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Inflation, Liquidity and Innovation

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Abstract

This paper presents a simple model with financial frictions where inflation increases the cost faced by firms holding liquid assets to hedge risky production against expenditure shocks. Inflation tilts firms' technology choice away from innovative activities and toward safer but return-dominated ones, and therefore reduces long-run growth. The theory makes specific predictions about how the severity of this adverse effect depends on industry characteristics. These predictions are tested with novel harmonized firm-level data from 139 developing countries, overcoming small sample problems constraining previous work. The analysis finds that inflation affects the composition but not the overall quantity of investment. A one percentage point increase in inflation reduces the establishment-level probability of innovation by 4.3 percent but does not affect total investment. Moreover, innovating firms display a stronger dependence on liquid assets, which, in turn, are negatively related to inflation. Generalized difference-in-differences estimations corroborate the sector-specific predictions of the theoretical model.

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Inflation, liquidity and innovation

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1 Introduction

There is now a substantial body of evidence indicating that sustained – and therefore likely predictable – inflation can have adverse consequences for long-run growth. The theoretical discussion about the negative consequences of inflation has focused on the opportunity cost of holding money, distortions of relative prices and of the tax system, and particularly on the effects on the incentives for investment and saving. However, the empirical support for these ideas and their relevant implications for economic growth is mixed so that there is still no consensus about the causal mechanism underlying the relationship between inflation and growth.

Against this background, our paper makes two contributions. In the first part of the paper, we present a simple model formalizing the idea of a causal effect of inflation on growth, which is transmitted not via the level of aggregate investment, but instead via its composition (technology choice). In the model firms engage in two alternative technologies, basic and advanced. The advanced technology is innovative and yields higher expected returns, but it is subject to idiosyncratic expenditure shocks. By contrast, the basic technology is free from idiosyncratic risk but return-dominated. Firms operating the advanced technology can insure themselves against idiosyncratic risk by holding a precautionary buffer of readily marketable, liquid assets. However, the scope for such insurance is constrained by the limited pledgeability of firms' income from production. As a consequence, liquidity must be comitted ex-ante and hence carries a liquidity premium. Liquidity provision is therefore costly (Holmstrom and Tirole, 1998), and an increase in the liquidity premium induces firms to economize on its use. Thus, when the terms of hedging advanced production against expenditure shocks become less favorable, firms shift their physical investment towards the basic technology, which leads to less innovation and thereby diminished growth in aggregate productivity and output.

Since the relevant liquidity premium is given by the nominal interest rate, which is linked to the rate of inflation via the Fisher equation, this mechanism implies that increased inflation works like a tax on advanced investment and hence reduces innovation and productivity growth. Moreover, our theory makes predictions about how the severity of this adverse interest rate effect depends on firm or industry characteristics. Specifically, we show that the above liquidity mechanism is particularly relevant in fast growing and volatile industries, and in those with high income pledgeability. Liquidity demand and investment composition in these industries are therefore predicted to be more sensitive to variations in the rate of inflation.

In the second part of the paper, we test these predictions with firm-level data. Examining the microeconomic mechanism and the specific hypotheses of our model requires information on inflation episodes, firms' investment in advanced technologies (that is, their innovation activities), and the sources of finance available to firms for the working capital expenditure associated with such investment. Empirical work using this information is prone to suffer from small sample problems since inflation only varies at the country-year level and harmonized detailed firm-level panel data are typically only available for few countries or years. This lack of appropriate data has so far limited researchers in studying the impact of inflation on corporate activity, constraining their ability to scrutinize relevant macroeconomic transmission mechanisms on the basis of microeconomic data.

We use novel data from the World Bank Enterprise Surveys (WBES) to address this problem. The WBES provide representative establishment-level data for more than 100,000 establishments that are harmonized across 139 developing countries from 2006-2016. The harmonized WBES data provide substantial variation in firms' behavior across countries and time periods spanning a significant range of inflation, making it possible to empirically identify the relation between inflation and firms' innovation and financing activities. The data also include detailed information on establishments' innovation activity as well as sources to finance working capital and are thus well-suited to test the specific microeconomic mechanism underlying our model. A potential limitation is that the WBES do not provide direct balance sheet information on firms' short-term liquidity holdings, which we proxy with the extent of working capital finance via internal funds or retained earnings. As a robustness check, we therefore extend our analysis with detailed balance sheet data for U.S. firms from Compustat which include a direct measure of corporate liquidity holdings and also have meaningful variation in inflation rates over the period 1960-2016.

On the basis of the WBES data, we find that inflation reduces the probability of product and process innovation in developing countries but has no effect on total investment. Hence, inflation influences the quality but not the quantity of investment. The impact of inflation on the composition of investment via firms' technology choice is statistically and economically significant: a one percentage point (pp) increase in inflation reduces the probability of innovation at the establishment level by 4.3%. Consistent with the prediction that firms economize on the use of liquid assets in periods of increased inflation, we find that inflation reduces the share of working capital financed by internal funds or retained earnings, but not the share financed by formal bank loans. Finally, the adverse impact of inflation on innovation increases with establishments' reliance on internal funds or retained earnings to finance their working capital. The Compustat data, which allow for a tighter measurement of corporate liquidity holdings, further reveal that U.S. firms' R&D expenditure is increasing with their liquidity holdings: a 1% increase in corporate liquidity holdings is on average associated with a 6% increase in firms' R&D intensity. Corporate liquidity holdings, in turn, are negatively affected by inflation: a one pp increase in inflation reduces firms' liquidity holdings by 5.5%. Hence, the adverse effect of inflation on the composition of aggregate investment and its transmission via reduced liquidity holdings is corroborated also in the context of an industrialized economy with developed financial markets.

Finally, the sector-specific predictions of our theoretical model enable us to apply a generalized difference-in-difference specification as in Rajan and Zingales (1998), which also helps to address any remaining endogeneity concerns. We find that the negative impact of inflation on establishments' innovation or R&D activity is larger in (i) more volatile sectors, (ii) sectors with higher value added growth, (iii) more R&D intensive sectors, and (iv) sectors with higher asset tangibility. There is thus broad support for the specific mechanism laid out in our theoretical model.

The rest of this paper is organized as follows. Section 2 embeds our paper into the related literature. Section 3 presents the theoretical model. Section 4 discusses the data, the estimation strategy and our empirical findings. The final section concludes.

2 Related literature

There is a vast literature studying the effects of inflation on growth. Theoretical models used to examine the effects of inflation on growth typically combine a variant of an endogenous growth model with the assumption that consumption and capital investment are subject to a cash-in-advance constraint (Stockman, 1981; Abel, 1985). When capital accumulation faces a cash requirement, the long-term capital-to-labor ratio is decreasing in the nominal interest rate, which acts as a tax on capital. As a consequence, aggregate investment should decrease in inflation, but this is not consistent with the empirical evidence. For example, De Gregorio (1993) finds a significant negative correlation between inflation and growth, whereas the relationship between inflation and aggregate investment is negative but not significant. Moreover, cross-country growth regressions reveal that the coefficient of inflation remains virtually unchanged when controlling for investment. Thus, contrary to the theoretical predictions from traditional models, the growth effects of inflation appear to unfold independent from aggregate investment.

Instead, the transmission mechanism from inflation to growth seems to operate via the 'productivity of investment'. Our model captures this channel in terms of the composition of aggregate investment, that is, in terms of the choice between a basic and an advanced but risky technology,[1] which can be partially insured via corporate liquidity holdings whose costs increase with the rate of inflation. Closely related ideas are pursued in Berentsen, Rojas Breu, and Shi (2012) and Chu and Cozzi (2014). Berentsen, Rojas Breu, and Shi (2012) explore the link between the opportunity cost of holding cash, R&D investment and growth on the basis of a money search model where liquidity is essential for trade to take place in the innovation sector. Similarly, Chu and Cozzi (2014) analyze the effects of inflation on economic growth in a Schumpeterian model with a cash-in-advance requirement on R&D investment.[2] By contrast, in our model, the cost of inflation does not arise from a simple liquidity requirement but from the need for firms to keep a precautionary buffer to self-insure their advanced production against liquidity shocks in the spirit of Holmstrom and Tirole (1998).

This connects our modeling approach to the investment composition effect studied in Aghion, Angeletos, Banerjee, and Manova (2010). Concerned with the relationship between volatility and growth, these authors decompose aggregate investment in order to examine how credit

[1]This obviously resonates with ideas from the literature about occupational choice (Banerjee and Newman, 1993).

