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DISCUSSION PAPER

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R&D Investment under Financing Constraints

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R&D investments under financing constraints

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Abstract

This paper tests for the sensitivity of R&D to financing constraints conditional on restrictions in external financing. Financing constraints of firms are identified by an exogenously calculated rating index. Restrictions in external financing are determined by (i) the specific time period (crisis vs. non-crisis) and (ii) the balance sheet strength of the firm's main bank in terms of bank capital. Results of difference-in-differences estimations utilizing three time periods: 2002-2006 (pre-crisis) 2007-2009 (crisis) and 2010-2012 (post-crisis) support the theoretical prediction that financing constraints affect R&D. Moreover, we find that the effect of firm financing constraints is more intense (i) in times of stress on financial markets and (ii) when the firm faces restrictions in external financing. Additionally, our results indicate that on average the effect does not persist over time.

JEL Codes: G01, G21, G24, G30, O16, O30, O31, O32

Keywords: R&D investment, financing constraints, credit rating, financial crisis, bank capital, external financing of innovation

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1 Introduction

The social (i.e. technological progress, growth) and private (i.e. competitive advantages) incentives to invest in R&D have been known for some time (Aghion et al. 2005; Jones and Williams 1998; Solow 1957; Zachariadis 2004). In spite of this insight, financing constraints remain one of the major factors leading to an underinvestment in R&D (European Commission 2010a; European Commission 2010b; Eurostat 2008; Hall and Lerner 2010). This is mainly rooted in the special characteristics of this kind of expenditure, including significant uncertainties, huge sunk costs, low collateral and a high proportion of expenditure for personnel (Hall 2002; Hall and Lerner 2010). Moreover, capital market imperfections due to adverse selection and moral hazard make R&D financing by external sources difficult (Hall 2002; Hall and Lerner 2010). These theoretical considerations of the impact of financing constraints on R&D are widely discussed (e.g. Hall 2002; Hall and Lerner 2010).

Although financing constraints for R&D have also been investigated empirically for some time (e.g. Czarnitzki and Hottenrott 2010; Hall et al. 2016; He and Tian 2018), it remains questionable whether R&D reacts sensitively to the supply of external financing in general and bank financing in particular (e.g. Hall 2002; Brown et al. 2012; Kerr and Nanda 2015). This is said to be rooted in the characteristics of R&D projects which make their financing unattractive for debt holders like banks (Hall 2002). Accordingly, it is assumed that R&D is largely financed by internal means (e.g. Bougheas et al. 2003; Knudsen and Lien 2014). However, studies find that there is an impact of bank characteristics (frequently measured as averages on the regional level) on R&D or its inputs (e.g. Benfratello et al. 2008; Hsu et al. 2014; Nanda and Nicholas 2014). Thus, the question of the relevance of bank financing for R&D remains under debate (e.g. Hall 2002; He and Tian 2018; Kerr and Nanda 2015). The aim of this paper is to contribute to this discussion by providing first evidence of how the relevance and intensity of the individual constraints of a firm to finance R&D differ as a function of the general financial market situation and the specific situation of their main bank. For this purpose, the paper analyzes two main research questions. First, what effect do fundamental changes to the situation on the financial market have on the firms' financial restrictions (in terms of relevance and intensity)? Second, to what extent does this effect depend on the constraints of their main bank as supplier of external finance?

To answer these questions, we utilize the firms' credit rating as a measure for financing constraints. Additionally, we consider the financial crisis (2008–2009) and the simultaneous

introduction of the Basel II accord (2007) as periods in which the degree of financing constraints for R&D intensifies. The reason for this lies in the fact that the enactment of the Basel II accord in 2007 was accompanied by stronger regulations concerning bank capital requirements, credit risk assessment by banks and a stronger emphasis on the borrower's credit rating (e.g. Scellato and Ughetto 2010; Schindele and Szczesny 2016).[1] Additionally, the financial crisis of 2008/2009 marks a period of increased information asymmetries between borrower and lender (e.g. Gilchrist and Mojon 2018), stronger collateral requirements (e.g. Gilchrist and Mojon 2018) and credit supply reductions (e.g. Puri et al. 2011). Thus, both events affected banks and lead us to expect that financially constrained firms (i.e. firms with worse credit ratings) would face even more serious problems in financing their R&D expenditure between 2007 and 2009 compared to the prior period.[2] By additionally utilizing a post-crisis period (2010–2012), we have the opportunity to test whether the firm's sensitivity of R&D to financing constraints returns to its pre-crisis level.[3]

