi(\delta_2)$, where $\delta_1 \equiv \frac{\log(V/D)+(r+0.5\sigma_V^2)T}{\sigma_V^2\sqrt{T}}$, and $\delta_2 \equiv \delta_1 - \sigma_V\sqrt{T}$, where r is the daily one-year constant maturity Treasury-yield (data source: Federal Reserve Board of Governors H.15 Selected Interest Rates release).

   iv. Iterate on steps [ii.] and [iii.] until convergence.

5. *Real sales growth*: measured as log-differences in sales (`saleq`, item 2) deflated using CPI.

6. *Size*: measured as the log of total assets.

7. *Liquidity*: defined as the ratio of cash and short-term investments (`cheq`, item 36) to total assets.

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[41] We measure the face value of debt D as the sum of the firm's short-term debt (`dlcq`, item 45) and one-half of long-term debt (`dlttq`, item 71), following Gilchrist and Zakrajšek (2012) and a common practice by credit rating agencies (Moody's/KMV).

8. *Cash flow*: measured as EBITDA divided by capital stock.

9. *Dividend payer*: defined as a dummy variable taking a value of one in firm-quarter observations in which the firm paid dividends to preferred stock of the company (constructed using `dvpq`, item 24).

10. *Tobin's q*: defined as the ratio market to book value of assets. The market value of assets is measured as the book value, plus the market value of common stock, minus the book value of common stock `ceq`, plus deferred taxes and investment tax credit (item `txditcq`, item 52). The market value of common stock is computed as the product of price at quarter close (`prccq`) and common shares outstanding (`cshoq` item 61). We winsorize 1% of observations in each tail of the distribution.

11. *Sectoral dummies.* We consider the following sectors: (i) agriculture, forestry, and fishing: `sic` < 10; (ii) mining: `sic`$\in [10, 14]$; (iii) construction: `sic`$\in [15, 17]$; (iv) manufacturing: `sic`$\in [20, 39]$; (v) transportation, communications, electric, gas, and sanitary services: `sic`$\in [40, 49]$; (vi) wholesale trade: `sic`$\in [50, 51]$; (vii) retail trade `sic`$\in [52, 59]$; (viii) services: `sic`$\in [70, 89]$.

Sample Selection Our empirical analysis excludes (in order of operation):

1. Firms in finance, insurance, and real estate sectors (`sic`$\in [60, 67]$) and public administration (`sic`$\in [91, 97]$).

2. Firms not incorporated in the United States.

3. Firm-quarter observations with acquisitions (constructed based on `aqcy`, item 94) larger than 5% percent of assets.

4. Firm-quarter observations that satisfy one of the following conditions, aimed at excluding extreme observations:

   i. Investment rate is in the top and bottom 0.5 percent of the distribution.

   ii. Leverage higher than 10.

FIGURE 9: Aggregate Investment: NIPA vs. Compustat
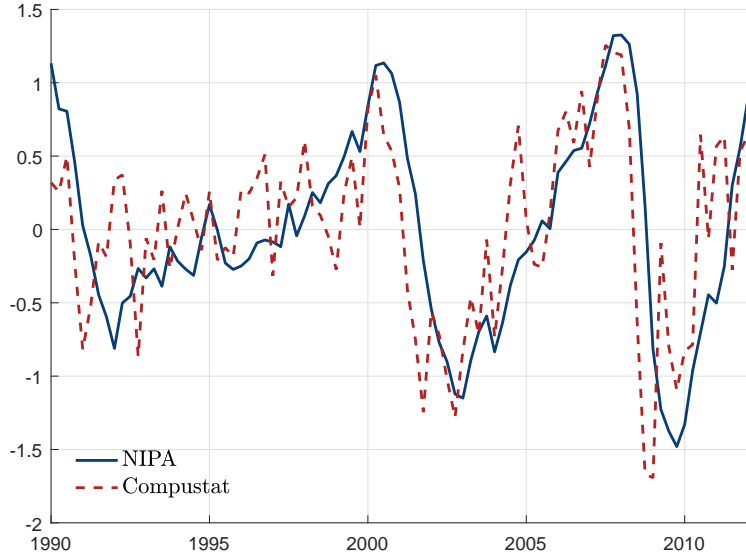
Notes: comparison of aggregate NIPA investment to aggregated Compustat investment. NIPA investment measured as log nonresidential fixed investment and aggregated Compustat investment measured as average $\Delta \log k_{jt}$ across firms. Figure reports the cyclical component using an HP filter with smoothing parameter $\lambda = 1600$.

iii. Net current assets as a share of total assets higher than 10 or below -10.

iv. Quarterly real sales growth above 1 or below -1.

After applying these sample selection operations, we winsorize observations of leverage and distance to default at the top and bottom 0.5% of the distribution.

Figure 9 plots the cyclical component the average firm-level investment from our Compustat data to nonresidential fixed investment from NIPA. Both series exhibit similar business cycle patterns, with a correlation of around 60%. Our aggregated Compustat time series also behaves similarly to NIPA investment in response to an identified monetary shock (estimated using the external-instruments VAR model in Gertler and Karadi (2015)). Results are available upon request.

A.2 Robustness of Main Results

This appendix performs a number of robustness checks of our main results. Subsection A.2.1 contains a number of results concerning the monetary policy shock $\varepsilon_t^{\mathrm{m}}$. Subsection A.2.2

contains results concerning the firm-level heterogeneity.

A.2.1 Robustness with respect to the monetary shock

Controlling for information channel of monetary policy One concern about our monetary shocks $\varepsilon_t^{\mathrm{m}}$ is that the FOMC announcements on which they are based also release information about the future path of economic activity (see, for example, Nakamura and Steinsson (2013)). Table 9 show that our results are not driven by this information channel of monetary policy. Following Miranda-Agrippino and Ricco (2018), we control for information using the Greenbook forecast revisions between concurrent FOMC announcements. Our main results are robust to including this control. In addition, Table 10 shows that our results are also robust to controlling for the level of the forecasts.

TABLE 9

CONTROLLING FOR GREENBOOK FORECAST REVISIONS

	(1)	(2)	(3)	(4)	(5)	(6)
leverage × ffr shock	-0.80***		-0.96***		-1.10***	
	(0.29)		(0.35)		(0.34)	
dd × ffr shock		1.11***		0.78*		0.74*
		(0.40)		(0.44)		(0.43)
Forecast rev controls	GDP	GDP	GDP Inflation	GDP Inflation	GDP Inflation Unemployment	GDP Inflation Unemployment
Observations	219702	151433	219702	151433	219702	151433
R^2	0.124	0.137	0.124	0.137	0.124	0.137
Firm controls	yes	yes	yes	yes	yes	yes

Notes: Results from estimating the baseline specification (5), including as controls in the interaction between our variable of interest, $x_{jt} - E_j[x_{jt}]$, and forecast revisions of output growth, inflation, and unemployment in FOMC announcements.

Results not driven by differential cyclical sensitivities Our baseline specification (5) controls for the interaction between $x_{jt} - \mathbb{E}_j[x_{jt}]$ with lagged GDP growth in order to control for differences in cyclical sensitivities across firms. Our motivation for this choice is that the monetary shocks are potentially correlated with cyclical conditions, and that our heterogeneous responses to monetary shocks are in fact driven by differences in cyclical sensitivities across firms. However, Table 11 shows that this is not the case upon impact of

TABLE 10

CONTROLLING FOR GREENBOOK FORECASTS

	(1)	(2)	(3)	(4)	(5)	(6)
leverage × ffr shock	-1.08***		-0.73**		-0.75*	
	(0.29)		(0.32)		(0.44)	
dd × ffr shock		1.14***		0.92**		0.90*
		(0.41)		(0.37)		(0.53)
Forecast	GDP	GDP	GDP	GDP	GDP	GDP
controls			Inflation	Inflation	Inflation	Inflation
					Unemployment	Unemployment
Observations	219702	151433	219702	151433	219702	151433
R^2	0.124	0.137	0.124	0.137	0.124	0.137
Firm controls	yes	yes	yes	yes	yes	yes

Notes: Results from estimating the baseline specification (5), including as controls in the interaction between our variable of interest, $x_{jt} - E_j[x_{jt}]$, and forecasts of output growth, inflation, and unemployment in FOMC announcements.

the shock; our results upon impact are nearly identical if we do not control for differences in cyclical sensitivities.

Figure 10 plots the dynamics of the differential responses from specification (5) without controlling for differential responses to GDP growth as in the main text. Not controlling for these differences leaves the point estimates largely unchanged but increases the standard errors, suggesting that differences in cyclical sensitivities confound inference about the monetary shock. In any event, Figure 10 makes clear that our conclusion that long-run dynamics are imprecisely estimated is not due to controlling for differences in cyclical sensitivities.

Using raw changes in Fed Funds rate Another concern with the monetary policy shocks is that their time-series variation is limited. Table 12 shows that our main results hold if we use the full variation in the Fed Funds Rate instead of the shocks. However, the magnitude of the heterogeneous responses in this specification is smaller, consistent with the facts that (i) changes in the raw Fed Funds Rate are correlated with economic activity and (ii) the results above that firms with different financial positions x_{jt} also have different cyclical sensitivities.

TABLE 11

CONTROLLING FOR DIFFERENCES IN CYCLICAL SENSITIVITIES

	(1)	(2)	(3)	(4)	(5)	(6)
leverage × ffr shock	-0.68**		-0.64**		-0.36	
	(0.28)		(0.29)		(0.26)	
dd × ffr shock		1.10***		1.12***		0.88**
		(0.39)		(0.39)		(0.35)
leverage × dlog gdp	-0.14**		-0.15***			
	(0.06)		(0.06)			
dd × dlog gdp		0.11		0.09		
		(0.11)		(0.11)		
leverage × dlog cpi			-0.12			
			(0.09)			
dd × dlog gdp				-0.09		
				(0.12)		
leverage × ur					0.00	
					(0.00)	
dd × ur						0.00
						(0.00)
Observations	219702	151433	219702	151433	219702	151433
R^2	0.124	0.137	0.124	0.137	0.124	0.137
Firm controls	yes	yes	yes	yes	yes	yes

Notes: results from estimating variants of the baseline specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta_y(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_1' Z_{jt-1} + \mathbf{\Gamma}_2'(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + ejt,$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is leverage or distance to default, $\mathbb{E}_j[x_{jt}]$ is the average financial position x_{jt} of firm j in our sample, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Y_{t-1} is GDP growth (dlog gdp), the inflation rate (dlog cpi), or the unemployment rate (ur), and Z_{jt-1} is a vector of firm-level controls containing x_{jt}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized within-firm leverage $(\ell_{jt} - \mathbb{E}[\ell_{jt}])$ and within-firm distance to default $(\mathrm{dd}_{jt} - \mathbb{E}[\mathrm{dd}_{jt}])$ over the entire sample, so their units are in standard deviations relative to the mean.

FIGURE 10: Dynamics Without Controlling for Differences in Cyclical Sensitivities
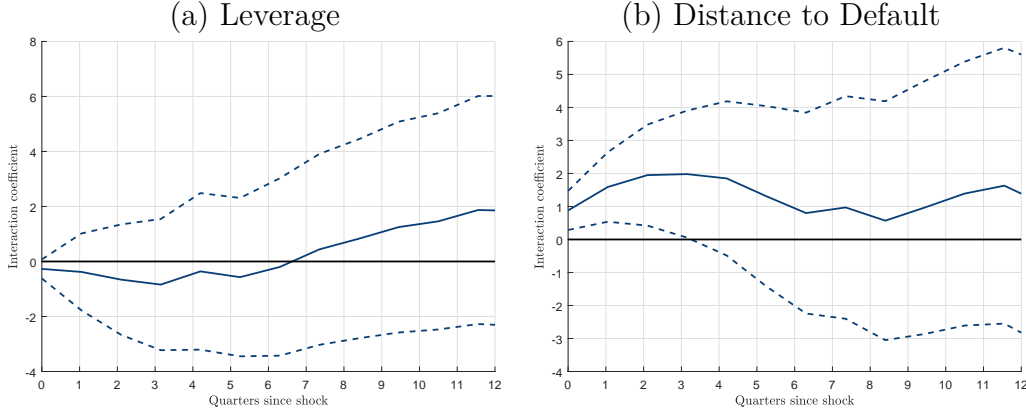
(a) Leverage

(b) Distance to Default

Notes: dynamics of the interaction coefficient between leverage and monetary shocks over time. Reports the coefficient β_h over quarters h from

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_h(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_h' Z_{jt-1} + e_{jt},$$

where α_{jh} is a firm fixed effect, α_{sth} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is either the firm's leverage ratio or distance to default, $\mathbb{E}_j[\ell_{jt}]$ is the average of x_{jt} for firm j in the sample, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and time. Dashed lines report 90% error bands. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized within-firm leverage ($\ell_{jt} - \mathbb{E}[\ell_{jt}]$) and within-firm distance to default ($\mathrm{dd}_{jt} - \mathbb{E}[\mathrm{dd}_{jt}]$) over the entire sample, so their units are in standard deviations relative to the mean.

Results driven by effect of monetary shocks on short rates   Table 13 shows that the differential responses across firms are primarily driven by how monetary policy affects the overall level of interest rates rather than long rates in particular. Following Gurkaynak, Sack and Swanson (2005), we decompose monetary policy announcements into a "target" component that affects the level of the yield curve and a "path" component that affects the slope of the yield curve. The table shows that only the interactions of financial position with the target component are statistically significantly.

Results hold in the post-1994 sample   Another concern is that our monetary shocks may become less powerful after the Fed began making formal policy announcements in 1994. Table 14 shows that our main results concerning heterogeneous responses continue to hold in the post-1994 sample. However, the average effect of monetary policy becomes insignificant because there is less variation in the post-1994 sample.

TABLE 12

CHANGES IN FED FUNDS RATE

	(1)	(2)	(3)	(4)
leverage × ffr shock	-0.67**			
	(0.28)			
leverage × Δffr		-0.12**		
		(0.06)		
dd × ffr shock			1.08***	
			(0.39)	
dd × Δffr				0.16*
				(0.08)
Observations	219674	278800	151422	195672
R^2	0.124	0.114	0.137	0.122
Firm controls	yes	yes	yes	yes
Time sector FE	yes	yes	yes	yes
Time clustering	yes	yes	yes	yes

Notes: results from estimating variants of the baseline specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta_y(x_{jt-1} - \mathbb{E}_j[x_{jt}])v_t^{\mathrm{m}} + \mathbf{\Gamma}_1' Z_{jt-1} + \mathbf{\Gamma}_2(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + \varepsilon_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is leverage or distance to default, $\mathbb{E}_j[x_{jt}]$ is the average financial position x_{jt} of firm j in our sample, $v_t^{\mathrm{m}} \in \{\varepsilon_t^{\mathrm{m}}, \Delta\mathrm{ffr}_t\}$ is the monetary shock or the change in the Fed Funds rate, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized within-firm leverage $(\ell_{jt} - \mathbb{E}[\ell_{jt}])$ and within-firm distance to default $(\mathrm{dd}_{jt} - \mathbb{E}[\mathrm{dd}_{jt}])$ over the entire sample, so their units are in standard deviations relative to the mean.