[2]Chu and Lai (2013) examine the growth effects of inflation in a quality ladder model with a money-in-utility specification.

constraints affect the cyclical behavior of productivity-enhancing investment. In analogy to the inflation-growth nexus, their cross-country regressions indicate that the observed negative relation between volatility and growth is independent of aggregate investment.[3] However, in the presence of financial constraints the impact of business-cycle shocks on the share of productivity-enhancing investment in total private investment is greater for countries facing tighter financial constraints. Aghion, Askenazy, Berman, Cette, and Eymard (2007) corroborate this idea with firm-level evidence about the relationship between credit constraints and firms' R&D activity over the business cycle. And Aghion, Farhi, and Kharroubi (2012) exploit industry variation in the prevalence of credit and liquidity constraints to establish that R&D expenditure is more affected by countercyclical monetary policy than physical investment.

Indeed, R&D expenditure is a natural proxy for productivity-enhancing investment at the firm-level and, given its limited tangibility, also particularly prone to financial constraints. Building on these facts, our theoretical model and empirical analysis rest on two key relationships. First, that higher inflation works to reduce corporate liquidity holdings; and second, that these liquidity holdings play an essential role in shaping the composition of aggregate investment. The background for most studies of corporate liquidity holdings is the view that external finance is costly and that firms hold liquid assets in order to survive bad times and to have funds readily available if investment opportunities arise. These benefits of corporate liquidity must then be balanced against its cost which materializes in terms of a liquidity premium (Mulligan, 1997). Opler, Pinkowitz, Stulz, and Williamson (1999) examine the determinants and implications of holdings of cash and marketable securities by publicly traded non-financial U.S. firms (1974-1994). They find that (i) firms facing tighter constraints hold a larger share of their total assets in the form of liquid assets, that (ii) firms with strong growth opportunities and riskier cash flows hold particularly high ratios of cash to total non-cash assets,[4] and that (iii) cash holdings increase with the firms' R&D-to-sales ratio. Moreover, there is evidence that firms build cash buffers mainly from retained earnings and that these reserves are generally not used for planned activities (capital expenditures, acquisition spending or payouts to

[3]Similar findings are obtained by Fischer (1993), Cukierman, Kalaitzidakis, Summers, and Webb (1993), Ramey and Ramey (1995), Bruno and Easterly (1998) and Easterly (2005).

[4]We see these features – high growth potential and risky cash flow – as the defining characteristics of the advanced technology in our model. The importance of growth opportunities is also emphasized in Almeida, Campello, and Weisbach (2004).

shareholders) but instead depleted by (unexpected) operating losses. That is, there is a precautionary motive for holding corporate liquidity to provide insurance against expenditure risk. More recently, Bates, Kahle, and Stulz (2009) document that the average cash-to-assets ratio for U.S. industrial firms has more than doubled between 1980 and 2006 and argue that this increase in cash holdings can be traced back to changing firm characteristics, in particular more risky cash flows and increasing R&D intensity. More broadly, the empirical corporate finance literature provides ample evidence that innovations and R&D are cash-intensive, and that liquidity requirements are more important than for physical investment.[5] On the other hand, the relationship between inflation and corporate liquidity holdings has received less attention by the empirical literature. Our paper thus contributes to the macroeconomic literature on inflation and growth with systematic firm-level evidence concerning both the relation between inflation and corporate liquidity and the mechanism tying liquidity holdings to the composition of investment.

3 A simple model

In the following, we develop a simple model illustrating the causal transmission mechanism from inflation to firms' decisions about liquidity holdings and technology adoption.[6] The model is partial equilibrium in nature and takes inflation as exogenously given. The Fisher equation then relates the nominal interest rate to the (expected) rate of inflation π,

$$1 + R = \beta^{-1}(1 + \pi), \tag{1}$$

where β^{-1} measures the gross real interest rate, which we normalize to one. More generally, interest rates and inflation are endogenously determined in the general equilibrium of a fully-dynamic, monetary economy nesting the environment laid out below. However, the details

[5] The literature uncovers a significant relationship between R&D expenditure and either cash flow or corporate liquidity (Himmelberg and Petersen, 1994; Brown and Petersen, 2011; He and Wintoki, 2016), and that this relationship is more robust and pronounced than for physical investment (Brown, Fazzari, and Petersen, 2009; Brown and Petersen, 2009). Moreover, firms tend to smooth R&D expenditure by maintaining a buffer stock of liquidity in the form of cash reserves (Brown, Martinsson, and Petersen, 2012).

[6] The model's underlying structure shares some similarities with Brutti (2011), but it has a quite different focus and introduces ex-ante heterogeneity and technology choice.

of this nesting model are not essential for our key argument that liquidity provision is costly and priced by the relevant scarcity indicator for nominal funds, that is, the nominal interest rate. In essence, the distortion at work in our model is akin to that arising from a cash-in-advance constraint: Self-insurance for entrepreneurs is possible only via liquid assets. Given their exclusive role, these assets therefore carry a liquidity premium, captured by the fact that liquid assets held by entrepreneurs do not pay interest. Just like in the presence of a cash-in-advance constraint, the nominal interest rate thus distorts the allocation in an otherwise real economy. In view of the generality of this mechanism, it plays out in a variety of nesting model environments.[7] We therefore suppress this supporting structure and instead go on to describe the liquidity problem for our simple model. Notice that this is also in line with our empirical approach, which analyzes disaggregate data to examine the firm-level consequences of inflation.

3.1 Economic environment

Consider an economy that lasts for three periods, $t = 0, 1, 2$, and is populated by a continuum of entrepreneurs and a financial intermediary, both of them risk neutral. For simplicity, there is no discounting. The rate of inflation between date 0 and date 2 is given by π. The financial intermediary has deep pockets and can lend at an opportunity cost equal to the nominal interest rate R. This nominal interest rate is pinned down by the Fisher equation, that is, $R = \pi$. Entrepreneurs have no endowment but access to two alternative investment technologies, called *basic* and *advanced*. The two technologies are alternative means to produce a single homogenous good and are based on potentially risky investment projects, one per entrepreneur. At date 0, entrepreneurs must choose which technology to operate.

The basic technology is riskless.[8] Investment into a basic project costs one unit in $t = 0$ and yields a nominal return of $(1 + \pi)B$ in $t = 2$. Expressed in date 0 units, the basic technology's real return is thus B. We assume $B > 1$, so date 0 investment is profitable.

[7] In an earlier working paper version of this paper (Evers, Niemann, and Schiffbauer, 2007), we describe a complete model embedding a contracting problem about scarce liquidity into a dynamic monetary framework with an explicit endogenous growth mechanism. Fully-developed general equilibrium environments are also considered in Berentsen, Rojas Breu, and Shi (2012) and Chu and Cozzi (2014).

[8] The key difference between basic and advanced projects is that the former are free from idiosyncratic risk, while the latter are not. The model can be easily generalized to include also aggregate risk, which, however, plays no essential role as long as it affects both technologies symmetrically. We therefore abstract from aggregate risk in order to illustrate the economic mechanism in the simplest possible environment.

The advanced technology is subject to idiosyncratic risk. Investment into advanced project j costs one unit in $t = 0$ and yields a nominal return of $(1 + \pi)\alpha^j$ in $t = 2$. Expressed in date 0 units, the advanced technology's return thus is α^j, where α^j denotes the idiosyncratic shock realized in $t = 1$. The idiosyncratic shock α^j is private information and takes values $\alpha^j = A^j > 0$ with probability ω_l (lucky) and $\alpha^j = 0$ with probability $\omega_u = 1 - \omega_l$ (unlucky). Unlucky projects admit an additional investment with variable size i which returns ρi in $t = 2$, both expressed in real terms. Assuming $\omega_l A^j > 1$ for all j and $\rho > 1$ ensures both date 0 investment and date 1 reinvestment are profitable. Notice, however, that the idiosyncratic expenditure shock α^j introduces an element of ex-ante heterogeneity across advanced projects. This heterogeneity will be seen to drive the entrepreneurial choice between the basic and the advanced technology.

Regardless of which technology they operate, entrepreneurs have limited access to credit. Specifically, we assume entrepreneurs can pledge only a fraction $\gamma < 1$ of their project's expected revenues. Moreover, we make the following assumption on model parameters.

Assumption 1. *Assume $\gamma B > 1$, $\gamma\omega_l A^j > 1$ for all j and $\gamma\rho < 1$.*

Accordingly, date 0 lending is profitable for the financial intermediary, but date 1 lending, which is relevant only for advanced projects, is not. The advanced technology is therefore associated with a demand for liquidity in the spirit of Holmstrom and Tirole (1998): Unlucky advanced entrepreneurs cannot borrow on the spot market to finance additional investment. Instead, liquidity must be committed already at the initial investment stage (date 0). Moreover, also contingent contracts with the financial intermediary are not available since the idiosyncratic expenditure shock is private information.[9] The limited pledgeability of income and the unavailability of contingent financial contracts together imply that advanced entrepreneurs need to precaution for their date 1 investment needs, and they can do so only by saving a buffer stock of liquid funds. This liquidity must be obtained at date 0 from the financial intermediary who refinances at cost R.[10]

[9] A contingent contract would stipulate a positive transfer in the case of an adverse expenditure shock and a negative transfer in the alternative case. For details, see Holmstrom and Tirole (1998).