In a second step, we provide first evidence of whether the sensitivity (in terms of strength and duration) of R&D to financing constraints during the financial crisis is conditional on the firm's main bank balance sheet strength. Bank capital serves as an indicator for bank balance sheet strength and plays a particularly important role in the resilience of banks to adverse shocks and their impact on the real economy e.g. via bank lending (Diamond and Rajan 2000; Holmstrom and Tirole 1997; Jiménez et al. 2012; Kapan and Minoiu 2018). In that respect, it is empirically shown that banks with higher bank capital realize larger loan growth rates (e.g. Kapan and Minoiu 2018; Gambacorta and Shin 2018) and are subject to a lower probability of default (e.g. Berger and Bouwman 2013) in the recent financial crisis. Moreover, bank capital requirements play an important role in the Basel II accord to improve the banks' risk management (Schindele and Szczesny 2016). Consequently, it is to be expected that the effect of financial constraints for R&D in the period between 2007 and 2009 depends on the degree of capitalization of the firm's main bank.

Our data basis is the Mannheim Innovation Panel (MIP), i.e. the German part of the Community Innovation survey (CIS), for the years 2002 to 2012. We combine the MIP with

[1] See Schindele and Szczesny (2016) as well as Scellato and Ughetto (2010) for a detailed description of the Basel II guidelines.

[2] See e.g. Lee et al. (2015) who show that financing problems of firms became more severe in the recent financial crisis. Also Kulicke et al. (2010) and Rammer (2011) show that R&D of German companies decreased in the recent financial crisis.

[3] See e.g. Giebel and Kraft (2019) as well as Hud and Hussinger (2015) who also consider 2010 as a post-crisis year in the context of R&D financing. Our approach, however, extends this post-crisis time-period even further.

two additional data sets. First, we add a credit rating index calculated by Creditreform, the leading firm rating agency in Germany. Second, having information on the firm's main bank identifier allows us to merge the MIP with bank balance sheet information from Bankscope, compiled by Bureau van Dijk. Having access to this rich data set allows us to test whether firms react more sensitively to financing constraints in the financial crisis by applying a difference-in-differences estimation approach. For this objective, we utilize the firm's credit rating as a continuous treatment indicator which measures the firm's degree of financing constraints (i.e. the situation of internal financing and access to external financing).[4] This allows us to test whether there is a change in impact of the extent of a firm's financial constraints on R&D from the pre-crisis period (2002–2006) to the financial crisis (2008–2009) and the simultaneous introduction of the Basel II accord (2007). Utilizing a post-crisis period (2010-2012) gives us the opportunity to test whether the effect persists in the period after the financial crisis or returns to its pre-crisis level. Taking advantage of the information on the firm's main bank, we measure for its capitalization to classify the banks as low or high-capitalized banks. This allows us to subsequently apply difference-in-differences regressions for firms related to high and low-capitalized banks.

The difference-in-differences results with two treatment periods indicate that the sensitivity of R&D to financing constraints is stronger during the financial crisis than the period before. Thus, firms with higher constraints reduced their R&D spending more strongly than firms with lower constraints during the main crisis period. Making use of the bank's capital endowment and applying difference-in-differences regressions for firms related to high and low-capitalized banks leads to the following results: The intensity of financing constraints for R&D in times of stress on financial markets and the enactment of the Basel II accord depends on the firm's main bank characteristics. In other words, firms related to banks with less capital resources suffered particularly in the crisis period. Consequently, the greater impact of financing constraints on R&D during the crisis is driven by the financial crisis and only partly – if at all – by the implemented Basel II guidelines. Corporate customers of banks with better capitalization show no significantly different behavior with respect to R&D expenditures when the pre-crisis and the post-crisis periods are compared to the crisis period. The validity of these results is underlined by various robustness tests (e.g. scaling the dependent variable, alternative modelling choices, changes to the rating variable, adjustments to the bank

[4] See e.g. Czarnitzki (2006), Czarnitzki and Hottenrott (2011a), Czarnitzki and Hottenrott (2011b), Czarnitzki and Kraft (2007) as well as Peters et al. (2017) for applications.

measures, changes to sample size and time period re-definitions). Moreover, accounting for a possible endogenous matching between firms and banks as well as sample selection does not alter the results considerably.