Alternative Time Aggregation Finally, Table 15 shows that our baseline results hold when we time-aggregate the high-frequency shocks by taking the simple sum within the quarter, rather than the weighted sum in the main text.

A.2.2 Robustness with respect to firm heterogeneity

Results robust to controlling for lagged investment Eberly, Rebelo and Vincent (2012) show that lagged investment is a powerful predictor of current investment in a balanced panel of large firms in Compustat. Motivated by this finding, Table 16 shows that our main results continue to hold when we control for lagged investment. In addition, the top panel of Figure 11 shows that the dynamics of these differential responses are also persistent to controlling for lagged investment.

TABLE 13

TARGET VS. PATH DECOMPOSITION

	(1)	(2)	(3)	(4)
leverage $\times$ ffr shock	-0.68**			
	(0.28)			
leverage $\times$ target shock		-0.98**		
		(0.45)		
leverage $\times$ path shock		-0.70		
		(1.30)		
dd $\times$ shock			1.10***	
			(0.39)	
dd $\times$ target shock				1.47**
				(0.67)
dd $\times$ path shock				-0.41
				(1.65)
Observations	219702	214301	151433	147986
R^2	0.124	0.125	0.137	0.138
Firm controls	yes	yes	yes	yes
Time sector FE	yes	yes	yes	yes
Time clustering	yes	yes	yes	yes

Notes: results from estimating variants of the baseline specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta_y(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^m + \mathbf{\Gamma}_1' Z_{jt-1} + \mathbf{\Gamma}_2(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is leverage or distance to default, $\mathbb{E}_j[x_{jt}]$ is the average financial position x_{jt} of firm j in our sample, ε_t^m is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Columns (2) and (4) run separate interactions of financial position x_{jt} with the target and path component of interest rates, as defined in Campbell et al. (2016). Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shock ε_t^m so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized within-firm leverage $(\ell_{jt} - \mathbb{E}[\ell_{jt}])$ and within-firm distance to default $(\mathrm{dd}_{jt} - \mathbb{E}[\mathrm{dd}_{jt}])$ over the entire sample, so their units are in standard deviations relative to the mean.

Unlike Eberly, Rebelo and Vincent (2012), the R^2 of our regressions does not significantly increase when we control for lagged investment. The bottom panel of Figure 11 suggests that the main reason for this difference is that we use quarterly data while Eberly, Rebelo and Vincent (2012) use annual data. It shows that the R^2 of the regression increases as we take longer-run changes in capital on the left-hand side. In addition, Eberly, Rebelo and Vincent (2012) use a balanced panel of only large firms, while we use an unbalanced panel of all firms.

FIGURE 11: Dynamics Controlling by Lagged Investment

(a) Leverage (b) Distance to Default

Interaction coefficient

R^2 of the regression

Notes: dynamics of the interaction coefficient between leverage and monetary shocks over time. Reports the coefficient β_h over quarters h from

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \rho\Delta\log k_{jt} + \beta_h(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_h' Z_{jt-1} + \mathbf{\Gamma}_{2h}'(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + e_{jt},$$
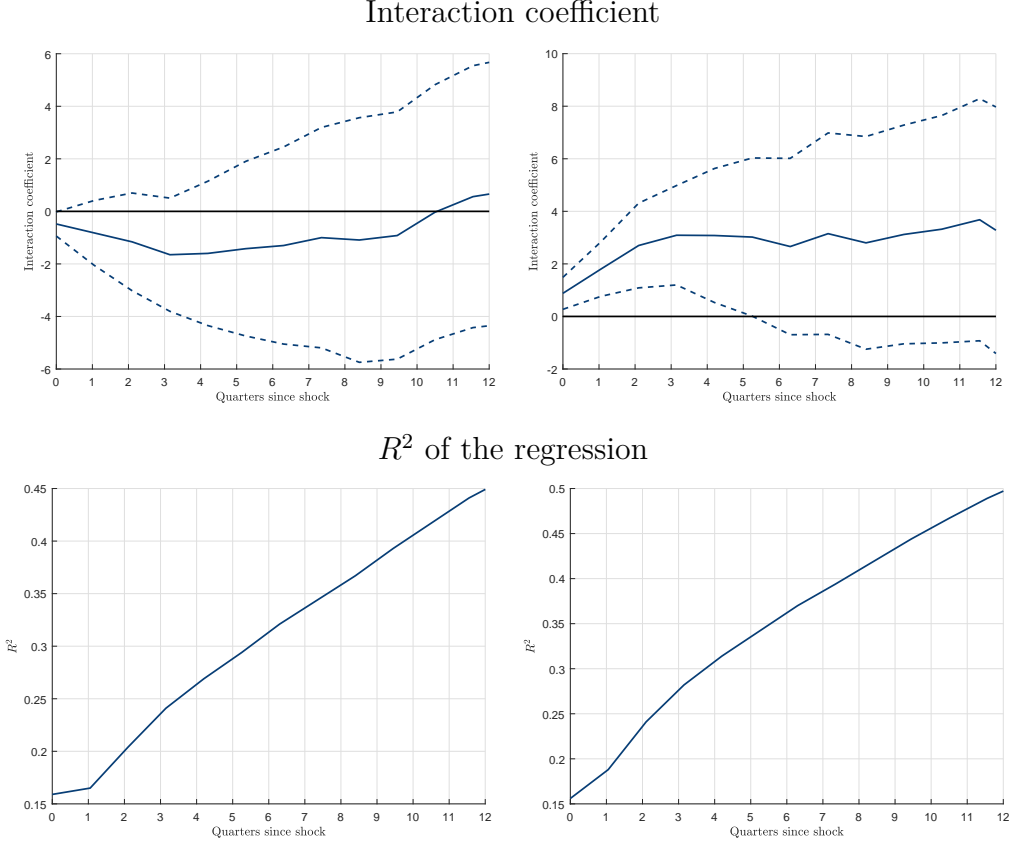
where α_{jh} is a firm fixed effect, α_{sth} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is either the firm's leverage ratio or distance to default, $\mathbb{E}_j[x_{jt}]$ is the average of x_{jt} for firm j in the sample, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter, and Y_{t-1} is GDP growth. Standard errors are two-way clustered by firms and time. Dashed lines report 90% error bands. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized within-firm leverage ($\ell_{jt} - \mathbb{E}[\ell_{jt}]$) and within-firm distance to default ($\mathrm{dd}_{jt} - \mathbb{E}[\mathrm{dd}_{jt}]$) over the entire sample, so their units are in standard deviations relative to the mean.

TABLE 14
POST-1994 ESTIMATES

	(1)	(2)	(3)	(4)
leverage × ffr shock	-0.80**		-0.54	-0.55
	(0.37)		(0.49)	(0.52)
dd × ffr shock		0.80*	0.54	0.75
		(0.43)	(0.40)	(0.56)
ffr shock				0.25
				(1.19)
Observations	174546	118782	118782	118782
R^2	0.138	0.150	0.152	0.137
Firm controls	yes	yes	yes	yes
Time sector FE	yes	yes	yes	no
Time clustering	yes	yes	yes	yes

Notes: results from estimating variants of the baseline specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta_y(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_1' Z_{jt-1} + \mathbf{\Gamma}_2(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is leverage or distance to default, $\mathbb{E}_j[x_{jt}]$ is the average financial position x_{jt} of firm j in our sample, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Only data after 1994 is used in the estimation. Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized within-firm leverage ($\ell_{jt} - \mathbb{E}[\ell_{jt}]$) and within-firm distance to default ($\mathrm{dd}_{jt} - \mathbb{E}[\mathrm{dd}_{jt}]$) over the entire sample, so their units are in standard deviations relative to the mean.

Results not driven by other firm-level covariates Table 17 shows that our main results are not driven by differences in firms' sales growth, realized future sales growth, size, or liquidity. It expands the baseline specification using within-firm variation as:[42]

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta_y(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \beta_z z_{jt-1}\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_1' Z_{jt-1} + \mathbf{\Gamma}_2(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + e_{jt},$$

where z_{jt-1} is lagged sales growth, realized future sales growth in one year, lagged size, or lagged liquidity. In each case, the coefficients on leverage ℓ_{jt-1} and distance to default dd_{jt-1} remain stable. Hence, firm-level shocks or characteristics that are correlated with these additional variables do not drive the heterogeneous responses by default risk that we document in the main text.

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[42]The results for the baseline specification (3) are very similar.

Table 15
Alternative Time Aggregation

	(1)	(2)	(3)	(4)
leverage $\times$ ffr shock (sum)	-0.68***		-0.61**	-0.54**
	(0.19)		(0.25)	(0.27)
dd $\times$ ffr shock (sum)		0.81***	0.54**	0.69**
		(0.26)	(0.25)	(0.32)
ffr shock (sum)				0.47
				(0.53)
Observations	222475	153520	153520	151433
R^2	0.123	0.135	0.138	0.126
Firm controls	yes	yes	yes	yes
Time sector FE	yes	yes	yes	no
Time clustering	yes	yes	yes	yes

Notes: results from estimating variants of the baseline specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta_y(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_1' Z_{jt-1} + \mathbf{\Gamma}_2(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + \varepsilon_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is leverage or distance to default, $\mathbb{E}_j[x_{jt}]$ is the average financial position x_{jt} of firm j in our sample, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized within-firm leverage $(\ell_{jt} - \mathbb{E}[\ell_{jt}])$ and within-firm distance to default $(\mathrm{dd}_{jt} - \mathbb{E}[\mathrm{dd}_{jt}])$ over the entire sample, so their units are in standard deviations relative to the mean. We time-aggregate the monetary shock by simply summing the high-frequency shocks that occur in a given quarter.

Other indices of financial constraints less powerful   We have interpreted our three measures of financial position as primarily proxying for default risk across firms. Consistent with this interpretation of the data, Table 18 shows that other measures of financial position that are less closely associated with default risk – size, cash flows, dividend payments, and available liquid assets – do not generate statistically significant differential responses to monetary policy. However, the point estimates do indicate that larger firms, firms with higher cash flows, dividend-paying firms, and firms with more liquid assets are more responsive to monetary shocks.

Results stronger when instrument financial position with past financial position
One concern about our measures of financial position x_{jt} is that they contain measurement error. Table 19 corrects for this measurement error by instrumenting financial position

TABLE 16
LAGGED INVESTMENT

	(1)	(2)	(3)	(4)
leverage × ffr shock	-0.48*		-0.20	-0.10
	(0.28)		(0.38)	(0.39)
dd × ffr shock		0.88**	0.73**	0.93**
		(0.37)	(0.35)	(0.42)
investment $(t-1)$	0.20***	0.15***	0.15***	0.16***
	(0.01)	(0.01)	(0.01)	(0.01)
ffr shock				1.14*
				(0.65)
Observations	219702	151433	151433	151433
R^2	0.159	0.156	0.158	0.148
Firm controls	yes	yes	yes	yes
Time sector FE	yes	yes	yes	no
Time clustering	yes	yes	yes	yes

Notes: results from estimating variants of the baseline specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \rho\Delta \log k_{jt} + \beta_y(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_1' Z_{jt-1} + \mathbf{\Gamma}_2(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is leverage or distance to default, $\mathbb{E}_j[x_{jt}]$ is the average financial position x_{jt} of firm j in our sample, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, an indicator for fiscal quarter, and lagged investment $\Delta \log k_{jt}$. Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized within-firm leverage $(\ell_{jt} - \mathbb{E}[\ell_{jt}])$ and within-firm distance to default $(\mathrm{dd}_{jt} - \mathbb{E}[\mathrm{dd}_{jt}])$ over the entire sample, so their units are in standard deviations relative to the mean.

x_{jt} with the financial position in the previous year x_{jt-4}. The heterogeneous responses are stronger in this specification, consistent with measurement error generating attenuation bias in our baseline specification in the main text.

A.3 Additional Results

This subsection contains a number of additional results that were not included in the main text. Subsection A.3.1 shows that high-risk firms see higher increases in interest rates and lower increases in financing flows following a monetary expansion, consistent with our model. Subsection A.3.2 shows that the heterogeneous responses are primarily driven by expansionary monetary shocks. Finally, subsection A.3.3 shows that the heterogeneous responses by leverage hold when we measure leverage using only short term debt, long term debt, or other

TABLE 17
INTERACTION WITH OTHER FIRM-LEVEL COVARIATES

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
leverage × ffr shock	-0.68**		-0.70**		-0.68**		-0.73**	
	(0.28)		(0.30)		(0.28)		(0.28)	
dd × ffr shock		1.10***		1.13***		1.12***		1.13***
		(0.39)		(0.39)		(0.39)		(0.39)
sales growth × ffr shock	-0.18	0.07						
	(0.25)	(0.27)						
future sales growth × ffr shock			-0.37	-0.69				
			(0.44)	(0.57)				
size × ffr shock					0.37	0.56		
					(0.29)	(0.40)		
liquidity × ffr shock							-0.24	-0.31
							(0.31)	(0.35)
Observations	219702	151433	208917	145073	219702	151433	219578	151353
R^2	0.124	0.137	0.128	0.140	0.124	0.137	0.126	0.138
Firm controls	yes	yes	yes	yes	yes	yes	yes	yes
Time sector FE	yes	yes	yes	yes	yes	yes	yes	yes
Time clustering	yes	yes	yes	yes	yes	yes	yes	yes

Notes: results from estimating variants of the baseline specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta_y(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \beta_z z_{jt-1}\varepsilon_t^{\mathrm{m}} + \boldsymbol{\Gamma}_1' Z_{jt-1} + \boldsymbol{\Gamma}_2(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is leverage or distance to default, $\mathbb{E}_j[x_{jt}]$ is the average financial position x_{jt} of firm j in our sample, z_{jt-1} is the firm's lagged sales growth, future sales growth, size, or liquidity, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and quarter. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized within-firm leverage $(\ell_{jt} - \mathbb{E}[\ell_{jt}])$ and within-firm distance to default $(\mathrm{dd}_{jt} - \mathbb{E}[\mathrm{dd}_{jt}])$ over the entire sample, so their units are in standard deviations relative to the mean.

liabilities.