[10] Since the idiosyncratic expenditure shocks are private information, there is no scope for liquidity pooling via the financial intermediary.

3.2 Equilibrium

At date $t = 0$, entrepreneurs face the choice between the two alternative technologies. If entrepreneur j operates the basic technology, she borrows an amount b^j from the financial intermediary to finance her initial unit investment subject to the date 0 borrowing constraint $(1+R)b^j \leq \gamma(1+\pi)B$, or in real terms,

$$b^j \leq \gamma B. \tag{2}$$

Given our assumption that $\gamma B > 1$, the borrowing constraint is not binding and $b^j = 1$. Nominal income from the basic technology net of borrowing costs then is $(1+\pi)B-(1+R)b^j$, or in real terms,

$$y^j_{basic} = B - 1. \tag{3}$$

If entrepreneur j instead operates the advanced technology, she borrows an amount d^j from the financial intermediary to finance her initial unit investment and her liquidity holdings l^j used to self-insure against subsequent expenditure shocks. This is done so as to maximize the expected profit $(1+\pi)\left[\omega_l y^j_l + (1-\omega_l)y^j_u\right] - (1+R)d^j$, or in real terms,

$$Ey^j_{advanced} = \left[\omega_l y^j_l + (1-\omega_l)y^j_u\right] - d^j, \tag{4}$$

where

$$y^j_l = A^j + \frac{l^j}{(1+R)}, \tag{5}$$

$$y^j_u = \rho\frac{l^j}{(1+R)}. \tag{6}$$

These expressions make the costs of holding liquidity for self-insurance evident. Liquidity must be obtained at cost $(1+R)$ at date 0 and then kept until date 1 when the expenditure shock materializes. The real return to a unit of idle liquidity is thus given by $1/(1+R)$. Notice also that expression (6) implicitly imposes that, on date 1, unlucky entrepreneurs fully reinvest into their project, that is, $i^j = l^j/(1+R)$. This is without loss of generality since reinvestment at date 1 has strictly positive returns. The date 0 budget constraint facing entrepreneur j is

$$1 + l^j = d^j, \tag{7}$$

whereby the limited pledgeability of revenues from production constrains date 0 borrowing to $(1+R)d^j \leq \gamma(1+\pi)\left[\omega_l y_l^j + (1-\omega_l)y_u^j\right]$, or in real terms,

$$d^j \leq \gamma\left[\omega_l y_l^j + (1-\omega_l)y_u^j\right]. \tag{8}$$

Maximizing (4) subject to (7) and (8) yields a corner solution where the borrowing constraint is binding, provided the expected return on liquidity held by the entrepreneur is higher than the cost of borrowing. We assume this condition to be satisfied.

Assumption 2. *Assume* $\bar{\rho} \equiv [\omega_l + (1-\omega_l)\rho] > (1+R)$.

The entrepreneur's date 0 borrowing and savings then satisfy

$$d^j = \gamma\left(\omega_l A^j + \bar{\rho}\frac{l^j}{(1+R)}\right) \tag{9}$$

and

$$l^j = \frac{\gamma\omega_l A^j - 1}{1 - \gamma\bar{\rho}\frac{1}{(1+R)}} = \frac{(1+R)(\gamma\omega_l A^j - 1)}{(1+R) - \gamma\bar{\rho}}. \tag{10}$$

Given the cost of self-insurance, the liquidity demand of entrepreneur j is decreasing in the nominal interest rate, $\frac{\partial l^j}{\partial(1+R)} < 0$.[11] Substituting (10) back into (4), expected income from the advanced technology is

$$Ey^j_{advanced} = \left[\omega_l y_l^j + (1-\omega_l)y_u^j\right] - d^j = (1-\gamma)\frac{(1+R)\omega_l A^j - \bar{\rho}}{(1+R) - \gamma\bar{\rho}}. \tag{11}$$

Importantly, given that the scope for self-insurance via liquidity holdings is distorted by the nominal interest rate, also the expected income from the advanced technology is decreasing in the nominal interest rate. This is because higher interest rates induce entrepreneurs to hold

[11] Formally, $\frac{\partial l^j}{\partial(1+R)} < 0$ as, by Assumption 1, $\gamma\omega_l A^j > 1$.

less liquidity, which, in turn, reduces the date 1 reinvestment following an expenditure shock.

Comparing (3) and (11), entrepreneur j adopts the advanced technology if $Ey^j_{advanced} \geq y^j_{basic}$, or equivalently,

$$A^j \geq \frac{1}{\omega_l} \frac{\frac{(B-1)}{(1-\gamma)}[(1+R) - \gamma\bar{\rho}] + \bar{\rho}}{(1+R)}. \tag{12}$$

Hence, entrepreneurs whose upside risk A^j of operating an advanced project is sufficiently strong self-select into the advanced technology. By contrast, those with lower A^j prefer the basic technology. Condition (12) therefore defines the threshold level for A^j in terms of model parameters and the exogenous interest rate R. The right-hand side of condition (12) is increasing in the nominal interest rate.[12] That is, in environments with higher inflation and nominal interest rates there are tighter conditions for adopting the advanced over the basic technology.

3.3 Empirical predictions

Since the income from the basic technology y^j_{basic} is invariant to variations in parameters other than B, it follows that the inequality condition (12) for adoption of the advanced technology is driven by variations in the expected income from the advanced technology $Ey^j_{advanced}$ given by equation (11). Based on the comparative statics for $Ey^j_{advanced}$, we obtain the following empirical predictions.

Proposition 1. *In the economy under consideration, there is an adverse interest rate effect:*

(i) An increase in the nominal interest rate makes the advanced technology less attractive,

$$\frac{\partial Ey^j_{advanced}}{\partial(1+R)} < 0,$$

and will therefore tilt the composition of investment towards the basic technology.

(ii) Keeping the expected return $\bar{\rho} \equiv [\omega_l + (1-\omega_l)\rho]$ on liquidity fixed, the adverse interest rate effect is more pronounced for entrepreneurs whose advanced projects have more upside

[12] Formally, this result obtains as, by Assumption 1, $\gamma B > 1$.

potential $\omega_l A^j$,

$$\frac{\partial^2 E y^j_{advanced}}{\partial(1+R)\partial\omega_l A^j} < 0.$$

(iii) Keeping upside potential $\omega_l A^j$ *fixed, the adverse interest rate effect is more pronounced for entrepreneurs whose advanced projects are more risky in the sense of a mean-preserving spread via an increase in* A^j *and a decrease in* ω_l *such that* $\bar{\rho} \equiv [\omega_l + (1-\omega_l)\rho]$ *increases,*

$$\frac{\partial^2 E y^j_{advanced}}{\partial(1+R)\partial\bar{\rho}} < 0.$$

(iv) The adverse interest rate effect is more pronounced for entrepreneurs with higher pledgeable income γ,

$$\frac{\partial^2 E y^j_{advanced}}{\partial(1+R)\partial\gamma} < 0.$$

The intuition behind the adverse interest rate effect established in part (i) of Proposition 1 is straightforward. Unlike the basic technology, the advanced technology is subject to idiosyncratic risk, which can be partially insured through a liquidity buffer. However, holding liquidity is subject to an opportunity cost given by the nominal interest rate. Higher interest rates therefore decrease the demand for liquidity,[13] and in consequence also the relative attractiveness of advanced projects. Hence, condition (12) becomes tighter, and the composition of investment is tilted towards the basic technology. That is, the adverse interest rate effect manifests in terms of an investment composition effect.

The following three parts of Proposition 1 establish that the relative attractiveness of advanced projects is more sensitive to variations in the nominal interest rate when they are potentially more profitable (part (ii)), more volatile (part (iii)), or characterized by higher pledgeable income (part (iv)). The underlying mechanism rests on the fact that higher expected profitability $\omega_l A^j$ or higher pledgeable income γ allows for a higher debt capacity, see (8). Given the unit investment scale, an increasing share of the initial debt is held as liquidity, see (7).[14] The role of

[13] Appendix A.1 formally derives the comparative static effects on the demand for liquidity in (10).

[14] The model can be generalized to allow for variable investment scale at date 0. Given the linear specification

liquidity for self-insurance and its dependence on the interest rate are thus more relevant when the advanced technology is more profitable or pledgeable. The same logic also applies when the advanced technology is more risky. This is because the mean-preserving spread described in part (iii) works to increase the expected return to liquidity $\bar{\rho} \equiv [\omega_l + (1 - \omega_l)\rho]$.