The results of the study contribute to the literature in several ways. First, we extend the strand of literature investigating the effect of financial constraints (i.e. cash flow) on R&D (e.g. Harhoff 1998; Hall et al. 2016; Himmelberg and Petersen 1994) and literature that uses a credit rating index as indicator for financing constraints to explain R&D expenses (e.g. Czarnitzki 2006; Czarnitzki and Hottenrott 2011a; Czarnitzki and Hottenrott 2011b; Peters et al. 2017). We add to both strands of literature by investigating whether the effect of financial constraints on R&D is stronger in times of stress on financial markets or when banks scrutinize the credit worthiness of their borrowers more closely. In that respect, our study largely extends the above-mentioned literature by additionally considering potential changes in the supply of external financing. Thus, we add novel evidence to this strand of literature by investigating the heterogeneity of this effect when exploiting information on the supplier of external financing – the firm's main bank. For this reason, we also contribute to and extend the strand of literature investigating the effect of financing constraints on R&D spending in dependence of restricted supply of external (equity) financing (e.g. Brown et al. 2009; Brown et al. 2012; Brown et al. 2013; Brown and Petersen 2009; Brown and Petersen 2011). This is mainly due to the fact that, in contrast to these studies, we concentrate on restricted bank financing and use the financial crisis as a period of stress on financial markets.

Secondly, we extend work that utilizes bank characteristics to determine the effect of bank financing on firm innovation (Amore et al. 2013; Benfratello et al. 2008; Chava et al. 2013; Cornaggia et al. 2015; Hsu et al. 2014; Nanda and Nicholas 2014). We begin by addressing the effect of firm financing constraints in combination with bank financing constraints. Then, by applying firm-bank level data, we are able to draw a more detailed picture than the above-mentioned studies, which use regional indicators to identify bank characteristics. Finally, we also add to those studies which use patents as identifiers for innovation activities (e.g. Amore et al. 2013; Chava et al. 2013; Cornaggia et al. 2015; Nanda and Nicholas 2014) by considering R&D expenditures. This allows us to overcome issues related to the use of patents as a dependent variable (He and Tian 2018). Moreover, using R&D opens up the possibility to determine the direct effects of a negative shock to banks on innovation inputs.

Thirdly, we complement and extend studies which investigate the impact of firm financing on R&D in the recent financial crisis (e.g. Hud and Hussinger 2015). In that context we also add

to studies which investigate the impact of firm characteristics on innovation during the crisis (e.g. Archibugi et al. 2013a; Archibugi et al. 2013b; Campello et al. 2010; Filippetti and Archibugi 2011; Paunov 2012). We do so by considering financial constraints of firms and bank characteristics to identify constraints from the supply side. Additionally, we extend these studies significantly by considering the changing impact of financing constraints over time. Moreover, utilizing a period after the financial crisis is informative since it otherwise remains unclear whether the original situation will return. This third period is not usually considered by other studies (e.g. Archibugi et al. 2013a; Archibugi et al. 2013b; Campello et al. 2010; Filippetti and Archibugi 2011; Paunov 2012) or is treated as a prolongation of the post-crisis period already used (e.g. Hud and Hussinger 2015).