A.3.1 Response of borrowing costs and financing flows

Our model implies that high-risk firms are less responsive to monetary policy shocks because they face a more steeply sloped marginal cost curve for financing investment. Therefore, these firms should see a smaller increase in financing flows and larger increase in borrowing costs in response to a monetary policy expansion. Figure 12 shows that these implications hold

TABLE 18

INTERACTION WITH OTHER MEASURES OF FINANCIAL POSITIONS

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
leverage × ffr shock	-0.68**		-0.67**		-0.68**		-0.73**	
	(0.28)		(0.28)		(0.28)		(0.28)	
dd × ffr shock		1.12***		1.09***		1.09***		1.13***
		(0.39)		(0.39)		(0.39)		(0.39)
size × ffr shock	0.37	0.56						
	(0.29)	(0.40)						
cash flows × ffr shock			-0.02	-0.35				
			(0.46)	(0.63)				
$\mathbb{I}\{\text{dividends} > 0\}\times$ ffr shock					0.39	0.24		
					(0.60)	(0.64)		
liquidity × ffr shock							-0.24	-0.31
							(0.31)	(0.35)
Observations	219702	151433	218185	150350	219482	151311	219578	151353
R^2	0.124	0.137	0.130	0.142	0.125	0.137	0.126	0.138
Firm controls	yes	yes	yes	yes	yes	yes	yes	yes
Time sector FE	yes	yes	yes	yes	yes	yes	yes	yes
Time clustering	yes	yes	yes	yes	yes	yes	yes	yes

Notes: results from estimating variants of the baseline specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta_y(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_1' Z_{jt-1} + \mathbf{\Gamma}_2(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, x_{jt} is leverage, distance to default, size (measured by log of current assets), cash flows, an indicator for whether the firm pays dividends, or liquidity, $\mathbb{E}_j[x_{jt}]$ is the average financial position x_{jt} of firm j in our sample, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized each of the demeaned financial variables $x_{jt} - \mathbb{E}_j[x_{jt}]$ over the entire sample, so their units are in standard deviations relative to the mean.

true in the data, further validating our mechanism.

Panel (a) of Figure 12 shows that borrowing costs persistently increase for high-risk firms relative to low-risk firms following a monetary shock. We define borrowing costs as the ratio of interest and related expenses (`xintq`, item 22) to total liabilities (`ltq`, item 54), which measures the firms' average borrowing costs on both existing and new borrowing. In contrast, the interest rate in the model corresponds to the marginal borrowing cost on new borrowing. Therefore, in the model comparison in Section 6.2, we compare the model's interest rate to the data's average borrowing costs after twelve quarters (which is close to the average

FIGURE 12: Dynamics of Differential Responses of Additional Variables to Monetary Shocks

(a) Response of Average Interest Rates

(b) Response of Financing Flows
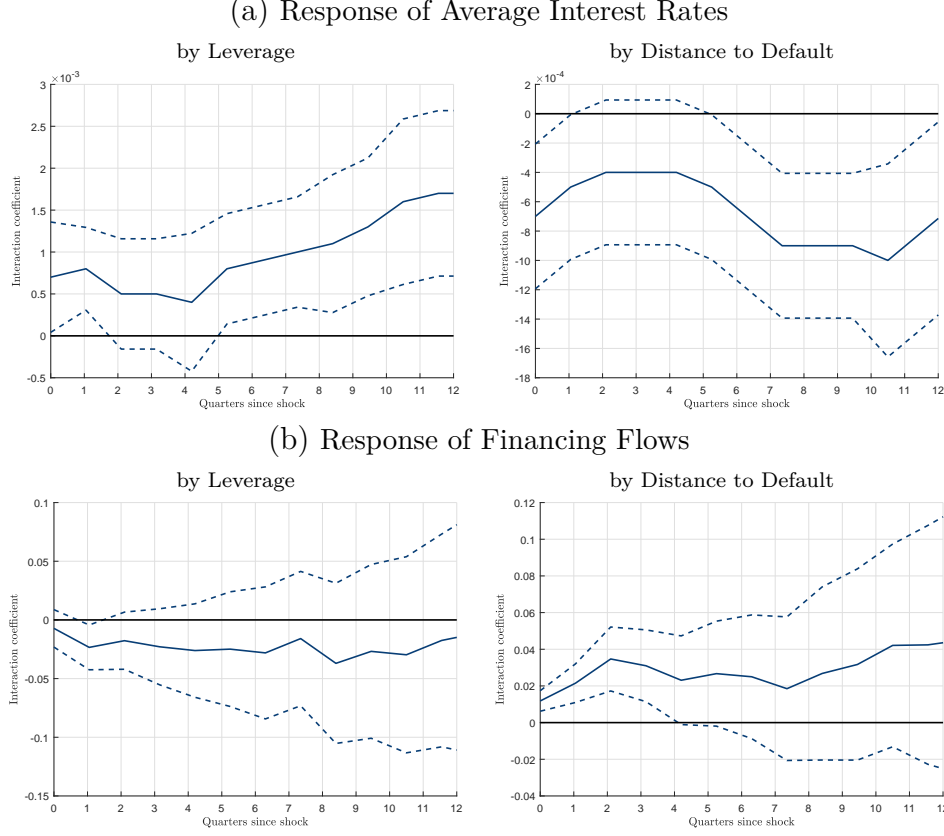
Notes: Reports the coefficient β_h over quarters h from

$$y_{jt+h} = \alpha_{jh} + \alpha_{sth} + \beta_h(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_h' Z_{jt-1} + \mathbf{\Gamma}_{2h}'(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + e_{jt},$$

where y_{jt+h} is either the average interest rate in period $t+h$ or the external financing flows between periods $t+h$ and t, α_{jh} is a firm fixed effect, α_{sth} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is either the firm's leverage ratio or distance to default, $\mathbb{E}_j[x_{jt}]$ is the average of x_{jt} for firm j in the sample, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter, and Y_{t-1} is GDP growth. Standard errors are two-way clustered by firms and time. Dashed lines report 90% error bands. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized within-firm leverage ($\ell_{jt} - \mathbb{E}[\ell_{jt}]$) and within-firm distance to default ($\mathrm{dd}_{jt} - \mathbb{E}[\mathrm{dd}_{jt}]$) over the entire sample, so their units are in standard deviations relative to the mean.

TABLE 19

INSTRUMENTING FINANCIAL POSITION WITH PAST FINANCIAL POSITION

	(1)	(2)	(3)	(4)	(5)	(6)
leverage × ffr shock	-0.72**	-0.84**	-1.35***			
	(0.36)	(0.39)	(0.47)			
dd × ffr shock				1.17***	1.23**	1.24*
				(0.44)	(0.53)	(0.70)
Observations	219674	217179	213207	138989	128745	122547
R^2	0.020	0.019	0.018	0.021	0.021	0.019
Firm controls, Time-Sector FE	yes	yes	yes	yes	yes	yes
Instrument	1q lag	2q lag	4q lag	1q lag	2q lag	4q lag

Notes: IV results from estimating the baseline specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta_y(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^m + \mathbf{\Gamma}_1' Z_{jt-1} + \mathbf{\Gamma}_2(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is leverage or distance to default, $\mathbb{E}_j[x_{jt}]$ is the average financial position x_{jt} of firm j in our sample, ε_t^m is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Within-firm financial position $x_{jt} - \mathbb{E}_j[x_{jt}]$ is instrumented with the past quarter, past two quarters or past four quarters financial position. Standard errors are two-way clustered by firms and quarter. We have normalized the sign of the monetary shock ε_t^m so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized within-firm leverage $(\ell_{jt} - \mathbb{E}[\ell_{jt}])$ and within-firm distance to default $(\mathrm{dd}_{jt} - \mathbb{E}[\mathrm{dd}_{jt}])$ over the entire sample, so their units are in standard deviations relative to the mean.

maturity of debt in Compustat).

Panel (b) of Figure 12 shows that high-risk firms also increase their financing flows by less than low-risk firms following a monetary expansion. We define financing flows as the sum of the change in total debt plus the change in total equity, scaled by assets. We include equity because it is a source of external finance for firms in the data. However, since our model features not equity finance, we do not report its implications for this regression in the main text.

A.3.2 Heterogeneous responses driven by expansionary shocks

Table 20 separately estimates heterogeneous responses for expansionary and contractionary shocks. Although the heterogeneous responses by leverage or distance to default are only significant for expansionary shocks, the differences between the two are at best marginally significant. This result is largely due to the fact that there are relatively few observations of

TABLE 20

EXPANSIONARY VS. CONTRACTIONARY SHOCKS

	(1)	(2)	(3)	(4)
leverage × ffr shock	-0.68**			
	(0.28)			
leverage × pos ffr shock		-0.71**		
		(0.30)		
leverage × neg ffr shock		-0.56		
		(0.96)		
dd × ffr shock			1.10***	
			(0.39)	
dd × pos ffr shock				1.38***
				(0.50)
leverage × neg ffr shock				0.12
				(0.77)
Observations	219702	219702	151433	151433
R^2	0.124	0.124	0.137	0.137
Firm controls	yes	yes	yes	yes
Time sector FE	yes	yes	yes	yes
Time clustering	yes	yes	yes	yes

Notes: results from estimating variants of the baseline specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta_y(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_1' Z_{jt-1} + \mathbf{\Gamma}_2(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is leverage or distance to default, $\mathbb{E}_j[x_{jt}]$ is the average financial position x_{jt} of firm j in our sample, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Columns (2) and (4) contain separate interactions for expansionary and contractionary shocks. Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized within-firm leverage $(\ell_{jt} - \mathbb{E}[\ell_{jt}])$ and within-firm distance to default $(\mathrm{dd}_{jt} - \mathbb{E}[\mathrm{dd}_{jt}])$ over the entire sample, so their units are in standard deviations relative to the mean.

contractionary shocks in our sample, generating large standard errors.

A.3.3 Heterogeneous responses for different measures of leverage

Table 21 decomposes leverage into various types of debt and shows that our results hold for each of these types of debt.[43] In addition, the table shows that our results hold when use

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[43]This decomposition sheds light on the role of the "debt overhang" hypothesis in driving our results. Under this hypothesis, equity holders of highly leveraged firms capture less of the return on investment; since equity holders make the investment decision, they will choose to invest less following the monetary policy shock. However, because investment is long lived, this hypothesis would predict much stronger differences by long term debt. We find that this is not the case; if anything, the differences across firms are stronger for debt due in less than one year.

TABLE 21
DECOMPOSITION OF LEVERAGE

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
leverage × ffr shock	-0.68** (0.28)						
net leverage × ffr shock		-0.71** (0.30)					
ST debt × ffr shock			-0.37 (0.31)		-0.44 (0.31)		
LT debt × ffr shock				-0.20 (0.25)	-0.35 (0.24)		
other liabilities × ffr shock						-0.23 (0.28)	
liabilities × ffr shock							-0.69** (0.31)
Observations	219702	219702	219702	219702	219702	219682	219682
R^2	0.124	0.125	0.124	0.121	0.125	0.124	0.126
Firm controls	yes	yes	yes	yes	yes	yes	yes
Time sector FE	yes	yes	yes	yes	yes	yes	yes
Time clustering	yes	yes	yes	yes	yes	yes	yes

Notes: results from estimating variants of the baseline specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta_y(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_1' Z_{jt-1} + \mathbf{\Gamma}_2(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is leverage or distance to default, $\mathbb{E}_j[x_{jt}]$ is the average financial position x_{jt} of firm j in our sample, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. "Leverage" refers to leverage constructed as in the main text. "Net leverage" is leverage net of current assets. "Short term debt" is current debt (coming due in less than one year) divided by total assets. "Long term debt" is total debt minus current debt divided by total assets. "Other liabilities" is other liabilities divided by total assets. "Liabilities" is total debt plus other liabilities divided by total assets. Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized within-firm leverage ($\ell_{jt} - \mathbb{E}[\ell_{jt}]$) and within-firm distance to default ($\mathrm{dd}_{jt} - \mathbb{E}[\mathrm{dd}_{jt}]$) over the entire sample, so their units are in standard deviations relative to the mean.

leverage net of current assets.

A.4 Comparison to Existing Literature

In this subsection, we relate our findings to empirical studies documenting heterogeneous responses across firms with different size, age, and liquidity. Subsection A.4.1 replicates the results of Gertler and Gilchrist (1994) regarding firm size in our sample and shows that

including their measure of size does not affect our results. Subsection A.4.2 replicates the results of Cloyne et al. (2018) regarding firm age and shows that including their measure of age also does not affect our results. Finally, subsection A.4.4 reconciles our results with recent work by Jeenas (2018).

A.4.1 Relation to Gertler and Gilchrist (1994) and firm size

Gertler and Gilchrist (1994) showed that small firms' sales and inventory holdings were more sensitive to monetary contractions. In this subsection, we replicate their results in our sample and show that they do not affect our main findings. Following Gertler and Gilchrist (1994), we identify a small firm if their average sales over the past ten years is below the 30th percentile of the distribution.[44] We then estimate our baseline dynamic model (6) using this measure of size as the financial position x_{jt}.

Figure 13 replicates the spirit of Gertler and Gilchrist (1994)'s results for investment in our sample. Panel (a) measures monetary contractions as the Romer and Romer (1990) dates in our version of Gertler and Gilchrist (1994)'s time period 1972-1989. It shows that small firms cut investment by more than large firms following a monetary contraction. Panel (b) show that these results also hold using our measure of monetary shocks $\varepsilon_t^{\mathrm{m}}$ in our time period 1990-2007, although the estimates are only marginally statistically significant.[45]

Figure 14 shows that our main results are unaffected by controlling for Gertler and Gilchrist (1994)'s measure of size using the local projection:

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_{1h}(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \beta_{2h}size_{jt-1}^s\varepsilon_t^{\mathrm{m}}$$
$$+ \mathbf{\Gamma}_{1h}'Z_{jt-1} + \mathbf{\Gamma}_{2h}(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + \mathbf{\Gamma}_{3h}size_{jt-1}^sY_{t-1} + e_{jth}. \quad (17)$$

Panel (a) reports results for x_{jt} = leverage and panel (b) reports results for x_{jt} = distance to default. In both cases, the dynamics of the differential response β_{1h} are virtually identical to the main text.[46] This occurs because size and our measures of financial position are largely uncorrelated in our sample. Hence, we view our work as simply focusing on a different feature

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[44]These results are similar if we use five or twenty year averages.

[45]Our findings here are consistent with the analysis in Crouzet and Mehrotra (2017).