Notice that parts (ii) to (iv) above also allow a direct interpretation in terms of empirically observed outcomes. Industries where $\omega_l A^j$, $\bar{\rho}$ or γ is higher will be more exposed to the advanced technology. This technology allows for higher expected returns, but is also more volatile due to the presence of idiosyncratic liquidity risk. The empirical hypothesis therefore is that the liquidity mechanism should be particularly relevant in fast growing and volatile industries, and in those with high income pledgeability.

4 Empirical analysis

In this section, we use firm-level panel data from the World Bank Enterprise Surveys (WBES) to examine the model's key predictions regarding the effects of inflation on corporate innovation and financing activity. To that end, the WBES are particularly useful as they provide harmonized cross-country data for a large number of developing countries with significant variation in inflation.

4.1 Data

World Bank Enterprise Surveys. The WBES are designed to provide internationally comparable establishment-level data for a large number of developing countries that are representative for the formal private sector economy (that is, establishments with at least five employees) for each country-year episode. They include information on innovation activities, sources of finance, and other key characteristics for over 100,000 establishments in 139 developing countries between 2006 and 2016. The harmonized surveys are conducted about every three years in each country. The surveys provide sampling weights for each country-year episode so that the weighted estimations are representative at the country level. Appendix A.3 provides

of technology, the analysis is then per unit of initial investment, with unchanged comparative statics.

additional details on the survey design and sampling.[15]

The harmonized WBES data capture substantial variation in firms' behavior across countries and time periods spanning a significant range of financial development and inflation, making it possible to empirically identify the relation between inflation and firms' innovation and financing activities. The data are thus well-suited to test the specific microeconomic mechanism underlying our model (cf. Proposition 1).

We proxy firms' investment in advanced technologies with their innovation activity. The surveys distinguish between different dimensions of innovation, that is, between product and process innovation. Both are relevant for our analysis as they are expected to be more risky than conventional investments and to increase future productivity, and ultimately growth. We thus define three variables to measure innovation, indicating whether an establishment introduced a new product, a new production process, or both. Specifically, innovation is measured by a dummy variable equal to one if the establishment either introduced a new product or a new production process in the last three years and zero if not; analogous variables are defined for product and process innovation, separately.

The surveys also provide information on establishments' sources of finance for their working capital expenditure. This is relevant since the idiosyncratic shock associated with the advanced technology (e.g., an unexpected cost overrun when introducing a new product or process) is captured as part of establishments' working capital expenditure, which is financed via corporate liquidity in the form of internal funds or retained earnings. Specifically, we exploit the following survey question:

- *Over the last fiscal year, please estimate the proportion of this establishment's working capital that was financed from each of the following sources? Internal funds/Retained earnings; Banks; Other.*[16]

The dependence on internal funds/retained earnings to finance working capital expenditure can be regarded as a close counterpart to the requirement of using corporate liquidity holdings to meet unforseen expenditure needs associated with the advanced technology formulated in our

[15]The harmonized WBES data for all countries are available online at `https://www.enterprisesurveys.org/portal/index.aspx\#/library?dataset=Combined`.

[16]The category 'other' financing sources includes non-bank financial institutions, supplier and customer credit, friends and relatives.

model. By contrast, bank finance is less likely to be available for this purpose due to the limited pledgeability of income and the non-contingent nature of debt contracts for risky investment, especially in developing countries where financial markets are less developed. We thus expect that establishments that have a higher share of retained earnings in financing their working capital are more likely to innovate.[17]

Moreover, we use total investment to examine the impact of inflation and corporate liquidity holdings on establishments' overall investment. We also include the following establishment-level control variables: Establishment size, measured by the log of the number of employees; the establishments' age; a dummy variable indicating if it is a subsidiary of a larger firm having access to intra-firm credit; and a dummy variable indicating if it has any formal bank loan (that is, different from credit lines for working capital).

Other data sources. We measure inflation by consumer price inflation from the World Bank World Development Indicators (WDI) for all countries and years included in the WBES.[18] We remove inflation outliers by excluding country-year observation with excessive rates above 100% as well as significant deflation episodes with rates below -2% since firms' incentives to adjust their investment behavior might be driven by different factors during these extreme episodes. Qualitatively, our results remain unchanged if we do not impose any range for inflation or use alternative restrictions (only including inflation episodes above 0% and below 20% or 50%). The average (median) inflation rate in the WBES sample is 7% (5.8%). We also use real GDP per capita in constant US dollars from the WDI as a macro-level control variable. Our empirical specification works with the first lag of both inflation and real GDP per capita since the variables from the WBES refer to the previous year.

Moreover, we use two-digit sector-level information to test the 'difference-in-difference' predictions (ii)-(iv) in Proposition 1. Specifically, the sector variables allow us to examine whether the adverse effect of inflation on innovation is more pronounced in more productive sectors, in

[17]While there are several potential financing sources for working capital, we show (cf. Table 1 below) that retained earnings are the predominant form. By contrast, formal bank loans are available only to relatively few firms, and their share in working capital finance is minor.

[18]Data on consumer price inflation are available for all countries and time periods. Alternative measures for the cost of liquidity such as nominal deposit or lending interest rates are available only for about two-thirds of the country-year pairs. Where available, however, these interest rates are highly correlated with our inflation measure.

more volatile sectors, in sectors with a higher R&D intensity, and in sectors with a lower capacity to pledge collateral for external financing. Importantly, these sector-specific predictions permit a generalized difference-in-difference specification as in Rajan and Zingales (1998) to address any remaining endogeneity concerns.

We identify firms whose projects have more upside potential in the sense of hypothesis (ii) of Proposition 1 through their economic activity in the U.S., which serves as a benchmark country. This is done by computing the average value added growth across two-digit ISIC Rev 3.1 sectors for all years in the UNIDO (2017) Industrial Statistics Database and, alternatively, by the average R&D intensity of two-digit sectors provided by Samaniego and Sun (2016). Similarly, we record the volatility of economic activity as measured by the standard deviation of value added in two-digit ISIC Rev 3.1 sectors for all years in UNIDO (2017) to identify more risky projects as in hypothesis (iii) of Proposition 1. Finally, we approximate the pledgeable income of entrepreneurs as in hypothesis (iv) of Proposition 1 by the industry-level asset tangibility taken from Samaniego and Sun (2016), which is measured as the ratio of fixed assets to total assets. That is, firms in sectors with higher asset tangibility can pledge more collateral and thus have better access to external finance.

Descriptive statistics. The descriptive statistics, summarized in Table 1 show that about half (53%) of all formal establishments in developing countries engage in some form of innovation activity; 39% introduced a product which was new to the firms' main market, and 43% introduced a new production process. But only relatively few establishments (35%) have access to formal bank loans. Similarly, the share of bank finance for firms' working capital expenditure amounts to only 13%. Instead, the predominant form of working capital finance is internal funds/retained earnings; their share accounts for 72%. Moreover, about half (46%) of the establishments report internal funds/retained earnings as their only source of working capital financing, and for 78% they are the primary source (financing more than half of their working capital expenditure). These statistics are consistent with the view that investment in innovation is largely intangible and risky; the associated working capital expenditure is therefore difficult to finance externally and must be covered by corporate liquidity holdings in the form of internal funds/retained earnings.

Table 1: Descriptive statistics

	Observations	mean	s.d.	min	max
WBES and WDI:					
Innovation	79,608	.529	.499	0	1
New product	79,379	.392	.488	0	1
New process	77,742	.434	.496	0	1
loan	125,992	.349	.477	0	1
share retained earnings in WC	114,174	.718	.339	0	1
share bank finance in WC	114,174	.126	.240	0	1
share other finance in WC	114,174	.149	.255	0	1
share of firms for which retained earnings is the only source of WC finance	114,174	.461	0	.461	.461
share of firms for which retained earnings exceed half of their WC finance	114,174	.775	0	.775	.775
ln(inv)	48,660	13.8	3.32	0	29.0
ln(empl)	130,089	3.25	1.39	0	11.1
ln(age)	129,046	3.01	.570	0	5.89
subsidiary	127,496	.178	.383	0	1
inflation	129,309	7.02%	68.3	-2%	100%
ln(real GDP pc)	133,141	7.93	1.05	5.25	10.9

4.2 Empirical specification

The data allow us to examine the key relationships in the mechanism linking inflation to technology choice and to test the specific predictions in Proposition 1. In detail, we test the two key components of the model mechanism: First, that firms reduce their liquidity holdings in periods of higher inflation, $\frac{\partial l^j}{\partial(1+R)} < 0$; and second, that firms reduce their investment in innovation activities in periods of higher inflation (part (i) in Proposition 1).