Fourthly, we contribute to the strand of literature that utilizes a matched firm-bank data set to determine the effects of changes in credit supply on German firms during the recent financial crisis (e.g. Dwenger et al. 2018, Giebel and Kraft 2019; Huber 2018). We extend Dwenger et al. (2018) and complement Giebel and Kraft (2019) as well as Huber (2018) by analyzing the impact of the changing conditions on financial markets and a restrictive supply of external financing on the sensitivity of R&D to firm financing constraints. In contrast to Giebel and Kraft (2019), as well as Huber (2018), we utilize a credit rating index as a measure for financing constraints and determine its changing impact over time. Unlike these two studies, we utilize bank capital to identify bank credit supply restrictions and their impact on R&D. Thus, especially in contrast to Huber (2018), we consider R&D expenses as innovation input while Huber (2018) uses patents as an innovation output measure. We also extend Giebel and Kraft (2019) by adding a period after the financial crisis to determine whether the impact of financing constraints remains enhanced or whether it declines to the pre-crisis level. Utilizing a matched firm-bank data set, we also extend studies which investigate the impact of banks' capital resources on banking during the financial crisis (e.g. Beltratti and Stulz 2012; di Patti and Sette 2016; Gambacorta and Shin 2018; Kapan and Minoiu 2018; Košak et al. 2015) by adding evidence for the effects on the real economy, namely RaD expenditures of firms. Moreover, analyzing the effect of financing constraints on R&D by utilizing a credit rating index and bank capital indicators, we contribute to and extend studies which investigate the impact of the Basel II reform on firms (e.g. Schindele and Szczesny 2016; Scellato and Ughetto 2010).

Our paper proceeds as follows: Section 2 focuses on financing constraints and the impact of distress in the financial system on firm financing and R&D. Data, variables and methodology

are explained in Section 3. The regression results are covered in Section 4. Section 5 covers the description and results of several robustness tests. Finally, Section 6 presents our concluding remarks.

2 Financing constraints and R&D expenditures

2.1 Theoretical framework

In case of a perfect capital market, obtaining the necessary amount of external funding to finance any type of investment might be no problem (Modigliani and Miller 1958). However, imperfections on capital markets exist that are rooted in agency conflicts and asymmetric information problems (Holmstrom and Tirole 1997; Stiglitz and Weiss 1981). These issues lead to higher costs for external funding and difficulties in switching between financing sources (Holmstrom and Tirole 1997; Stiglitz and Weiss 1981). Thus, in imperfect capital markets, a difference in the costs between internal and external funds exists (Fazzari et al. 1988).

R&D investments are particularly subject to this type of problem as they are usually sunk, provide low collateral and are connected with uncertainties (Hall 2002). The latter point refers to the fact that the future success of the innovation process and the prospective market acceptance are not known to the firm (Hall 2002). Moreover, asymmetric information between borrower and lender prevail (Hall 2002). These are likewise severe, as the borrower might not want to provide a valuable signal about the value of the R&D project (Bhattacharya and Ritter 1983) although a patent could serve as a quality signal (Hottenrott et al. 2016; Hochberg et al. 2018).

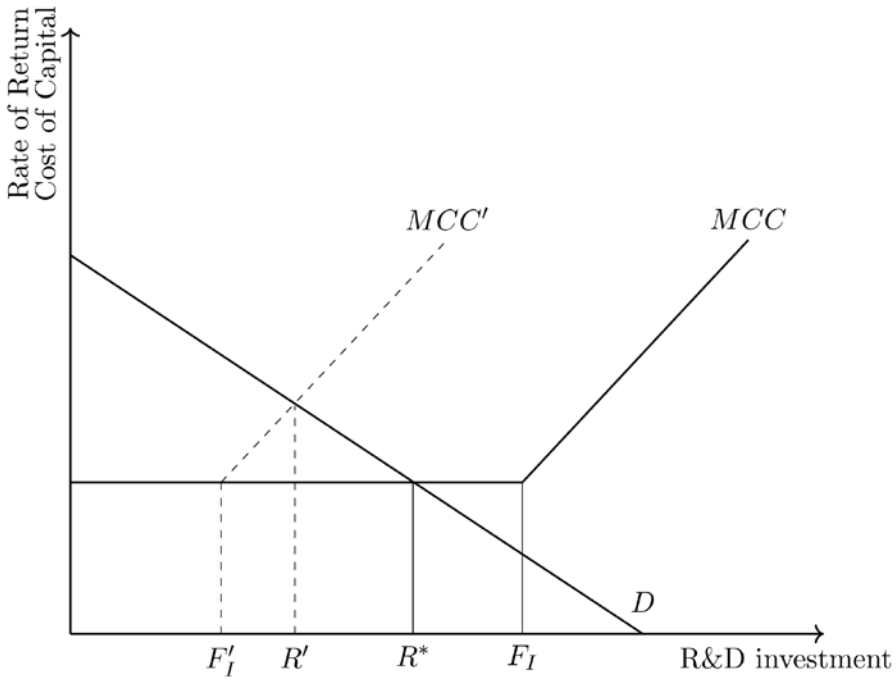
The relation between R&D expenditures and cost of capital is shown in Figure 1.[5] As increasing costs of capital make R&D expenses less attractive, the demand for R&D investment is depicted by the downward sloping marginal rate of return curve D. Its location is determined by the future profits of the R&D investment. The marginal cost of capital curve depicts the supply of capital and consists of two parts. The horizontal part represents the constant marginal costs of capital for internal funds. The amount of available internal means is denoted by (F_I) and external capital costs are depicted by the steeper part of the MCC-curve. The upward slope results from the increased costs of capital for this type of funds as, argued earlier. Due to the characteristics of innovation highlighted above, it is argued that this