[46]This result is robust to measuring size with capital or total assets instead of sales.

FIGURE 13: Dynamics of Differential Responses to Monetary Shocks by Size

(a) Period 1972–1989   (b) Period 1990–2007
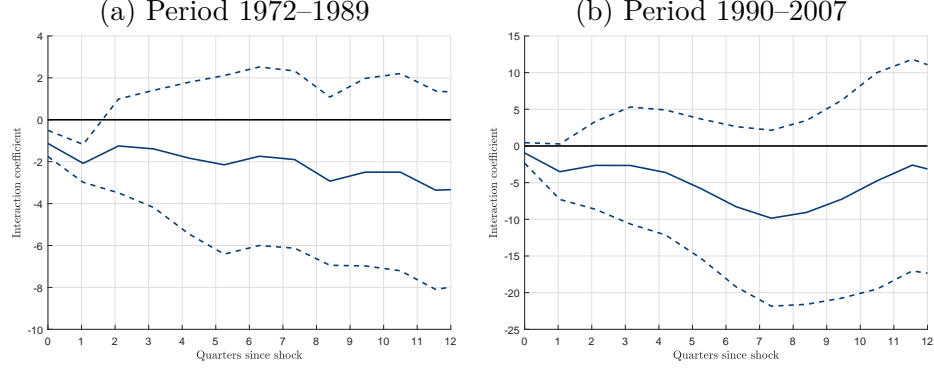
Notes: Estimated coefficients β_h over quarters h from

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_h size_{jt-1}^s \varepsilon_t^m + \mathbf{\Gamma}'_{1h} Z_{jt-1} + \mathbf{\Gamma}'_{2h} size_{jt-1}^s Y_{t-1} + \varepsilon_{jth},$$

where α_{jh} is a firm fixed effect, α_{sth} is a sector-by-quarter fixed effect, $size_{jt}^s$ is a measure of firm size taking the value of one if firm j is "large" in period t and zero otherwise (see main text for definition), ε_t^m is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing $size_{jt}^s$, sales growth, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firm and time. Dashed lines report 90% error bands. We have normalized the sign of the monetary shocks ε_t^m so that a positive shock is expansionary (corresponding to a decrease in interest rates). Monetary shocks in panel (a) correspond to the Romer and Romer (1990) dates.

of the data than Gertler and Gilchrist (1994).

A.4.2   Relation to Cloyne et al. (2018) and firm age

Recent work Cloyne et al. (2018) argues that younger firms are more responsive to monetary policy in both the U.S. and the U.K. In this subsection, we replicate the spirit of their results in our sample and show that they do not affect our main results. Following Cloyne et al. (2018), we measure age as time since incorporating, which we download from Datastream.

Figure 15 replicates the spirit of Cloyne et al. (2018)'s results in our sample. Following Cloyne et al. (2018), we classify firms as "young" (whose age since incorporation is less than fifteen years), "middle aged" (between fifteen and fifty years), and "older" (more than fifty years). Middle-aged and old firms are less responsive to monetary shocks, although these differences are not statistically significant for most horizons in our specification and sample.[47]
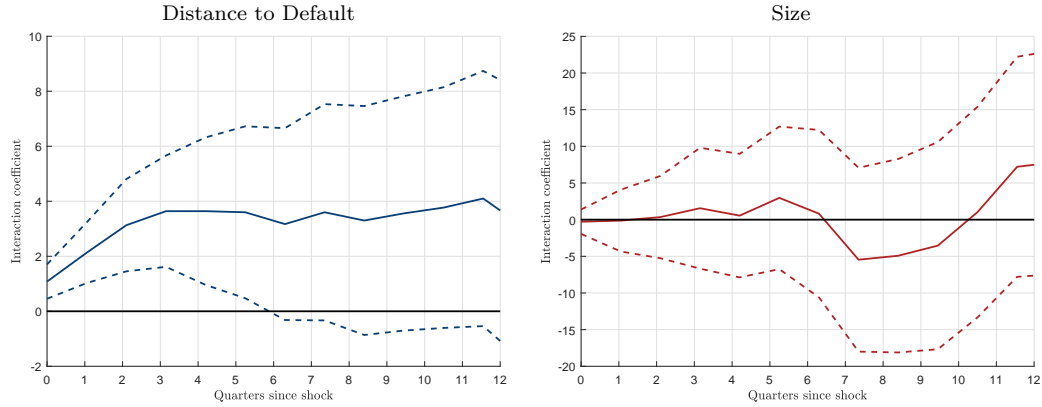
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[47]A potentially important difference between our specifications is that Cloyne et al. (2018) measure monetary policy shocks with a VAR approach and use the high-frequency shocks as an instrumental variable.

FIGURE 14: Joint Dynamics of Financial Position and Size

(a) Leverage and Size
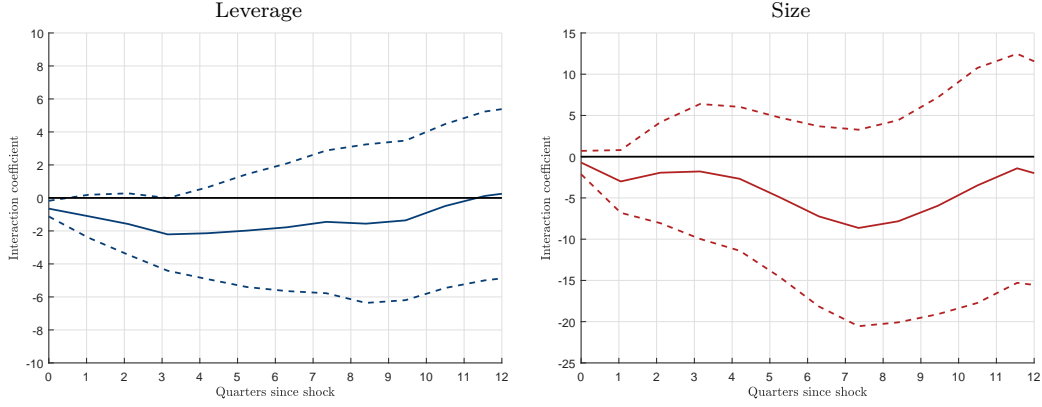


(b) Distance to Default and Size

Notes: Estimated coefficients β_{1h} and β_{2h} over quarters h from

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_{1h}(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \beta_{2h}size_{jt-1}^s\varepsilon_t^{\mathrm{m}}$$
$$+ \mathbf{\Gamma}_{1h}'Z_{jt-1} + \mathbf{\Gamma}_{2h}'(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + \mathbf{\Gamma}_{3h}'size_{jt-1}^sY_{t-1} + e_{jt},$$

where α_{jh} is a firm fixed effect, α_{sth} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, dd_{jt}\}$ is leverage or distance to default, $size_{jt}^s$ is a measure of firm size taking the value of one if firm j is "large" in period t and zero otherwise (see main text for definition), $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and time. Dashed lines report 90% error bands. Panel (a) runs our baseline specification with leverage $x_{jt} = \ell_{jt}$. Panel (b) runs our preferred specification with distance to default $x_{jt} = dd_{jt}$. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized the demeaned financial position variables $x_{jt} - \mathbb{E}_j[x_{jt}]$ and demeaned liquidity $x_{jt} - \mathbb{E}_j[x_{jt}]$ over the entire sample, so their units are in standard deviations relative to the mean.

FIGURE 15: Dynamics of Differential Responses to Monetary Shocks by Age

(a) Middle-age Firms

(b) Older Firms
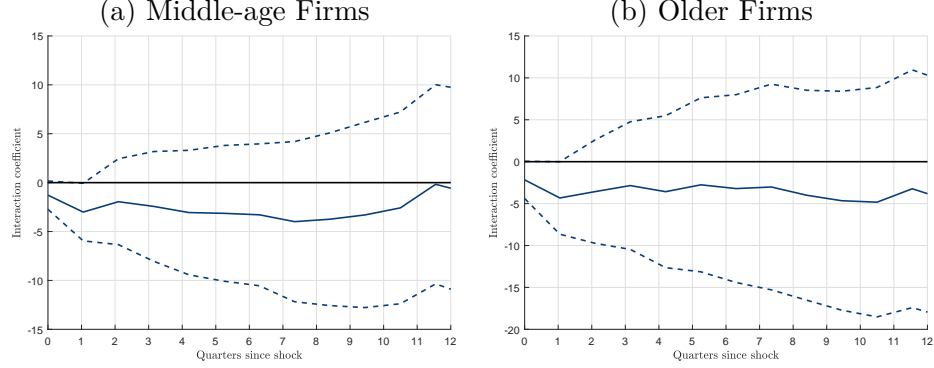
Notes: Estimated coefficients $\boldsymbol{\beta}_h$ over quarters h from

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \boldsymbol{\beta}'_h age_{jt} \varepsilon_t^{\mathrm{m}} + \boldsymbol{\Gamma}'_{1h} Z_{jt-1} + \boldsymbol{\Gamma}'_{2h} age_{jt} Y_{t-1} + \varepsilon_{jth},$$

where α_{jh} is a firm fixed effect, α_{sth} is a sector-by-quarter fixed effect, $age_{jt} \equiv [middleage_{jt}\ oldage_{jt}]'$ is a vector with two dummy variables measuring firm age (see main text for definition), $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Y_{t-1} is lagged GDP growth and Z_{jt-1} is a vector of firm-level controls containing age, size, sales growth, current assets as a share of total assets, and an indicator for fiscal quarter. Panel (a) shows the interactive coefficient associated with the variable $middleage_{jt}$ and Panel (b) shows $oldage_{jt}$. Standard errors are two-way clustered by firm and time. Dashed lines report 90% error bands. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates).

Figure 16 shows that our main results are robust to controlling for these measures of firm age. We view these findings as reflecting the fact that we analyze a different dimension of the data than Cloyne et al. (2018). We obtain similar results if we interact the monetary shock with the level of the firm's age rather than these coarse categories.

A.4.3 Relation to firm volatility literature

In this subsection, we explore the empirical link between firm-level volatility and the response to monetary policy. Our motivation is a growing strand of literature that has argued that firm-level volatility is an important determinant of how those firms respond to shocks (see, e.g., Vavra (2013) or Bloom et al. (2015)). Indeed, one can view volatility as a proxy for default risk, since all else equal firms with more volatile cash flows will default more frequently. We measure volatility vol_{jt} as the standard deviation of the firm's year-on-year sales growth over the past twenty quarters.

Panel (a) of Figure 17 shows that firms with more volatile sales growth are less respon-

FIGURE 16: Joint Dynamics of Financial Position and Age

(a) Leverage and Age

(b) Distance to Default and Age
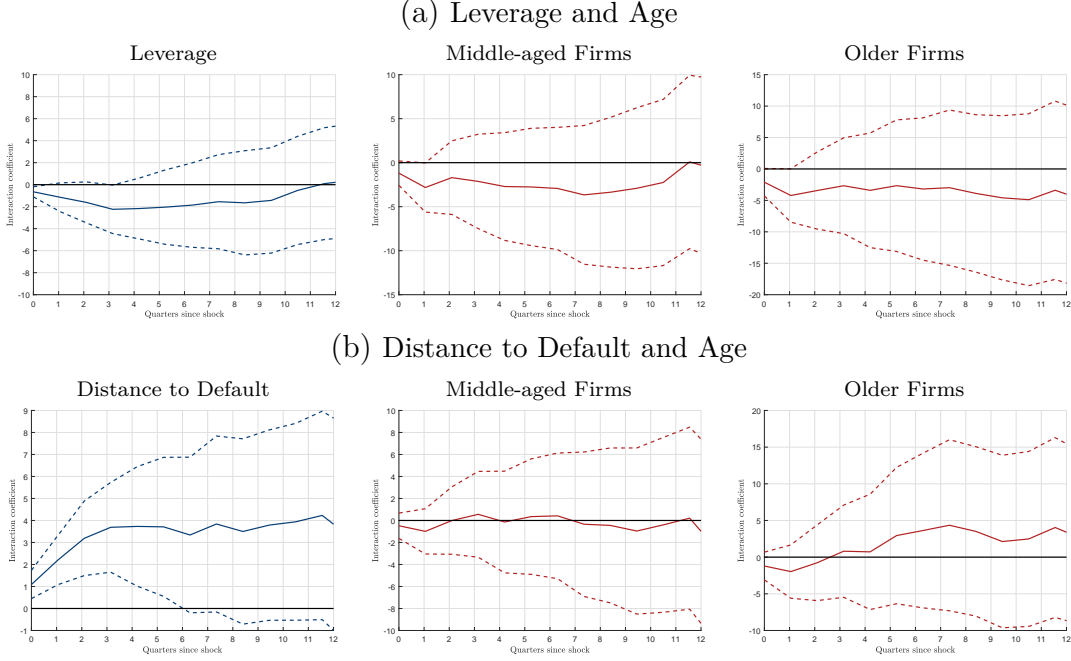
Notes: Estimated coefficients β_{1h} and $\boldsymbol{\beta}_{2h}$ over quarters h from

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_{1h}(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \boldsymbol{\beta}_{2h}' age_{jt}\varepsilon_t^{\mathrm{m}}$$
$$+ \boldsymbol{\Gamma}_{1h}' Z_{jt-1} + \boldsymbol{\Gamma}_{2h}'(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + \boldsymbol{\Gamma}_{3h}' age_{jt}Y_{t-1} + e_{jt},$$

where α_{jh} is a firm fixed effect, α_{sth} is a sector-by-quarter fixed effect, $age_{jt} \equiv [middleage_{jt}\ oldage_{jt}]'$ is a vector with two dummy variables measuring firm age (see main text for definition) $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and time. Dashed lines report 90% error bands. Panel (a) runs our baseline specification with leverage $x_{jt} = \ell_{jt}$. Panel (b) runs our preferred specification with distance to default $x_{jt} = dd_{jt}$. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized the demeaned financial position variables $x_{jt} - \mathbb{E}_j[x_{jt}]$ and demeaned liquidity $x_{jt} - \mathbb{E}_j[x_{jt}]$ over the entire sample, so their units are in standard deviations relative to the mean.