We consider empirical specifications of the form

$$y_{jsct} = \beta_0 + \beta_1 infl_{ct} + \beta_2 X_{jsct} + \beta_3 X_{ct} + I_s + I_c + \epsilon_{jsct}, \tag{13}$$

where y_{jsct} is either given by the innovation dummies or by the share of working capital financing through retained earnings, bank credit, and other sources for firm j in sector s, country c, and year t. $infl_{ct}$ measures the level of inflation firm j faces in country c and year t. X_{jsct} is the matrix of firm-level control variables, X_{ct} the vector of macro-level control variables (real GDP per capita), I_s is a vector of two-digit sector fixed effects, I_c is a vector of country fixed effects, and ϵ_{jsct} an independent and identically distributed error.[19] We always cluster the error

[19]Note that we cannot include establishment fixed effects since the panel dimension of the WBES data is not representative at the aggregate level. But the cross-section of establishments is representative for the formal

terms at the country-year level so that the standard errors are robust to within-group (serial) correlation.[20]

The mix of macro- and microeconomic data allows to examine causality. Specifically, we can exclude the possibility of reverse causality since the innovation decision of a single firm has no significant feedback effect on the aggregate level of inflation. It may of course still be possible that inflation correlates with other country-level variables that influence an establishment's investment decision. For this reason, we include the following control variables. First, we include country fixed effects to control for any time-invariant aggregate factors that may be correlated with inflation and firms' incentives to innovate such as countries' level of institutional and financial development (these move slowly over time and are hence considered quasi-fixed for the WBES time horizon). We thus measure the impact of the within-country variation in inflation. Second, we control for establishment-level variables and sector fixed effects to control for firm characteristics that may be correlated with their innovation decision and aggregate inflation. Third, we control for variation in countries' economy activities over time.

When the dependent variable is an innovation dummy, we estimate (13) using a probit regression. The main coefficient of interest (β_1) measures the impact of the within-country variation in inflation on the average innovation activity of establishments operating in the same two-digit sector within this country, after controlling for changes in the establishment-specific control variables as well as for changes in the country's aggregate economic activity. That is, β_1 measures the effect of a change in a country's inflation rate on the establishment's innovation activity in that country. To estimate the impact of inflation on establishments' financing sources for their working capital, we use a quasi maximum likelihood fractional multinomial logit estimator (fmlogit), which is efficient if the dependent variable ranges between zero and one and consists of multiple shares which add up to one for each observation (Papke and Wooldridge, 1996). The excluded category is given by 'other' financing sources.

To test the model-specific predictions (ii)-(iv) in Proposition 1, we additionally consider

private sector in each country and year so that controlling for country fixed effects implies that we measure to what extent establishments within a given country adjust their innovation activity, on average, if the inflation rate in that country changes over time.

[20] Our standard errors are thus not subject to the Moulton (1990) critique in situations where the dependent variable is less aggregated (firm-level) than the independent one (country-year-level).

empirical specifications of the form

$$y_{jsct} = \beta_0 + \beta_1 infl_{ct} * sectorvar_s + \beta_2 X_{jsct} + I_s + I_{ct} + \epsilon_{jsct}, \tag{14}$$

where $sectorvar_s$ denotes either average value added growth, value added volatility, R&D intensity, or asset tangibility of sector s. I_{ct} are *country∗year* fixed effects, which control for changes in any time-varying country-level factors (including countries' levels of inflation, real GDP per capita, financial development, etc.) and thus reduce the empirical identification exclusively to the variation across sectors in the impact of inflation on innovation.[21]

The coefficient of interest (β_1) is the interaction term between inflation and the relevant sector-specific attribute. The interaction term reflects the idea that, *ceteris paribus*, the innovation activity in establishments within a sector that is, for instance, more R&D intensive should be more sensitive to variations in inflation than the activity of establishments in sectors that rely less on R&D. Equation (14) is thus a generalized difference-in-difference specification following the strategy of Rajan and Zingales (1998). It tests whether the sector-level effects of inflation on innovation activity are in line with our theoretical predictions, controlling for time-varying establishment-level control variables and for fixed and time-varying unobserved country characteristics. Apart from testing the model-specific hypotheses (ii)-(iv) in Proposition 1, (14) thus also provides a test for causality of the impact of inflation on establishments' innovation activity.

4.3 Empirical results

The first two columns of Table 2 show that inflation reduces the share of working capital financed by retained earnings relative to 'other' financing sources (supplier and customer credit, informal sources), but not the share financed by banks. That is, a one percentage point (pp) higher inflation reduces the share of working capital financed by retained earnings by 3.7 pp. Moreover, bank finance is more important for large firms and those that are subsidiaries of larger conglomerates. The results are consistent with our model prediction that, in periods

[21] Note that the inclusion of *country ∗ year* fixed effects also captures the level effect of inflation in 14 and thus cannot be included in 13. The sector fixed effects, in turn, capture the level effects of our sector-specific variables such as sectors' R&D intensity.

of higher inflation, firms reduce their holdings of liquid assets to finance unexpected working capital expenditure (see equation (10)). Column 3 of Table 2 shows that the probability for

Table 2: Harmonized firm panel for 139 countries from 2006-16:
Inflation reduces firms' liquidity holdings and innovation

	Retained earnings	Bank finance	Innovation	New product	New process	ln(Inv)
	fmlogit		probit (marginals)			ols
inflation	-.037**	.005	-.043**	-.029**	-.030**	.005
	(-3.53)	(0.35)	(-3.52)	(-2.22)	(-3.19)	(0.25)
ln(empl)	-.041	.202**	.061**	.044**	.062**	.726**
	(-1.46)	(7.61)	(12.6)	(13.1)	(9.01)	(14.7)
ln(age)	.014	.040	-.031**	-.028**	-.043**	-.087
	(0.21)	(.54)	(-3.12)	(-3.29)	(-2.93)	(-1.01)
subsidiary	.093	.251*	.108**	.111**	.081**	.342**
	(0.68)	(1.81)	(3.49)	(3.49)	(4.84	(3.88)
ln(real GDP pc)	-1.60**	-.182	-.625**	-.529**	-.969**	-3.23
	(-2.74)	(-0.26)	(-3.44)	(-3.08)	(-4.43)	(-1.57)
Sector FE	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Firms	103,050	103,050	72,643	72,451	70,909	41,155

World Bank Enterprise Surveys establishment-level data in 139 developing countries from 2006-16. Marginal effects are reported for the Probit estimations. Median inflation: 6%. Heteroscedasticity robust s.e. clustered at country∗year level; t-statistics in parenthesis. **,* significant at 5%, 10%.

establishments in a given country to engage in innovation activities is reduced during episodes of higher inflation. Higher inflation diminishes the probability of both product and process innovation (columns 4-5). The corresponding coefficients are significant at the 5% level. By contrast, inflation has no effect on total investment (column 6), implying that inflation influences the composition but not the overall volume of investment.

The results thus suggest that inflation shifts establishments' technology choice from advanced to basic processes/products that are less exposed to liquidity risk, confirming hypothesis (i) of Proposition 1 in the model. The marginal effects reported in column 3 of Table 2 imply that a 1 pp increase in inflation reduces the innovation probability by 4.3%. The adverse impact of inflation on firms' technology choice is thus statistically and economically significant.

In Table 3, we analyze how the adverse effect of inflation on innovation depends on establishments' access to external finance. First, we find that inflation reduces innovation also when

Table 3: Harmonized firm panel for 139 countries from 2006-16:
Adverse effects of inflation depend on firms' access to finance

	Innovation					
			RE=100%	RE>50%	RE<50%	RE<5%
inflation	-.041**	-.041**	-.046**	-.044**	-.024**	-.019**
	(-3.67)	(-3.56)	(-5.34)	(-3.86)	(-2.07)	(-2.02)
loan	.134**	.156**	.102**	.132**	.109**	.096**
	(5.44)	(5.96)	(4.37)	(5.27)	(2.89)	(2.03)
infl*loan		-.005**				
		(-1.98)				
ln(empl)	.051**	.051**	.054**	.051**	.050**	.018
	(16.2)	(16.9)	(15.4)	(13.4)	(6.80)	(1.04)
ln(age)	-.033**	-.032**	-.038**	-.031**	-.031	.023
	(-3.58)	(-3.54)	(-3.07)	(-2.01)	(-1.00)	(0.64)
subsidiary	.095**	.094**	.102**	.100**	.082**	.013
	(3.00)	(3.02)	(3.05)	(3.29)	(2.18)	(0.20)
ln(real GDP pc)	-.663**	-.666**	-.398**	-.570**	-.739**	-.046
	(-3.87)	(-3.83)	(-2.47)	(-3.66)	(-3.21)	(-1.64)
Sector FE	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Firms	70,499	70,499	33,193	54,826	15,656	4,900

World Bank Enterprise Surveys establishment-level data for 139 developing countries from 2006-16; marginal effects reported. "RE>50": Share of working capital financed through retained earnings larger than 50%. Heteroscedasticity robust s.e. clustered at country*year level; t-statistics in parenthesis.
**,* significant at 5%, 10%.

firms have access to formal bank loans. Access to bank loans – in general, not necessarily for financing working capital expenditure – has a positive direct effect on the probability that establishments innovate (column 1). However, the negative effect of inflation on innovation is stronger for those establishments that have access to a formal bank loan (column 2). This is intuitive since these establishments are more likely to innovate and thus more exposed to the associated expenditure shocks which need to be need to be precautioned against with a buffer of liquid assets whose opportunity cost increases with inflation. The relevant effects are sizeable. We find that a 1 pp increase in inflation reduces the probability that establishments without access to a formal bank loan innovate by 4.1%; having access to a formal bank loan reduces this probability by an additional 0.5 pp (to 4.6%).