[5] The graphic representation follows works like David et al. (2000); Hall (2002); Hottenrott and Peters (2012); Knudsen and Lien (2014).

type of investment is largely financed by internal means (e.g. Carpenter and Petersen 2002; Hall and Lerner 2010; Fazzari et al. 1988; Ughetto 2008). Thus, we assume that the intersection between the demand and costs of capital curves lies in the horizontal area of internal financing. This intersection point marks the optimal amount of R&D investment (R^*) for the firm.

Figure 1 also depicts the change in investment levels when a negative shock to internal financing occurs while external financing costs remain the same. The new costs of capital curve MCC' consists of a shorter horizontal part, ending at the point with the maximum available internal financing F_I'. The firm experiencing a negative shock to internal financing realizes investment amount R' which is lower than the optimal amount of investment R^*. Consequently, the contraction of internal financing from F_I to F_I' leads to an investment reduction from R^* to R'.[6] Empirical studies on financing constraints show that lower internal means are indeed associated with lower R&D spending (e.g. Czarnitzki and Hottenrott 2011a; Czarnitzki and Hottenrott 2011b; Hall 1992; Harhoff 1998; Himmelberg and Petersen 1994; Peters et al. 2017).

Figure 1: The optimal R&D investment with and without internal financing constraints



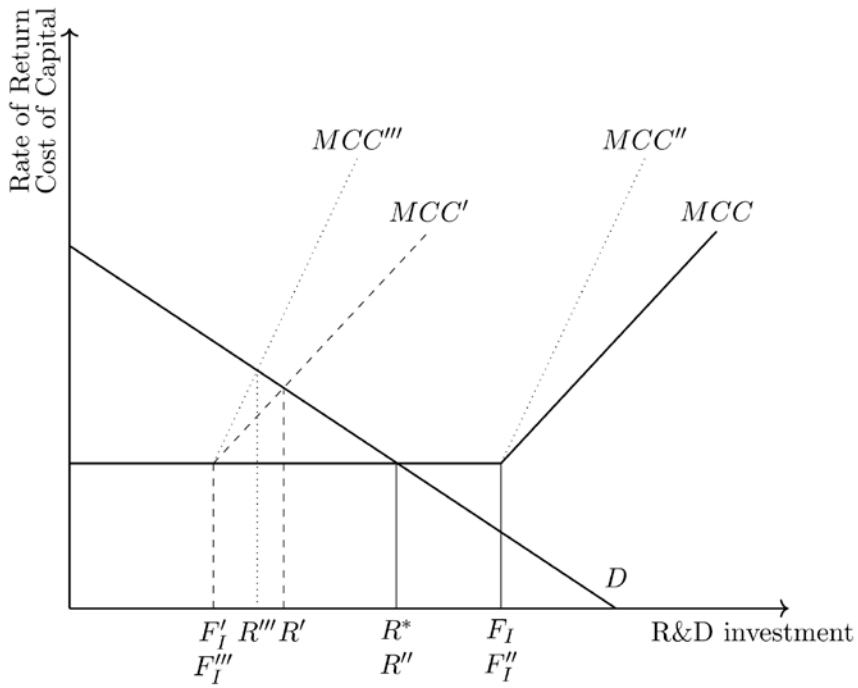
Notes: The figure shows the relationship between demand for financials resources to cover R&D expenditures