FIGURE 17: Dynamics of Differential Responses to Monetary Shocks by Volatility

(a) 5-year window

(b) 10-year window
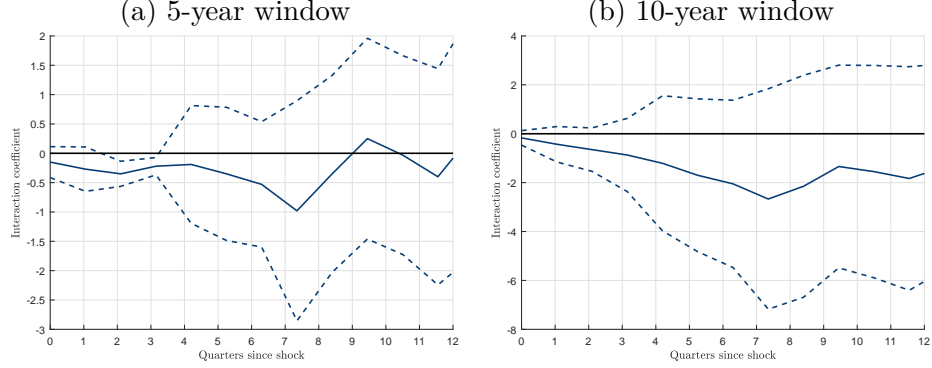
Notes: Estimated coefficients β_h over quarters h from

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_h \mathrm{vol}_{jt-1} \varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}'_{1h} Z_{jt-1} + \mathbf{\Gamma}'_{2h} \mathrm{vol}_{jt-1} Y_{t-1} + \varepsilon_{jth},$$

where α_{jh} is a firm fixed effect, α_{sth} is a sector-by-quarter fixed effect, vol_{jt} is the standard deviation of the firm's year-on-year sales growth over the past five or ten years, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing vol_{jt}, sales growth, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firm and time. Dashed lines report 90% error bands. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized volatility vol_{jt}, so their units are in standard deviations relative to the mean.

sive to monetary policy. Quantitatively, the estimates imply that a firm with one standard deviation higher volatility has an approximately 0.5 units low semi-elasticity of investment with respect to monetary policy. Panel (b) shows that these differential responses are larger if we measure volatility over the past forty quarters rather than the past twenty.

However, Panel (a) of Figure 18 shows that these heterogeneous responses by volatility become insignificant once we control for heterogeneity in distance to default. We therefore conclude that the differences by volatility are in fact driven by differences in default risk, consistent with our model. Panel (b) shows that controlling for leverage has a smaller effect on the heterogeneous responses by volatility.

### A.4.4 Relation to Jeenas (2018) and firm liquidity

In this subsection, we relate our findings to recent work by Jeenas (2018) along two dimensions. First, we show that the differences between our estimated dynamics are accounted for by permanent heterogeneity in responsiveness across firms. Second, we show that our results

FIGURE 18: Joint Dynamics of Financial Position and Volatility

(a) Distance to Default and Volatility
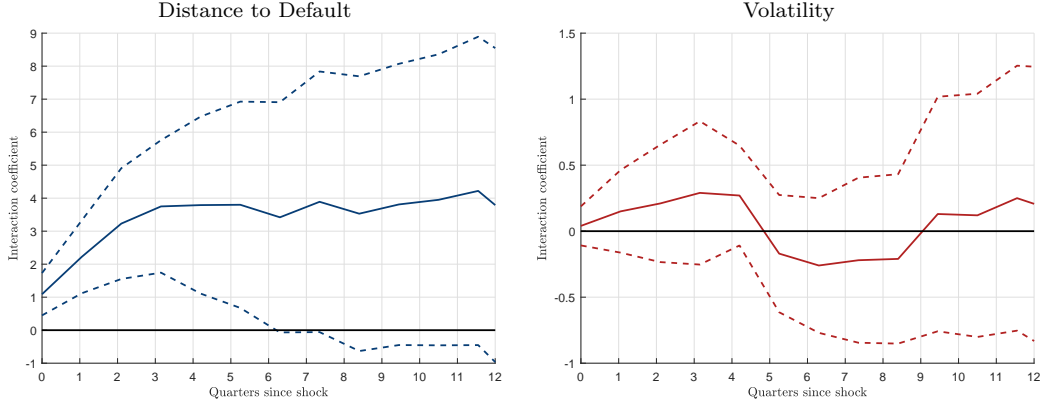
(b) Leverage and Volatility
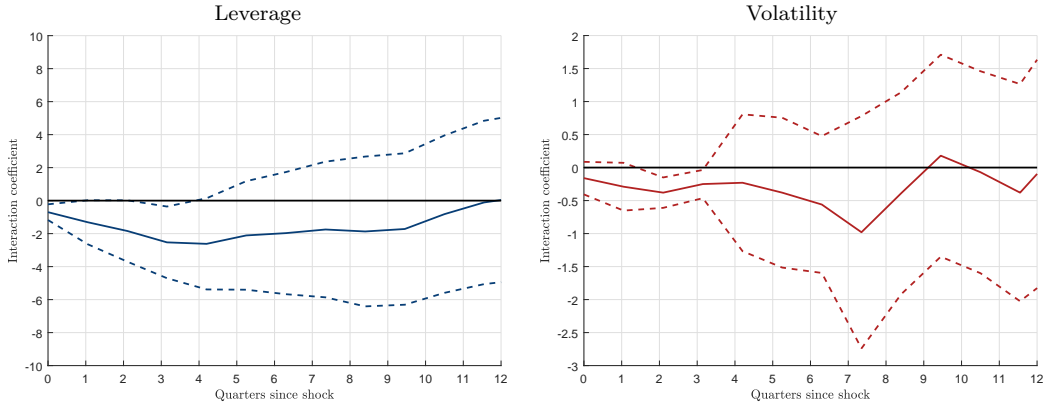
Notes: Estimated coefficients β_{1h} and β_{2h} over quarters h from

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_{1h}(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \beta_{2h}\mathrm{vol}_{jt-1}\varepsilon_t^{\mathrm{m}}$$
$$+ \mathbf{\Gamma}'_{1h}Z_{jt-1} + \mathbf{\Gamma}'_{2h}(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + \mathbf{\Gamma}'_{3h}\mathrm{vol}_{jt-1}Y_{t-1} + e_{jt},$$

where α_{jh} is a firm fixed effect, α_{sth} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, dd_{jt}\}$ is leverage or distance to default, vol_{jt} is the standard deviation of the firm's year-on-year sales growth over the past five or ten years, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing vol_{jt}, x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and time. Dashed lines report 90% error bands. Panel (a) runs our baseline specification with leverage $x_{jt} = \ell_{jt}$. Panel (b) runs our preferred specification with distance to default $x_{jt} = dd_{jt}$. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized the demeaned financial position variables $x_{jt} - \mathbb{E}_j[x_{jt}]$ and volatility vol_{jt}, so their units are in standard deviations relative to the mean.

are not driven by differences in liquidity across firms.

Dynamics   We begin by replicating Jeenas (2018)'s results in our sample. For reference, Panel (a) of Figure 19 plots the dynamics of the interaction of within-firm leverage and the monetary shock $(\ell_{jt-1} - \mathbb{E}_j[\ell_{jt-1}])\varepsilon_t^{\mathrm{m}}$ from the local projection

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_h(\ell_{jt-1} - \mathbb{E}_j[\ell_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_{1h}' Z_{jt-1} + \mathbf{\Gamma}_{2h}'(\ell_{jt-1} - \mathbb{E}_j[\ell_{jt}])Y_{t-1} + \varepsilon_{jth}, \quad (18)$$
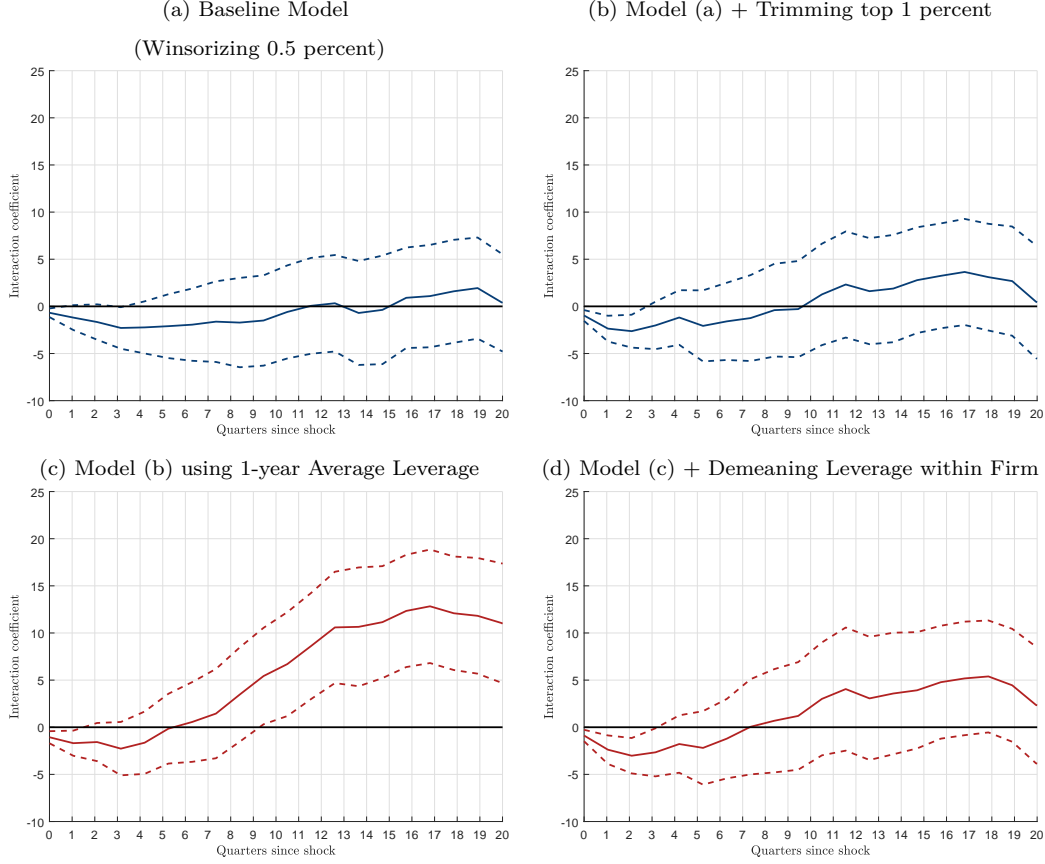
which simply extends Figure 1 from the main text out to twenty quarters. Jeenas (2018)'s specification differs from our's in two key ways. First, Jeenas (2018) drops observations in the top 1% of the leverage distribution while we winsorize the top 0.5%.[48] Second, Jeenas (2018) computes the interaction between the monetary shock and the firm's average leverage over the past four quarters, $\widehat{\ell}_{jt-1}$, rather than the within-firm variation in the stock of leverage in the past quarter, $\ell_{jt} - \mathbb{E}_j[\ell_{jt}]$. Panel (d) applies these two operations and recovers the spirit of Jeenas (2018)'s result: high-leverage firms become substantially more responsive to the shock after approximately four quarters. Quantitatively, this point estimate implies that four years after a one percentage point expansionary shock, a firm with one standard deviation more leverage than the average firm increases their capital stock by over ten percentage points more than the average firm.

The remaining panels of Figure 19 decompose the effect of these two differences between our specifications on the estimated dynamics. Panel (b) shows that Jeenas (2018)'s more aggressive trimming of high-leverage observations has an insignificant effect on the estimated dynamics. In this panel, we estimate our baseline specification (18) after dropping observations in the top 1% of the leverage distribution and find that high-leverage firms are not statistically significantly more responsive to monetary policy.

Panel (c) shows that sorting firms by the average of their past four quarters of leverage $\widehat{\ell}_{jt-1}$ accounts for the difference between our results. In this panel, we re-estimate our dynamic specification (18) after dropping the top 1% of leverage observations and replacing the within-firm variation in last quarter's stock of leverage $\ell_{jt} - \mathbb{E}_j[\ell_{jt}]$ with Jeenas (2018)'s moving average $\widehat{\ell}_{jt-1}$. The moving average eliminates high-frequency variation in leverage

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[48]We winsorize the top 0.5% rather than drop the top 1% because the most highly indebted firms are the most likely to have substantial default risk, which is our object of interest.

FIGURE 19: Comparison of Our Dynamic Results to Jeenas (2018)

(a) Baseline Model

(Winsorizing 0.5 percent)

(b) Model (a) + Trimming top 1 percent

(c) Model (b) using 1-year Average Leverage

(d) Model (c) + Demeaning Leverage within Firm

Notes: dynamics of the interaction coefficient between leverage and monetary shocks over time. Reports the coefficient β_h over quarters h from

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_h(\ell_{jt} - \mathbb{E}_j[\ell_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_{1h}' Z_{jt-1} + \mathbf{\Gamma}_{2h}'(\ell_{jt} - \mathbb{E}_j[\ell_{jt}])Y_{t-1} + e_{jt},$$

where α_{jh} is a firm fixed effect, α_{sth} is a sector-by-quarter fixed effect, ℓ_{jt-1} is leverage, $\mathbb{E}_j[\ell_{jt}]$ is the average leverage of firm j in our sample, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Y_{t-1} is lagged GDP growth, and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and time. Dashed lines report 90% error bands. Panel (b) drops the top 1% of the observations in the leverage variable used in the particular forecasting horizons. Panel (c) applies this operation and replaces demeaned leverage $\ell_{jt-1} - \mathbb{E}_j[\ell_{jt}]$ with the firm's average leverage over the last four quarters, $\widehat{\ell}_{jt-1}$. Panel (d) estimates this specification using only within-firm variation in averaged leverage $\widehat{\ell}_{jt-1} - \mathbb{E}[\widehat{\ell}_{jt}]$. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt}, averaged leverage $\widehat{\ell}_{jt}$, and demeaned average leverage $\widehat{\ell}_{jt} - \mathbb{E}[\widehat{\ell}_{jt}]$ over the entire sample, so their units are in standard deviations relative to the mean.

within a firm, implying that the estimated dynamics are more strongly driven by permanent heterogeneity across firms. Consistent with this idea, Panel (d) shows that using only within-firm variation in averaged leverage $\widehat{\ell}_{jt-1} - \mathbb{E}_j[\widehat{\ell}_{jt}]$ renders the long-horizon dynamics smaller and significantly insignificant, largely consistent with our baseline specification. We prefer our specification because it maps more directly into our economic model in which heterogeneity in leverage is driven by ex-post realizations of idiosyncratic shocks and lifecycle dynamics across firms. We focus our analysis of the model on the heterogeneous responses upon impact, which are robustly estimated in both our specification and Jeenas (2018) and survive the litany of robustness checks in Appendices A.2 and A.3.[49]