A more direct test of our model predictions is possible by examining the importance of retained earnings for working capital finance (columns 3-6). We find that the adverse impact of inflation on innovation increases with establishments' reliance on retained earnings to finance their working capital. For establishments that finance less than half of their working capital expenditure through retained earnings (column 5), a 1 pp increase in inflation reduces the probability to innovate by 2.4%. Recall, however, that the majority of firms do not have (sufficient) access to formal bank loans for financing their working capital expenditure and thus need to rely on internal funds or retained earnings. Among the establishments for whom retained earnings are the main source of working capital finance (78% of the sample, column 4), the adverse effect of inflation on innovation increases to 4.4%. And for the establishments that rely exclusively on retained earnings (47% of the sample, column 3), the innovation probability is reduced by 4.6%.

Table 4 provides the results of the generalized difference-in-difference estimation following the approach of Rajan and Zingales (1998). We test for the causal impact of inflation on innovation, exploiting variation in industry characteristics. The results confirm all four model predictions and address any remaining concerns about the endogeneity of country-level inflation for establishments' innovation decision. In line with Proposition 1, we find that the impact of inflation on establishments' innovation decision is larger in (i) more volatile sectors, (ii) sectors with higher value added growth, (iii) more R&D intensive sectors, and (iv) sectors with higher asset tangibility. The common ground here is that these sectors are more exposed to advanced but risky technologies so that the liquidity mechanism becomes particularly relevant.

4.4 Robustness

While the WBES include detailed information on firms' sources for financing their working capital expenditure, it does not provide direct balance sheet information on their short-term liquidity holdings. Balance sheet information on corporate holdings of cash and cash equivalents is, however, necessary to directly test the second key component of the model mechanism,

Table 4: Harmonized firm panel for 139 countries from 2006-16:
Sector-specific identification of inflation effects on innovation

	Innovation			
	sector volatility	sector growth	sector R&D intensity	sector fixed-assets
inflation ∗ sector-volatility	-.001**			
	(-2.14)			
inflation ∗ sector-growth		-.090**		
		(-3.68)		
inflation ∗ sector-R&D			-.004*	
			(-1.72)	
inflation ∗ sector-fix-asset				-.002**
				(-2.06)
loan	.133**	.132**	.132**	.133**
	(11.3)	(11.4)	(11.7)	(11.8)
ln(empl)	.046**	.046**	.062**	.046**
	(10.9)	(11.0)	(11.2)	(11.5)
ln(age)	-.024	-.024	-.024	-.024
	(-1.06)	(-1.08)	(-1.09)	(-1.12)
subsidiary	.090**	.088**	.089**	.089**
	(3.11)	(3.10)	(3.10)	(3.11)
Sector FE	Yes	Yes	Yes	Yes
Country∗Year FE	Yes	Yes	Yes	Yes
Firms	44,842	44,842	44,721	44,721

World Bank Enterprise Surveys establishment-level data for 139 developing countries from 2006-16; marginal effects reported. Heteroscedasticity robust s.e. clustered at country∗year level; t-statistics in parenthesis. **,* significant at 5%, 10%.

namely that firms that innovate hold more liquid assets to insure against the associated risk (see equation (10)).

To the best of our knowledge, reliable balance sheet information on corporate liquidity holdings is not available for developing countries. We thus complement our analysis of the WBES with balance sheet data for U.S. firms from Compustat. The data provide information about cash holdings, the direct counterpart to the concept of corporate liquidity in our model. The Compustat data are also well suited for our analysis since they have the longest available time period for a panel of firms for a single country, providing sufficient variation in inflation over time; they include all sectors of the U.S. economy from 1960-2016. The data further serve to test the empirical relevance of our mechanism for an industrialized economy with more developed financial markets.[22]

The Compustat sample is based on publicly traded firms. While these are relatively few compared to the total number of firms, they include the largest firms in the U.S. economy. In fact, the data account for one-third of total U.S. employment and about 41% of total U.S. sales (De Loecker and Eeckhout, 2017). While detailed measures of innovation in terms of technology choice (product and processs innovation) are not available, Compustat allows to measure the intensive margin of firms' innovation activity: we proxy firms' exposure to the risky advanced technology by their R&D intensity as measured by R&D expenses relative to total assets. We also use firms' total investment and balance sheet information on cash holdings as discussed earlier. Further, we include the stock of total assets and retained earnings as firm-level control variables.

The descriptive statistics are summarized in Table 5. The average (median) inflation rate in the sample is 3.6% (3.0%); and firms' average (median) share of R&D in total assets amounts to 26% (5%). Importantly, the data reveal that even in countries with relatively developed financial markets such as the U.S. firms hold a large amount of cash, accounting on average for 11% of firms' total assets (median of 4%). In line with earlier findings (Opler, Pinkowitz, Stulz, and Williamson, 1999), our model suggests that the principal motive for these cash holdings is to provision for liquidity needs arising due to expenditure shocks associated with the advanced technology, that is, with more productive but risky investment.

Table 5: Descriptive statistics

	Observations	mean	s.d.	min	max
Compustat and WDI:					
R&D/assets	125,709	.261	8.59	0	1
Corp. liquidity/assets	320,325	.113	.179	0	1
Inv/assets	357,136	.641	.230	0	1
ln(corp. liquidity)	326,943	2.22	2.05	-6.91	13.0
ln(total assets)	382,007	4.77	2.55	0	15.1
ln(retained earnings)	237,585	3.54	2.46	-6.91	12.9
inflation	428,482	3.64%	2.53	-.36%	13.5%
ln(real GDP pc)	428,482	6.38	.231	6.16	6.99

[22]Our Compustat results are also better comparable to those from the empirical corporate finance literature discussed in the Introduction.

For the Compustat sample we consider a slightly different empirical specification due to the different nature of the data,

$$y_{jst} = \beta_0 + \beta_1 infl_t + \beta_2 X_{jst} + \beta_3 X_t + I_j + \epsilon_{jst}, \quad (15)$$

where y_{jst} denotes either R&D expenses over total assets or cash holdings over total assets for firm j in sector s, and year t. X_{jst} is the matrix of firm-level control variables, X_t the vector of macro-level control variables, I_j is a vector of firm fixed effects, and ϵ_{jst} an independent and identically distributed error. The main coefficient of interest (β_1) measures to what extent a firm in the U.S. adjusts its R&D activity in periods of higher inflation, after controlling for all fixed firm attributes, for changes in the firm-specific control variables, and for changes in aggregate economic activity. We also report the results from the analogous specification to (15) where we control for industry instead of firm fixed effects. In that case, β_1 measures whether establishments operating in the same two-digit industry are, on average, less likely to innovate when inflation rises.

The results, reported in Table 6, show that U.S. firms indeed hold more cash when they invest in R&D.[23] A 1% increase in corporate cash holdings is associated with an increase of 1.5 pp in firms' share of R&D in total assets (column 1), corresponding to an average increase in firms' R&D intensity by 6%. The positive correlation between corporate cash holdings and R&D investment is significant across firms operating in the same two-digit sector (column 1) and within firms over time (column 2). The results in columns 3 and 4 further confirm that inflation raises the (opportunity) cost facing firms holding such liquidity. A 1 pp increase in inflation reduces firms' liquidity holdings by 5.5% (liquidity is reduced by 0.6 pp relative to an average across firms of 11%). Moreover, the results are robust if we restrict the sample to firms that actually report positive R&D investment (column 5). Taken together, columns 1 to 5 of Table 6 confirm our earlier findings from the WBES sample and thus further corroborate the theoretical model's central predictions.

In analogy to the WBES results for developing countries, we find that U.S. firms reduce their

[23] Our finding is consistent with Opler et al. (1999) who show that U.S. firms with higher growth opportunities, approximated by their market-to-book value and R&D expenses, hold on average more liquid assets (cash and marketable securities) relative to total assets.