Heterogeneous Responses Not Driven by Liquidity Jeenas (2018) argues that the dynamics of heterogeneous responses by leverage documented above are driven by differences in liquidity across firms. Table 18 above shows that the heterogeneous responses upon impact are not driven by liquidity once we use within-firm variation in our main specification (5). Figure 20 shows that our dynamics results are not driven by differences in liquidity either. We estimate the local projection
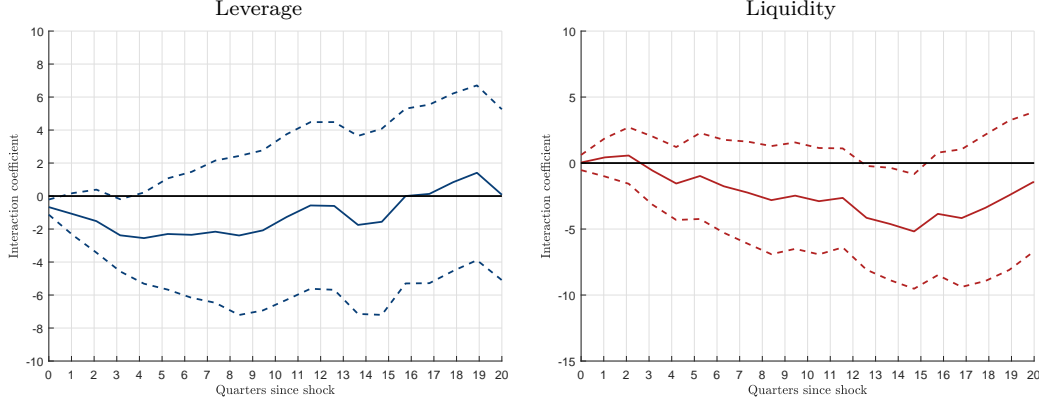
$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_{1h}(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \beta_{2h}(y_{jt-1} - \mathbb{E}_j[y_{jt}])\varepsilon_t^{\mathrm{m}} \qquad (19)$$
$$+ \mathbf{\Gamma}_{1h}' Z_{jt-1} + \mathbf{\Gamma}_{2h}(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + \mathbf{\Gamma}_{3h}(y_{jt-1} - \mathbb{E}_j[y_{jt}])Y_{t-1} + e_{jth},$$

where $y_{jt} - \mathbb{E}_j[y_{jt}]$ is the within-firm variation in liquidity. Panel (a) shows that the point estimate of the leverage dynamics are similar to those presented in the main text, although the standard errors are wider given the correlation between leverage and liquidity. Panel (b) shows that the dynamics of distance to default are strongly and significantly positive, as in the main text. In that case, the dynamics of liquidity are always statistically insignificant,

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[49]An additional difference between our specification and Jeenas (2018)'s is that we control for differences in cyclical sensitivities while Jeenas (2018) does not. We include these controls because we have found that there are significant differences in long-run cyclical sensitivities and that GDP growth is correlated with monetary shocks over these horizons in our sample. Appendix A.3 shows that excluding these controls does not affect the point estimates in our specification but does increase the standard errors. We have also found that excluding these controls does not strongly affect the point estimates or standard errors in Jeenas (2018)'s baseline specification with averaged leverage $\widehat{\ell}_{jt}$. Excluding these controls slightly increases the responsiveness of high demeaned average leverage firms $\widehat{\ell}_{jt} - \mathbb{E}_j[\widehat{\ell}_{jt}]$, but the difference from Panel (d) in Figure 19 is small and not statistically significant.

FIGURE 20: Joint Dynamics of Financial Position and Liquidity

(a) Leverage and Liquidity

(b) Distance to Default and Liquidity
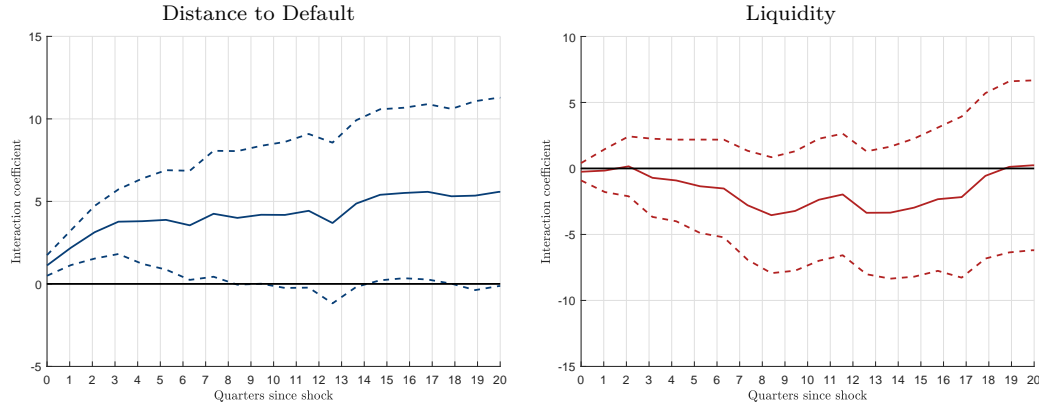
Notes: estimated coefficients β_{1h} and β_{2h} over quarters h from

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_{1h}(x_{jt-1} - \mathbb{E}_j[x_{jt}])\varepsilon_t^{\mathrm{m}} + \beta_{2h}(y_{jt-1} - \mathbb{E}_j[y_{jt}])\varepsilon_t^{\mathrm{m}}$$
$$+ \mathbf{\Gamma}_{1h}'Z_{jt-1} + \mathbf{\Gamma}_{2h}'(x_{jt-1} - \mathbb{E}_j[x_{jt}])Y_{t-1} + \mathbf{\Gamma}_{3h}'(y_{jt-1} - \mathbb{E}_j[y_{jt}])Y_{t-1} + e_{jt},$$

where α_{jh} is a firm fixed effect, α_{sth} is a sector-by-quarter fixed effect, $x_{jt} \in \{\ell_{jt}, \mathrm{dd}_{jt}\}$ is leverage or distance to default, y_{jt} is liquidity, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Y_{t-1} is lagged GDP growth and Z_{jt-1} is a vector of firm-level controls containing x_{jt-1}, liquidity, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and time. Dashed lines report 90% error bands. Panel (a) runs our baseline specification with leverage $x_{jt} = \ell_{jt}$. Panel (b) runs our preferred specification with distance to default $x_{jt} = \mathrm{dd}_{jt}$. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized the demeaned financial position variables $x_{jt} - \mathbb{E}_j[x_{jt}]$ and demeaned liquidity $y_{jt} - \mathbb{E}_j[y_{jt}]$ over the entire sample, so their units are in standard deviations relative to the mean.

suggesting that default risk the primary source of heterogeneous responses across firms when using within-firm variation.

B   Model Appendix

B.1   Proof of Proposition 1

We prove Proposition 1 in steady state; extending the proof to include transition dynamics is straightforward. To clarify the economic mechanisms, we work with a simple version of the model that abstracts from capital-quality shocks ($\sigma_\omega = 0$), has zero recovery value of debt ($\alpha = 0$), and has no exogenous exit shocks ($\pi_d = 0$). The proof in the full model follows the same steps with more complicated notation.

Default Threshold   As discussed in the main text, firms only default when they have no feasible choice which satisfies the non-negativity constraint on dividends, i.e., there is no (k', b') such that $n - k' + \mathcal{Q}(z, k', b')b' \geq 0$. Define the default threshold $\underline{n}(z) = \min_{k',b'} k' - \mathcal{Q}(z, k', b')b'$. Note that the largest feasible dividend payment of a firm is $n - \underline{x}(z)$. If $n \geq \underline{n}(z)$, then $\arg\min_{k',b'} k' - \mathcal{Q}(z, k', b')b'$ is a feasible choice and the firm will not default. On the other hand, if $n < \underline{n}(z)$, then $d \leq 0$ for all (k', b'), violating feasibility.

With this notation in hand, the Bellman equation of a continuing firm in this simple case is

$$v(z, n) = \max_{k',b'} n - k' + \mathcal{Q}(z, k', b')b' + \beta\mathbb{E}\left[v(z', n')\mathbb{1}\{n' > \underline{n}(z')\}|z, k', b'\right] \ \text{s.t.} \ d \geq 0, \quad (20)$$

where $\underline{n}(z')$ is the default threshold.

Although the continuation value is kinked at the default point, it is never optimal for a firm to choose this point (see Clausen and Strub (2017) and the discussion in Arellano et al. (2016)). Hence, the first order conditions are necessary at the optimum.

Unconstrained Firms   Define the *unconstrained capital accumulation rule $k^*(z)$* as

$$k^*(z) = \underset{k'}{\arg\max} -k' + \beta\mathbb{E}\left[\iota(z', k') + (1 - \delta)k'|z\right],$$

where $\iota(z, k) = \max_l zk^\theta l^\nu - wl$. After some algebra, one can show that the expression in the main text solves this maximization problem (extending the expression to the full model).

We will now fully characterize the decision rules for firms that can afford the unconstrained capital accumulation rule while have zero probability of default in all future states. We first claim that such a firm is indifferent over any choice of debt b' which leaves the firm unconstrained. To show this, note that since the firm has no default risk it borrows at the risk-free rate β. In this case, the first order condition for borrowing b' is $\beta = \beta$, which is obviously true for any value of b'.

Following Khan, Senga and Thomas (2016), we resolve this indeterminacy by defining the *maximum borrowing policy* $b^*(z)$ as the maximal borrowing b' the firm can do while having zero probability of default in all future states.[50] To derive the maximum borrowing policy $b^*(z)$, first note that if the firm if the firm invests $k^*(z)$ and borrows $b^*(z)$ in the current period, its dividends in the next period are

$$\iota(z', k^*(z)) + (1 - \delta)k^*(z) - b^*(z) - \xi - k^*(z') + \beta b^*(z'),$$

for a given realization of z'. The requirement that the firm has zero probability of default in all future states then implies that

$$b^*(z) = \min_{z'} \iota(z', k^*(z)) + (1 - \delta)k^*(z) - k^*(z') + \beta b^*(z').$$

Hence, $b^*(z)$ is the largest amount of borrowing the firm can do and be guaranteed to satisfy the non-negativity constraint on dividends.[51]

By construction, if a firm can follow the unconstrained capital accumulation policy $k^*(z)$ and the maximum borrowing policy $b^*(z)$ while satisfying the non-negativity constraint on dividends in the current period, it will also satisfy the non-negativity constraint in all future periods. Moreover, following $k^*(z)$ is indeed optimal for such firms because it solves the associated first-order condition of these firms. Hence, a firm is *unconstrained* and follows

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[50]Khan, Senga and Thomas (2016) refer to this object as the "minimum savings policy."

[51]To derive this expression, first re-arrange the non-negativity constraint on dividends conditional on a realization of the future shocks as an inequality with b' on the left-hand side. This results in a set of inequalities for each possible realization of the future shocks. The min operator ensures that all of these inequalities are satisfied.

these decision rules if and only if $d = n - k^*(z) + \beta b^*(z)$, i.e.,

$$n > \underline{n}(z) \equiv k^*(z) - \beta b^*(z).$$

Constrained Firms Consider again the constrained Bellman equation (20). We will show that firms with $n \in [\underline{n}(z), \overline{n}(z)]$ pay zero dividends. Invert the default threshold $\underline{n}(z)$ so that the firm defaults if $z' < \underline{z}(k', b')$. The Bellman equation (20) can then be written as

$$v(z, n) = \max_{k', b'} n - k' + \mathcal{Q}(z, k', b')b' + \beta \int_{\underline{z}(k', b')}^{\overline{z}} v(z', n')g(z'|z)\mathrm{d}z' \text{ s.t. } d \geq 0, \quad (21)$$

where $g(z'|z)$ is the density of z' conditional on z, $\overline{z}$ is the upper bound of the support of z, and $\mathcal{Q}_3(z, k', b')$ is the derivative of the debt price schedule with respect to b'.

Letting $\lambda(z, n)$ be the Lagrange multiplier on the $d \geq 0$ constraint, the first order condition for b' is

$$(1 + \lambda(z, n))(\mathcal{Q}(z, k', b') + \mathcal{Q}_3(z, k', b')b') =$$
$$\beta \left[\int_{\underline{z}(k', b')}^{\overline{z}} (1 + \lambda(z', k', b')g(z'|z)\mathrm{d}z' + g(\underline{z}(k', b')|z)v(\underline{z}(k', b'), \hat{n}'(k', b'))\frac{\partial \underline{z}(k', b')}{\partial b'} \right],$$

where $\hat{n}'(k', b') = \max_{n'} \underline{z}(k', b')(k')^\theta (n')^\nu - wn' + (1 - \delta)k' - b' - \xi$ and $\lambda(z', k', b') = \lambda(z', n')$ for the n' implied by (z', k', b'). The left hand side of this expression measures the marginal benefit of borrowing. The marginal resources the firm receives on borrowing is the debt price, adjusting for the fact that the marginal cost of borrowing changes on existing debt. The firm values those marginal resources using the Lagrange multiplier. The right hand side of this expression measures the discounted marginal cost of borrowing. In states of the world in which the firm does not default, it must give up one unit of resources, which it values using the next period's Lagrange multiplier. In addition, marginal borrowing implies that the firm defaults in additional future states.

Note that the debt price schedule is $\mathcal{Q}(z, k', b') = \beta \int_{\underline{z}(k', b')}^{\overline{z}} g(z'|z)\mathrm{d}z'$, which implies that

$\mathcal{Q}_3(z, k', b') = -\beta g(\underline{z}(k', b')|z)\frac{\partial \underline{z}(k', b')}{\partial b'}$. Plugging this into the first order condition gives

$$\beta(1 + \lambda(z, n))(\int_{\underline{z}(k',b')}^{\overline{z}} g(z'|z)\mathrm{d}z' - \beta g(\underline{z}(k', b')|z)\frac{\partial \underline{z}(k', b')}{\partial b'} =$$
$$\beta\left[\int_{\underline{z}(k',b')}^{\overline{z}} (1 + \lambda(z', k', b')g(z'|z)\mathrm{d}z' + g(\underline{z}(k', b')|z)v(\underline{z}(k', b'), \hat{n}'(k', b'))\frac{\partial \underline{z}(k', b')}{\partial b'}\right]. \quad (22)$$

We will now show that constrained firms set $d = 0$. We do so by contradiction: suppose that a constrained firm sets $d > 0$, implying that $\lambda(z, n) = 0$.

First consider a firm that has zero probability of default in the next period, i.e., $\underline{z}(k', b') = \underline{z}$ and $\frac{\partial \underline{z}(k',b')}{\partial b'} = 0$. In this case, the first order condition (22) can be simplified to

$$0 = \int_{\underline{z}}^{\overline{z}} \lambda(z', k', b')g(z'|z)\mathrm{d}z'.$$

Since the firm is constrained, $\lambda(z', k', b') > 0$ for some positive mass of realizations of z', leading to a contradiction.