Table 6: U.S. long firm-level panel data 1960-2016:
Firms adjust liquidity holdings and reduce R&D investment in periods of higher inflation

									1960-2008
	R&D/assets		Corp. liquidity/assets			R&D/assets		inv/assets	R&D/assets
inflation			-.006**	-.003**	-.003**	-.003**	-.001**	-.001*	-.001**
			(-5.97)	(-5.05)	(-3.75)	(-3.17)	(-3.87)	(-1.77)	(-4.86)
ln(Corporate liquidity)	.015**	.001**							
	(6.39)	(2.84)							
ln(total assets)	-.027**	-.017**	-.018**	-.015**	-.003	-.016**	-.016**	-.012**	-.015**
	(-4.31)	(-10.4)	(-11.6)	(-7.97)	(-1.22)	(-3.62)	(-9.20)	(-5.01)	(-9.74)
ln(retained earnings)	.004*	.005**	.008**	.006**	.005**	.005**	.005**	.022**	.004**
	(1.92)	(3.59)	(8.87)	(12.7)	(5.64)	(2.24)	(3.92)	(16.8)	(4.79)
ln(real GDP pc)	-.069**	-.046**	-.064**	-.029**	-.034**	-.062**	-.039**	.143**	-.040**
	(-4.02)	(-9.48)	(-5.50)	(-2.66)	(-2.66)	(-4.60)	(-9.46)	(10.9)	(-9.65)
Firm FE	No	Yes	No	Yes	Yes	No	Yes	Yes	Yes
Sector FE	Yes	No	Yes	No	No	Yes	No	No	No
Obs	62,104	62,104	202,285	202,285	61,691	68,500	68,500	234,610	59,893

U.S. firm-level balance sheet panel data from Compustat, 1950-2016. Median inflation: 3.0% (average 2.6%). Heteroscedasticity robust s.e. clustered at year level; t-statistics in parenthesis. **,* significant at 5%, 10%.

investment in advanced but risky technologies (as measured by their R&D share) in periods of higher inflation (columns 6-7 of Table 6). The result is robust to variations in sample periods, for instance, when excluding the years after the global financial crisis (column 9). As before, we do not find an equivalent impact of inflation on firms' total investment (column 8).[24]

Finally, the data for U.S. firms also support the theoretical model's sector-specific predictions in the generalized difference-in-difference estimation. Table 7 presents the results. We find that the negative impact of inflation on U.S. firms' R&D investment is larger in more volatile sectors, in sectors with higher value added growth, and in more R&D intensive sectors.[25]

[24] The coefficient is marginally significant at the 10% level. However, we find a significant negative impact of inflation on the ratio of R&D over total investment (not reported in Table 6), consistent with the notion that inflation has a stronger impact on R&D than on non-R&D investment.

[25] We do not test the model prediction for sectors with higher asset tangibility since we expect that firms in the U.S. can also leverage their intangible assets (e.g., their brand name) as collateral. We thus predict a meaningful correlation between firms' access to external finance and their ability to provide collateral exclusively through non-intangible assets only for firms in financially less developed countries. In fact, we find that, in the U.S., R&D intensive two-digit sectors have a lower asset tangibility.

Table 7: U.S. long firm-level panel data 1960-2016:
Sector-specific identification of inflation effects on R&D

	R&D/assets		
	sector volatility	sector growth	sector R&D intensity
inflation ∗ sector-volatility	-.001**		
	(-2.67)		
inflation ∗ sector-growth		-.002**	
		(-2.86)	
inflation ∗ sector-R&D			-.001**
			(-5.38)
ln(total assets)	-.016**	-.016**	-.016**
	(-9.79)	(-9.79)	(-9.85)
ln(retained earnings)	.004**	.004**	.004**
	(3.38)	(3.37)	(3.36)
Firm FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Obs	37,949	37,949	37,949

U.S. firm-level balance sheet panel data from Compustat, 1950-2016.
Median inflation: 3.0% (average 2.6%). Heteroscedasticity robust s.e. clustered at year level t-statistics in parenthesis. **,* significant at 5%, 10%.

5 Conclusion

Our paper makes two contributions to the literature concerned with the effects of inflation on innovation, productivity and growth. We first present a simple model proposing a negative causal effect of inflation on growth, which is transmitted not via aggregate investment, but instead via technology choice. Hence, inflation affects the composition of investment, tilting it away from innovative activities towards safer but return-dominated ones. The primary channel along which adverse effects of inflation materialize is therefore not in the volume of aggregate investment, but in the dynamics of aggregate productivity growth.

Our theory is based on the idea of costly liquidity provision in the presence of financial frictions and makes predictions about how the severity of the adverse inflation effect depends on firm (or industry) characteristics. Specifically, we show that the liquidity mechanism is particularly relevant in fast growing and volatile industries, and in those with high income pledgeability. The demand for liquidity and the composition of investment in these industries are therefore predicted to be more sensitive to variations in the rate of inflation.

Second, we test these predictions with firm-level data. We use novel data from the WBES to overcome the small sample problems typically encountered in empirical models that aim to examine the consequences of aggregate macroeconomic conditions (inflation) for individual microeconomic units (firms). For the harmonized panel covering firms in 139 developing countries, we find that inflation shifts the composition but not the overall quantity of investment. The impact of inflation on firms' technology choice is statistically and economically significant: a 1 pp increase in a given developing country's rate of inflation reduces the probability that establishments in that country engage in product or process innovation by 4.3%. Inflation also reduces the share of working capital financed by internal funds/retained earnings. And the adverse effects of inflation increase with establishments' dependence on retained earnings to finance their working capital, consistent with the view that innovation activities are hard to finance externally. Finally, exploiting variation in industry characteristics, our generalized difference-in-difference estimations validate the sector-specific predictions of our theoretical model.

In a further robustness exercise, we consider balance sheet data for U.S. firms which provide direct information about firms' liquidity holdings. We find that corporate liquidity (cash) holdings are increasing with firms' R&D investment but that inflation reduces their liquidity holdings. Our findings thus corroborate the key components of the transmission mechanism proposed in our theoretical model also in the context of an advanced economy with developed financial markets.

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A Appendix

A.1 Proof of Proposition 1

Proof. The claimed effects follow immediately from comparative statics of expression (11).

Part (i): $\frac{\partial Ey^j_{advanced}}{\partial(1+R)} = (1-\gamma)\frac{\bar{\rho}[1-\gamma\omega_l A^j]}{[(1+R)-\gamma\bar{\rho}]^2} < 0$, where the sign follows because $\gamma\omega_l A^j > 1$.

Part (ii): $\frac{\partial^2 Ey^j_{advanced}}{\partial(1+R)\partial\omega_l A^j} = (1-\gamma)\frac{-\gamma\bar{\rho}}{[(1+R)-\gamma\bar{\rho}]^2} < 0$.

Part (iii): $\frac{\partial^2 Ey^j_{advanced}}{\partial(1+R)\partial\bar{\rho}} = (1-\gamma)\frac{[1-\gamma\omega_l A^j][(1+R)+\gamma\bar{\rho}]}{[(1+R)-\gamma\bar{\rho}]^3} < 0$, where the sign follows because $\gamma\omega_l A^j > 1$.

Part (iv): $\frac{\partial Ey^j_{advanced}}{\partial\gamma} = Ey^j_{advanced}\left[\frac{\bar{\rho}-(1+R)}{(1-\gamma)[(1+R)-\gamma\bar{\rho}]}\right] > 0$ and
$\frac{\partial^2 Ey^j_{advanced}}{\partial\gamma\partial(1+R)} = \frac{\partial Ey^j_{advanced}}{\partial(1+R)}\left[\frac{\bar{\rho}-(1+R)}{(1-\gamma)[(1+R)-\gamma\bar{\rho}]}\right] - Ey^j_{advanced}\frac{(1-\gamma)^2\bar{\rho}}{[(1-\gamma)[(1+R)-\gamma\bar{\rho}]]^2} < 0$, where the sign follows because $\bar{\rho} > (1+R)$.

To clarify the transmission mechanism, it is also useful to consider the following comparative statics of expression (10).

Part (i): $\frac{\partial l^j}{\partial(1+R)} = \frac{\gamma\bar{\rho}[1-\gamma\omega_l A^j]}{[(1+R)-\gamma\bar{\rho}]^2} < 0$, where the sign follows because $\gamma\omega_l A^j > 1$.

Part (ii): $\frac{\partial^2 l^j}{\partial(1+R)\partial\omega_l A^j} = \frac{-\gamma^2\bar{\rho}}{[(1+R)-\gamma\bar{\rho}]^2} < 0$.

Part (iii): $\frac{\partial^2 l^j}{\partial(1+R)\partial\bar{\rho}} = \frac{\gamma[1-\gamma\omega_l A^j][(1+R)+\gamma\bar{\rho}]}{[(1+R)-\gamma\bar{\rho}]^3} < 0$, where the sign follows because $\gamma\omega_l A^j > 1$.