Now consider a firm that has some positive probability of default, implying that $\underline{z}(k', b') > \underline{z}$ and $\frac{\partial \underline{z}(k',b')}{\partial b'} > 0$. In this case, the first order condition (22) can be rearranged to

$$0 = \int_{\underline{z}(k',b')}^{\overline{z}} \lambda(z', k', b')g(z'|z)\mathrm{d}z' + \frac{\partial \underline{z}(k', b')}{\partial b'}g(\underline{z}(k', b')|z)(b' + v(z', k', b')),$$

where $v(z', k', b') = v(z', x')$ for the x' implied by (z', k', b'). By construction, risky constrained firms engage in strictly positive borrowing $b' > 0$. This implies that the right hand side is strictly greater than zero, leading to a contradiction.

B.2 Equilibrium Definition

Distribution of Firms We need to derive the evolution of the distribution of firms in order to precisely define an equilibrium. The distribution of firms in production is composed of incumbents who do not default and new entrants who do not default. Mathematically,

this distribution $\hat{\mu}_t(z, n)$ is given by

$$\hat{\mu}_t(z, n) = \int \left(\pi_d \chi^1(n_t(z, \omega, k, b)) + (1 - \pi_d)\chi_t^2(z, n_t(z, \omega, k, b)) \right) \mathrm{d}\mu_t(z, \omega, k, b) \qquad (23)$$

$$+ \overline{\mu}_t \int \left(\pi_d \chi^1(n_t(z, \omega, k_0, 0)) + (1 - \pi_d)\chi_t^2(z, n_t(z, \omega, k_0, 0)) \right) g(\omega)\mathrm{d}\omega \mathrm{d}\mu^{\mathrm{ent}}(z),$$

where $n_t(z, \omega, k, b) = \max_l p_t z(\omega k)^\theta l^\nu - w_t l + q_t(1 - \delta)\omega k - b - \xi$ is the implied net worth x of a firm with state (z, ω, k, b) and $g(\omega)$ is the p.d.f. of capital quality shocks.

The evolution of the distribution of firms $\mu_t(z, \omega, k, b)$ is given by

$$\mu_{t+1}(z', \omega', k', b') = \int (1 - \pi_d)\chi_t^2(z, n_t(z, \omega, k, b)) 1\{k_t'(z, n_t(z, \omega, k, b)) = k'\} \qquad (24)$$

$$\times \mathbb{1}\{\frac{b_t'(z, n_t(z, \omega, k, b))}{\Pi_{t+1}} = b'\} p(\varepsilon | e^{\rho \log z + \varepsilon} = z')g(\omega')\mathrm{d}\varepsilon \mathrm{d}\mu_t(z, \omega, k, b)$$

$$+ \overline{\mu}_t \int (1 - \pi_d)\chi_t^2(z, n_t(z, \omega, k_0, 0)) 1\{k_t'(z, n_t(z, \omega, k_0, 0)) = k'\}$$

$$\times \mathbb{1}\{\frac{b_t'(z, n_t(z, \omega, k_0, 0))}{\Pi_{t+1}} = b'\} p(\varepsilon | e^{\rho \log z + \varepsilon} = z')g(\omega')\mathrm{d}\varepsilon \mathrm{d}\mu^{\mathrm{ent}}(z),$$

where $p(\varepsilon | e^{\rho \log z + \varepsilon} = z')$ denotes the density of draws ε such that $e^{\rho \log z + \varepsilon} = z'$.

Equilibrium Definition An **equilibrium** of this model is a set of $v_t(z, n)$, $k_t'(z, n)$, $b_t'(z, n)$, $n_t(z, n)$, $\mathcal{Q}_t(z, k', b')$, Π_t, Δ_t, Y_t, q_t, $\mu_t(z, \omega, k, b)$, $\hat{\mu}_t(z, n)$, $\Lambda_{t,t+1}$, w_t, C_t, and I_t such that

(i) Production firms optimization: $v_t(z, n)$ solves the Bellman equation (9) with associated decision rules $k_t'(z, n)$, $b_t'(z, n)$, and $n_t(z, n)$.

(ii) Financial intermediaries price default risk according to (10).

(iii) New Keynesian block: Π_t, p_t, and q_t satisfy (11) and (13).

(iv) The distribution of firms in production $\hat{\mu}_t(z, n)$ satisfies (23) and the distribution $\mu_t(z, \omega, k, b)$ evolves according to (24).

(v) Household block: the stochastic discount factor is given by $\Lambda_{t,t+1} = \beta \frac{C_{t+1}^{-\sigma}}{C_t^{-\sigma}}$. The wage must satisfy $w_t = \Psi C_t$. The stochastic discount factor and nominal interest rate are

linked through the Euler equation for bonds, $1 = \mathbb{E}_t \left[\Lambda_{t,t+1} \frac{R_t^{\text{nom}}}{\Pi_{t+1}} \right]$.

(vi) Market clearing: aggregate investment is implicitly defined by $K_{t+1} = \Phi(\frac{I_t}{K_t})K_t + (1-\delta)K_t$, where $K_t = \int k \mathrm{d}\mu_t(z, \omega, k, b)$. Aggregate consumption is defined by $C_t = Y_t - I_t - \xi$.[52]

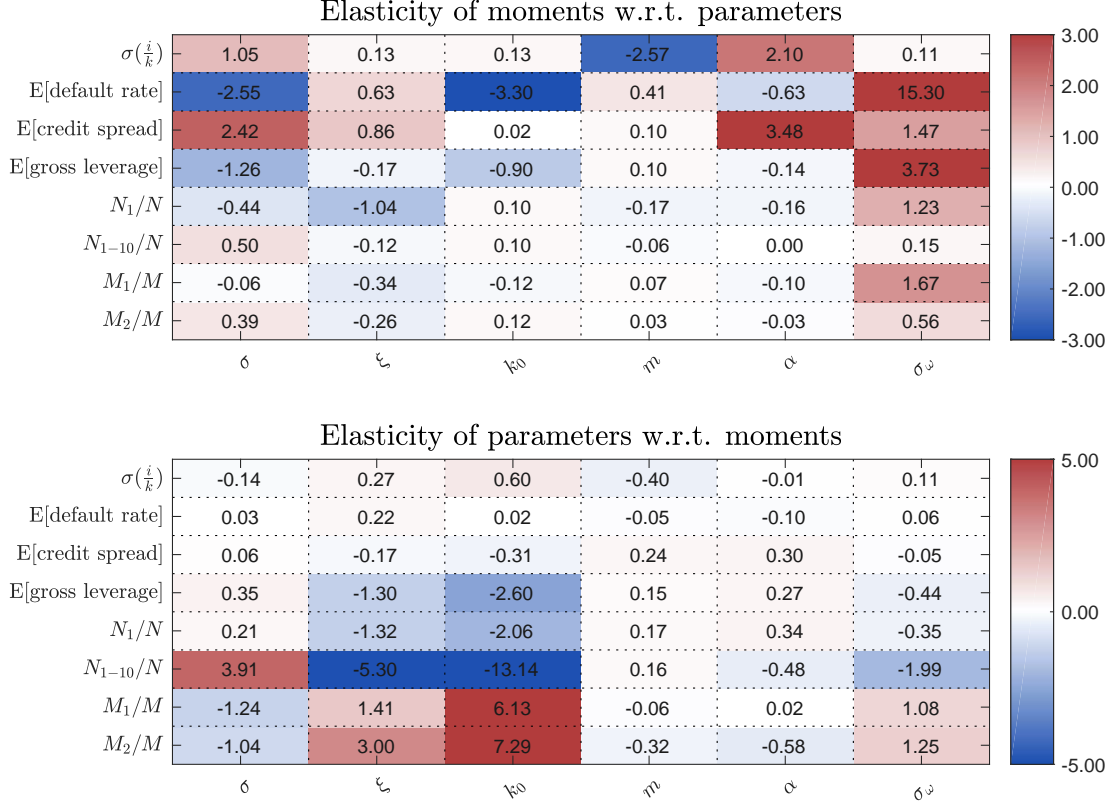## B.3   Analysis of Calibrated Model

In this appendix, we analyze firms' decision rules in our calibrated steady state and show that the financial heterogeneity in our model is broadly comparable to that in the data.

Identification of Fitted Parameters   Figure 21 reports information to help assess the sources of identification in our calibration exercise. The top panel reports the local elasticities of targeted moments with respect to the parameter chosen in our calibration, computed at the estimated parameters. The patterns which emerge are intuitive. For example, increasing the volatility of productivity shocks σ increases the dispersion of investment rates across firms but decreases default rates and leverage ratios (because it makes right-tail positive outcomes more likely). In contrast, increasing the volatility of capital quality shocks makes left-tail negative outcomes more likely and therefore increases default rates (consistent with our discussion in Footnote 16). Increasing the operating cost ξ or decreasing lenders' recovery rates α tightens the financial constraints and leads to higher default rates among firms. Finally, increasing the initial size of new firms k_0 or their productivity m makes default less likely/

The bottom panel of Figure 21 plots the inverse of the mapping in the top panel, i.e., it plots the local elasticities of estimated parameters with respect to moments as in Andrews, Gentzkow and Shapiro (2017). This inverse mapping clarifies how variation in targeted moments would influence estimated parameter values, taking into account the joint dependencies across moments in the data. An important limitation of this exercise is that the relevant size of the variation in the moments is not clear; nevertheless, we believe it contains additional useful information. For example, it shows that the dispersion of investment rates across firms

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[52]We normalize the mass of firms in production to 1, so ξ is the total resources lost from the fixed operating costs.

FIGURE 21: Sources of Identification

Elasticity of moments w.r.t. parameters

	δ	ξ	k_0	m	α	$\delta\omega$
$\sigma(\frac{i}{k})$	1.05	0.13	0.13	-2.57	2.10	0.11
E[default rate]	-2.55	0.63	-3.30	0.41	-0.63	15.30
E[credit spread]	2.42	0.86	0.02	0.10	3.48	1.47
E[gross leverage]	-1.26	-0.17	-0.90	0.10	-0.14	3.73
N_1/N	-0.44	-1.04	0.10	-0.17	-0.16	1.23
N_{1-10}/N	0.50	-0.12	0.10	-0.06	0.00	0.15
M_1/M	-0.06	-0.34	-0.12	0.07	-0.10	1.67
M_2/M	0.39	-0.26	0.12	0.03	-0.03	0.56

Elasticity of parameters w.r.t. moments

|	δ	ξ	k_0	m	α	$\delta\omega$
$\sigma(\frac{i}{k})$	-0.14	0.27	0.60	-0.40	-0.01	0.11
E[default rate]	0.03	0.22	0.02	-0.05	-0.10	0.06
E[credit spread]	0.06	-0.17	-0.31	0.24	0.30	-0.05
E[gross leverage]	0.35	-1.30	-2.60	0.15	0.27	-0.44
N_1/N	0.21	-1.32	-2.06	0.17	0.34	-0.35
N_{1-10}/N	3.91	-5.30	-13.14	0.16	-0.48	-1.99
M_1/M	-1.24	1.41	6.13	-0.06	0.02	1.08
M_2/M	-1.04	3.00	7.29	-0.32	-0.58	1.25

Notes: top panel computes the local elasticities of moments (rows) with respect to parameters (columns) at the estimated parameter values. Bottom panel computes the local elasticities of estimated parameters (columns) to moments (rows) computed as in Andrews, Gentzkow and Shapiro (2017).

is a particularly informative moment for all parameters, especially those governing the life-cycle of young firms. This result may be surprising in light of the top panel, which shows that the dispersion of productivity shocks is the only parameter which strongly influences the dispersion of investment rates; it is nonetheless an influential moment because changing the productivity process has changes other moments, and therefore other parameter estimates, as well.

Firms' Decision Rules Figure 22 plots the investment, borrowing, and dividend payment decisions of firms. Firms with net worth n below the default threshold $\underline{n}_t(z)$ do not operate. Once firms clear this default threshold, they lever up to increase their capital to its optimal

FIGURE 22: Steady State Decision Rules
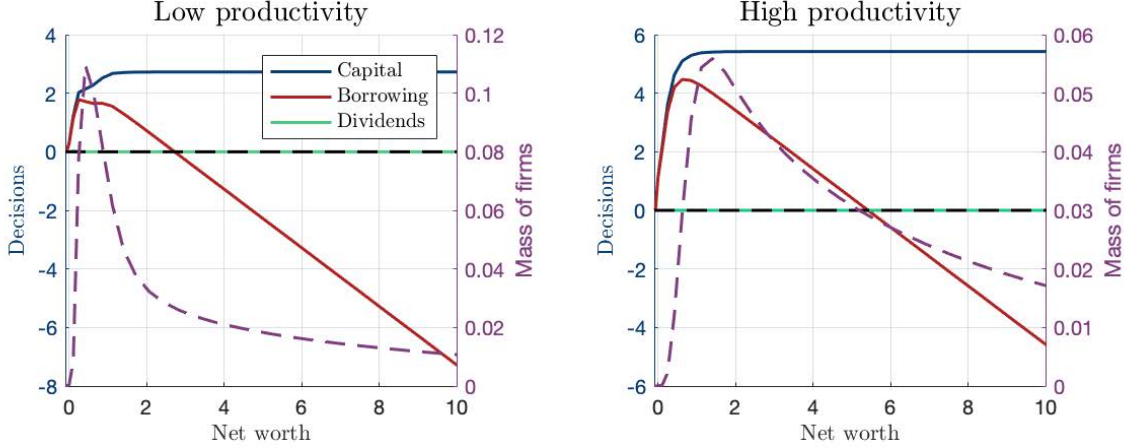
Notes: Left panel plots decision rules and stationary distribution of firms conditional on idiosyncratic productivity one standard deviation below the mean. Right panel plots the same objects conditional on productivity one standard deviation above the mean. The left y-axis measures the decision rules (capital accumulation, borrowing, and dividend payments) as a function of net worth n. The right y-axis measures the stationary distribution of firms (dashed purple line).

scale $k_t^*(z)$. Once capital is at its optimal level $k_t^*(z)$, firms use additional net worth to pay down their debt until they reach the unconstrained threshold $\overline{n}_t(z)$. Only unconstrained firms pay positive dividends.

The curvature in the policy functions over the region with low net worth n reflects the role of financial frictions in firms' decisions. Without frictions, all non-defaulting firms would borrow the amount necessary to reach the optimal scale of capital $k_t^*(z)$. However, firms with low net worth n would need to borrow a substantial amount in order to do so, increasing their risk of default and therefore borrowing costs. Anticipating these higher borrowing costs, low net worth n firms accumulate capital below its optimal scale.

The right axis of Figure 22 plots the stationary distribution of firms. 53.5% of firms pay a risk premium, i.e., are "risky constrained." These firms are in the region with curved policy functions described above. 45.8% of firms are constrained but do not currently pay a risk premium, i.e., are "risk-free constrained." These firms have achieved their optimal scale of capital $k_t^*(z)$ and have linear borrowing policies. The remaining 0.6% of firms are unconstrained.

Figure 22 makes clear that there are two key sources of financial heterogeneity in the

FIGURE 23: Effect of Net Worth Transfer
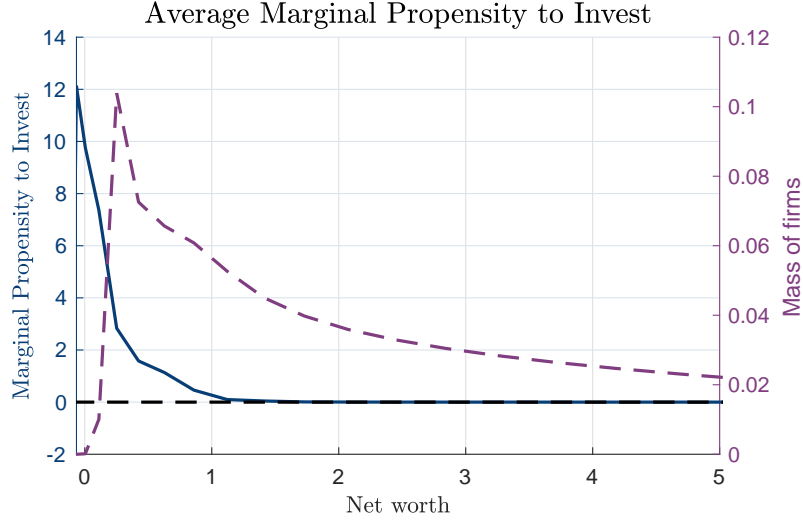
Notes: solid blue line plots the "marginal propensity to invest" out of a positive net worth transfer, i.e., $\frac{k(z,n+\Delta)-k(z,n)}{\Delta}$ as a function of net worth n. We average over idiosyncratic productivity shocks z using the ergodic distribution. Dashed purple line plots the stationary distribution of firms.

model. First, reading the graphs from left to right captures heterogeneity due to lifecycle dynamics; young firms accumulate debt in order to reach their optimal level of capital $k_t^*(z)$ and then pay down that debt over time. Second, moving from the left to the right panel captures heterogeneity due to idiosyncratic productivity shocks; a positive shock increases the optimal scale of capital $k_t^*(z)$, again leading firms to first accumulate and then decumulate debt.[53,54]

Figure 23 plots the response of firm-level investment to an exogenous increase in net worth n. We measure the response using the "marginal propensity to invest" $\frac{k(z,n+\Delta)-k(z,n)}{\Delta}$, which computes the fraction of the net worth transfer Δ used for investment. Consistent with the discussion above, firms with low net worth exhibit a positive response because they are below their optimal scale $k^*(z)$; in fact, firms with very low net worth invest more than one-for-one out because higher net worth decreases their default probabilities, allowing them to borrow more externally. The marginal propensity to invest then falls to zero once the firm

[53]A third source of financial heterogeneity are the capital quality shocks, which simply generate variation in firms' net worth n.

[54]Buera and Karmakar (2017) study how the aggregate effect of an interest rate shock depends on these two sources of heterogeneity in a simple two-period model.

FIGURE 24: Relationship between leverage and net worth
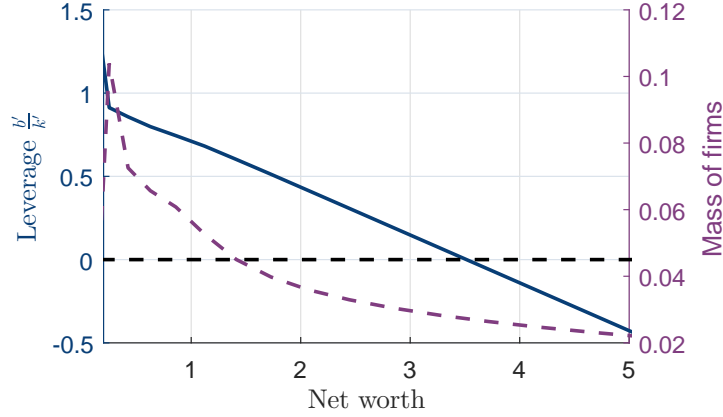
Notes: firms' optimal leverage choice $\frac{b'(z,n)}{k'(z,n)}$ as a function of net worth in steady state. We average over idiosyncratic productivity z using its ergodic distribution.

reaches its optimal scale $k^*(z)$. The average marginal propensity to invest in steady state is approximately 0.17.

Finally, Figure 24 shows that there is a strong a monotonic relationship between firms' leverage and net worth in our model. Given that firms only default when net worth is below the threshold $\underline{n}(z)$, this figure implies that there is a monotonically increasing relationship between leverage and default risk in our model.

Lifecycle Dynamics   Figure 25 plots the dynamics of key variables over the firm lifecycle. New entrants begin with a low initial capital stock k_0 and, on average, a low draw of idiosyncratic productivity z. As described above, young firms take on new debt in order to finance investment, which increases their default risk and credit spreads. Over time, as firms accumulate capital and productivity reverts to its mean, they reach their optimal capital stock $k_t^*(z)$ and begin paying down their debt.

Investment and Leverage Heterogeneity in the Data   Table 22 shows that our model is broadly consistent with key features of the distributions of investment and leverage not targeted in the calibration. The top panel analyzes the distribution of investment rates in the annual Census data reported by Cooper and Haltiwanger (2006). We present the

FIGURE 25: Lifecycle Dynamics in Model
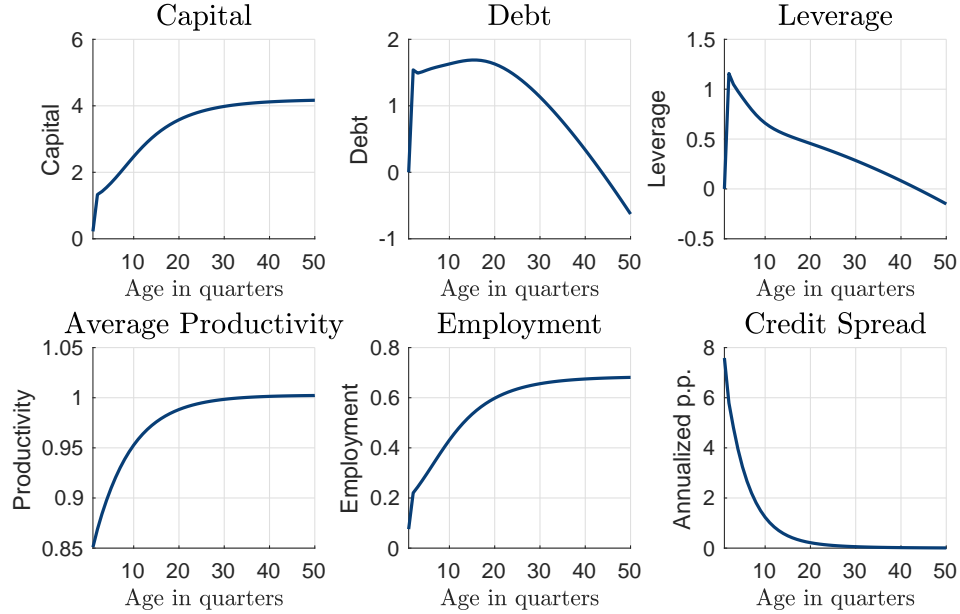
Notes: Average capital, debt, leverage, productivity, employment, and credit spread conditional on age in steady state.

corresponding statistics in our model for a selected sample – conditioning on firms that survive at least twenty years to mirror the selection into the LRD – and in the full sample. Although we have calibrated the selected sample to match the dispersion of investment rates, the mean and autocorrelation of investment rates in the selected sample are also reasonable. The mean investment rate in the full sample is higher than the selected sample because the full sample includes young, growing firms.

The bottom panel of Table 22 compare the model-implied distribution of investment rates and leverage to quarterly Compustat data. We mirror the sample selection into Compustat by conditioning on firms that survive for at least ten years. According to Wilmer et al. (2017), the median time to IPO has ranged from roughly six to eight years over the last decade.[55] Our model provides a close match of the persistence of leverage and its correlation with investment in the selected sample.

Table 23 shows that the model generates a positive measured investment-cash flow sensi-

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[55]Our results are robustness to sensitivity analysis around this cutoff.

TABLE 22
INVESTMENT AND LEVERAGE HETEROGENEITY

Moment	Description	Data	Model (selected)	Model (full)
Investment heterogeneity (annual LRD)				
$\mathbb{E}\left[\frac{i}{k}\right]$	Mean investment rate	12.2%	9.59%	22.3%
$\sigma\left(\frac{i}{k}\right)$	SD investment rate (calibrated)	33.7%	31.8%	44.8%
$\rho\left(\frac{i}{k}, \frac{i}{k}_{-1}\right)$	Autocorr investment rate	0.058	-0.16	-0.16
Joint investment and leverage heterogeneity (quarterly Compustat)				
$\rho\left(\frac{b}{k}, \frac{b}{k}_{-1}\right)$	Autocorr leverage ratio	0.94	0.95	0.09
$\rho\left(\frac{i}{k}, \frac{b}{k}\right)$	Corr. of leverage and investment	-0.08	-0.10	-0.20

Notes: Statistics about the cross-sectional distribution of investment rates and leverage ratios in steady state. Data for investment heterogeneity are drawn from Cooper and Haltiwanger (2006). Model (selected) for investment heterogeneity corresponds to firms alive for longer than twenty years in a panel simulation, time aggregated to the annual frequency. Model (full) corresponds to the full sample of firms in a panel simulation, time aggregated to the annual frequency. Data for joint investment and leverage heterogeneity drawn from quarterly Compustat data. Model (selected) for leverage heterogeneity corresponds to firms alive for longer than ten years in a panel simulation. Model (full) corresponds to the full sample of firms in a panel simulation.

tivity, consistent with the data. Following Gomes (2001), we compute investment-cash flow sensitivity using the regression

$$\frac{i_{jt}}{k_{jt}} = a_1 \frac{\mathtt{CF}_{jt-1}}{k_{jt}} + a_2 \mathtt{q}_{jt-1} + \varepsilon_{jt}, \tag{25}$$

where $\mathtt{CF}_{jt}$ is cash flow and $\mathtt{q}_{jt}$ is Tobin's q. The coefficient a_1 captures the statistical co-movement of investment with cash flow, conditional on the fixed effects and Tobin's q. In the model, we identify cash flow as the firm's flow profits $\max_l z_{jt}(\omega_{jt}k_{jt})^\theta l_{jt}^\nu - w_t l$ and Tobin's q as the ratio of market value to the book value of capital, k. In quarterly Compustat, we identify cash flow as earnings before tax, depreciation, and amortization (EBITDA) and Tobin's q as the market to book value of the firm.

Compustat Firms in the Model and the Data Table 24 compares public and private firms in our model to the data along three key dimensions. First, public firms are substantially larger than private firms in our model; however, our model comes nowhere close to the size gap observed in the data. An important reason for this discrepancy is that, in the data,

TABLE 23

MEASURED INVESTMENT-CASH FLOW SENSITIVITY

	Without cash flow		With cash flow	
	Data	*Model*	*Data*	*Model*
Tobin's q	0.01***	0.01	0.01***	0.01
cash flow			0.02***	0.07

Notes: Results from estimating the regression (25). Data refers to quarterly Compustat data. We measure cash flow as earnings before tax, depreciation, and amortization (EBITDA) and Tobin's q as the market to book value of the firm. Model refers to simulating a panel of firms from the calibrated model, conditional on surviving at least ten years. We measure cash flow as the firm's flow profits $\max_l z_{jt}(\omega_{jt}k_{jt})^\theta l_{jt}^\nu - w_t l$ and Tobin's q as the ratio of market value to the book value of capital, k.

TABLE 24

PUBLIC VS. PRIVATE FIRMS IN THE MODEL AND DATA

	Data	**Model**
$\frac{\mathbb{E}[n\vert\text{public}]}{\mathbb{E}[n\vert\text{private}]}$	62	1.53
$\frac{\mathbb{E}[age\vert\text{public}]}{\mathbb{E}[age\vert\text{private}]}$	2.18	3.28
$\frac{\sigma(\frac{1}{2}\frac{n_{jt}-n_{jt-1}}{n_{jt}+n_{jt-1}}\vert\text{public})}{\sigma(\frac{1}{2}\frac{n_{jt}-n_{jt-1}}{n_{jt}+n_{jt-1}}\vert\text{private})}$	0.58	0.62

Notes: comparison of public and private firms. "Public" firms in the model are those who reach 10 years old (the median time to IPO in Wilmer et al. (2017)). $\frac{\mathbb{E}[n\vert\text{public}]}{\mathbb{E}[n\vert\text{private}]}$ computes the average size of firms measured by employment; data comes from Dinlersoz et al. (2018b) Table 3. $\frac{\mathbb{E}[age\vert\text{public}]}{\mathbb{E}[age\vert\text{private}]}$ computes the average age; data comes from Dinlersoz et al. (2018b) Table 3. $\frac{\sigma(\frac{1}{2}\frac{n_{jt}-n_{jt-1}}{n_{jt}+n_{jt-1}}\vert\text{public})}{\sigma(\frac{1}{2}\frac{n_{jt}-n_{jt-1}}{n_{jt}+n_{jt-1}}\vert\text{private})}$ computes the dispersion of growth rates; data comes from Davis et al. (2006) Figure 2.5.

many firms are born small and never grow; therefore, there is a large mass of permanently small firms which is outside of our model.[56] Second, public firms are older than private firms in both our model and the data; the gap is larger in our model since we select firms based solely on age. Finally, the dispersion of growth rates is smaller among public firms in both the model and data. In our model, private firms' growth rates are more disperse since they

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[56]Gavazza, Mongey and Violante (2018) use permanent heterogeneity in returns to scale to match this group of permanently small firms. We have solved a related version of our model in which there are two types firms: one with low returns to scale, which reach their optimal size relative quickly, and another with the returns to scale of our baseline model. This model generates a skewed size distribution, as in the data, but by construction does not directly affect the behavior of the large "Compustat" firms in our model. In addition, these small firms make up a small share of aggregate investment and are therefore unlikely to have a substantial influence on aggregate dynamics.

are more strongly affected by financial frictions.