Part (iv): $\frac{\partial^2 l^j}{\partial(1+R)\partial\gamma} = \frac{\bar{\rho}[1-\gamma\omega_l A^j][(1+R)+\gamma\bar{\rho}]}{[(1+R)-\gamma\bar{\rho}]^3} < 0$, where the sign follows because $\gamma\omega_l A^j > 1$.

□

A.2 Variable investment scale

The model can be generalized to allow for variable investment scale at date 0. Given the linear specification of technology, the analysis then proceeds *per unit of initial investment.* In detail, suppose both basic and advanced projects can be adopted in variable scale. Entrepreneur j then has the choice between the basic project at scale k^j and the advanced project at initial scale i_0^j. The relevant condition $Ey^j_{advanced} \geq y^j_{basic}$ governing technology choice then reads

$$(1-\gamma)\frac{(1+R)\omega_l A^j - \bar{\rho}}{(1+R) - \gamma\bar{\rho}} i_0^j \geq (B-1)k^j.$$

Since the borrowing constraint facing advanced projects applies jointly for initial investment and liquid assets, there results a trade-off between the initial investment scale i_0^j and the scope for insurance against expenditure shocks via l^j; see the expressions below. Hence, i_0^j is naturally bounded. For basic projects, however, there is no such mechanism. Given the assumption $\gamma B > 1$, the borrowing constraint for the basic technology is not binding, so the choice of k^j is unconstrained. Given the linear specification, income from the basic technology then becomes unbounded along with the choice of k^j. An economically meaningful choice between the basic and the advanced technology is therefore possible only in terms of expected income per unit of initial investment. Under this caveat, the condition for technology choice is the same as under unitary project scale,

$$A^j \geq \frac{1}{\omega_l} \frac{\frac{(B-1)}{(1-\gamma)}[(1+R) - \gamma\bar{\rho}]\frac{k^j}{i_0^j} + \bar{\rho}}{(1+R)}.$$

To see this, consider an advanced project with variable initial investment scale i_0^j. Its state-contingent returns are

$$y_l^j = A^j i_0^j + \frac{l^j}{(1+R)},$$
$$y_u^j = \rho\frac{l^j}{(1+R)}.$$

The date 0 budget constraint is

$$i_0^j + l^j = d^j,$$

the (binding) borrowing constraint is

$$d^j = \gamma\left(\omega_l A^j i_0^j + \bar{\rho}\frac{l^j}{(1+R)}\right)$$

and the demand for liquidity is

$$l^j = \frac{(1+R)(\gamma\omega_l A^j - 1)}{(1+R) - \gamma\bar{\rho}} i_0^j,$$

or, expressed relative to the scale of initial investment,

$$\frac{l^j}{i_0^j} = \frac{(1+R)(\gamma\omega_l A^j - 1)}{(1+R) - \gamma\bar{\rho}}.$$

The expected income per unit of initial investment is then given by

$$\frac{Ey^j_{advanced}}{i_0^j} = (1-\gamma)\frac{(1+R)\omega_l A^j - \bar{\rho}}{(1+R) - \gamma\bar{\rho}}.$$

The last two expressions are identical to their counterparts under unitary investment scale presented in the main text. The same is obviously true for their comparative statics,

$$\begin{aligned}
\frac{\partial(l^j/i_0^j)}{\partial(1+R)} &= \frac{\gamma\bar{\rho}[1-\gamma\omega_l A^j]}{[(1+R)-\gamma\bar{\rho}]^2} < 0, \\
\frac{\partial^2(l^j/i_0^j)}{\partial(1+R)\partial\omega_l A^j} &= \frac{\gamma\bar{\rho}[1-\gamma\omega_l A^j]}{[(1+R)-\gamma\bar{\rho}]^2} < 0, \\
\frac{\partial^2(l^j/i_0^j)}{\partial(1+R)\partial\bar{\rho}} &= \frac{\gamma[1-\gamma\omega_l A^j][(1+R)+\gamma\bar{\rho}]}{[(1+R)-\gamma\bar{\rho}]^3} < 0, \\
\frac{\partial^2(l^j/i_0^j)}{\partial(1+R)\partial\gamma} &= \frac{\bar{\rho}[1-\gamma\omega_l A^j][(1+R)+\gamma\bar{\rho}]}{[(1+R)-\gamma\bar{\rho}]^3} < 0,
\end{aligned}$$

and

$$\begin{aligned}
\frac{\partial(Ey^j_{advanced}/i_0^j)}{\partial(1+R)} &= (1-\gamma)\frac{\bar{\rho}[1-\gamma\omega_l A^j]}{[(1+R)-\gamma\bar{\rho}]^2} < 0, \\
\frac{\partial^2(Ey^j_{advanced}/i_0^j)}{\partial(1+R)\partial\omega_l A^j} &= (1-\gamma)\frac{-\gamma\bar{\rho}}{[(1+R)-\gamma\bar{\rho}]^2} < 0, \\
\frac{\partial^2(Ey^j_{advanced}/i_0^j)}{\partial(1+R)\partial\bar{\rho}} &= (1-\gamma)\frac{[1-\gamma\omega_l A^j][(1+R)+\gamma\bar{\rho}]}{[(1+R)-\gamma\bar{\rho}]^3} < 0, \\
\frac{\partial^2(Ey^j_{advanced}/i_0^j)}{\partial(1+R)\partial\gamma} &= \frac{\partial Ey^j_{advanced}}{\partial(1+R)}\left[\frac{\bar{\rho}-(1+R)}{(1-\gamma)[(1+R)-\gamma\bar{\rho}]}\right] - Ey^j_{advanced}\frac{(1-\gamma)^2\bar{\rho}}{[(1-\gamma)[(1+R)-\gamma\bar{\rho}]]^2} < 0.
\end{aligned}$$

In sum, both the condition for technology choice and the underlying comparative static effects remain unchanged, provided they are considered per unit of initial investment.

A.3 World Bank Enterprise Surveys data description

The World Bank Enterprise Surveys (WBES) are designed to generate internationally comparable establishment-level panel data. They include information on establishments' characteristics, innovation activities, sources of finance, and key balance sheet items for 139 developing countries. The surveys are harmonized across countries and are conducted about every three years in each country. They include over 100,000 firms in developing countries between 2006 and 2016. The surveys provide sampling weights for each country-year episode and are representative for the formal private sector economy (that is, for firms with at least five employees). The weighted estimations are thus representative for the formal private sector at the country-year level.

The sampling considers the following industries (ISIC codes): all manufacturing sectors (group D), construction (group F), services (groups G and H), and transport, storage, and communications (group I). In particular, the sample size ensures a minimum precision of 7.5% for the 90% confidence interval about estimates of (i) the population proportion and (ii) the mean of log sales of these industries. A second level of stratification is firm size defined as small (5-19 employees), medium (20-99 employees), and large (100 or more employees). The targeted firms are establishments with at least five full-time employees with a minimum of eight working hours (or a complete work shift) per day. The restriction in firm size is supposed to limit the surveys to the formal economy; firms that are un-registered with the registrar/tax authority are thus excluded. An establishment is defined as a single physical business location and may be part of a firm. However, establishments are required to make their own financial decisions, have their own managerial oversight, and have books separated from the parent firm. Moreover, targeted establishments are located in major metropolitan areas of a country. The sampling methodology is the same in all countries.

The questionnaire is designed to be administered in face-to-face interviews with owners, managing directors, accountants, or other relevant staff. The interviewers as well as all other staff involved in the survey are thoroughly trained, whereas the World Bank experts supervise the training. The interviewers have to pass an exam in the end of the training in order to qualify for the work. The World Bank assures the strict confidentiality of the survey information. Any missing data or inconsistencies are checked by the interviewer and a field supervisor immediately after the interview and after the filing of the data.

Neither the name of the respondent nor the name of the firm is used in any document based on the survey. The high degree of confidentiality is necessary to avoid biased declarations of respondents, who are informed of these conditions at the outset of the interview. Moreover, the World Bank ensures a wide publicity of the launch of the survey, e.g., via newspaper advertisements, and contacts local agencies to gain the support of the local business communities. This creates a value of potential reform recommendations resulting from the survey and thereby improves a firm's incentives to respond to the questionnaire. Pilot surveys and field experience suggest that the completion of the core Enterprise Surveys lasts approximately 45 minutes. This limitation in the length also contributes to the quality of the responses. In spite of these carefully designed survey characteristics, non-responses could compromise the random nature of the sample if the rationales for non-responses vary systematically with the respondents' innovation activity. The WBES thus conduct additional field-work reports that examine the reasons for non-responds in each country, industry, and class of firm size.