[6] Alternatively, we could think about a continuum of firms with the same demand curve and the same difference between internal and external costs of financing. However, the firms differ with respect to internal means available such that the range of internal financing lies between F_I' and F_I. The resulting R&D expenditures would range from R' to R^*.

and the supply of capital. Demand is reflected by the marginal rate of return curve (D) while supply is indicated by the marginal cost of capital curve (MCC). The available internal financing is denoted by F and lies at the end of the constant part of the MCC curve. The intersection between supply and demand determines R, which is the amount of investment made.

Enhanced costs for external funding, for example due to a shock on financial markets, led to an inward shift of the upward sloping part of the MCC curve. This situation, assuming a shift in this part of the MCC curves for all firms, is depicted in Figure 2. A reduction in external financing is not binding if enough internal finance is available. This situation is illustrated by the rotation of the upward sloping part of MCC to MCC''.[7] However, if the firm faces a negative shock to internal financing and has higher external capital costs (i.e. due to a negative shock), the new cost of capital curve is denoted by MCC'''. The resulting optimal investment under these conditions is R'''. This point is further reduced than in the absence of a reduced supply of external finance, when MCC' would be relevant and R' would be realized. Accordingly, R''' is also below the initial, optimal investment volume (R^*). Thus, besides the availability of internal means, access to external finance plays a crucial role with respect to R&D financing (Hall 2002; Hall and Lerner 2010). Within the financial constraints literature, studies indeed find a higher R&D-to-cashflow sensitivity when controlling for the use of external finance by equity (e.g. Brown et al. 2012).

Figure 2: The optimal R&D investment under internal and external financing constraints



[7] The underlying assumption is that the firm does not reallocate capital away from investment R if the external capital costs increase to finance any other investment.

Notes: The figure shows the relationship between demand for financial resources to cover R&D expenditures and the supply of capital if external financing constraints are taken into account. Demand is reflected by the marginal rate of return curve (D) while supply is indicated by the marginal cost of capital curve (MCC). The available internal financing is denoted by F and lies at the end of the constant part of the MCC curve. The intersection between supply and demand determines R, which is the amount of investment made.

2.2 The impact of external financing supply in the recent financial crisis

Especially in bank-based systems like Germany, banks are the main supplier of external finance (Audretsch and Elston 1997; Edwards and Fischer 1996; Elsas and Krahnen 1998; De Massis et al. 2018) and firm financing depends largely on bank loan supply (e.g. Agarwal and Elston 2001; Berger and Udell 1995; Chava and Purnanandam 2011; Kahle and Stulz 2013). It is shown that financially distressed firms face problems in accessing external financing in normal times (e.g. Harhoff and Körting 1998). Thus, a negative bank shock might affect firm financing in the form of higher borrowing costs and lower credit supply (e.g. Upper and Worms 2004). This also holds for the recent financial crisis, a period in which firms faced increased costs for – and reduced supply of – external financing in terms of bank credit (e.g. Bundesbank 2009; Holton et al. 2014; Kapan and Minoiu 2018; Puri et al. 2011).[8] Consequently, firms with higher financing constraints face larger problems during the financial crisis and reduce their R&D spending to a greater extent than firms with lower financing constraints.

During the crisis the banks individually experienced varying degrees of problems due to the different amounts of equity or other reserves that strengthened their capital base (Adrian et al. 2018; Beltratti and Stulz 2012; Berger and Bouwman 2013; Jiménez et al. 2012; Kapan and Minoiu 2018). Bank capital reflects a bank's own funds (Adrian et al. 2018), determines its ability to absorb losses (Diamond and Rajan 2000; Kapan and Minoiu 2018; Mingo 1975), serves as proxy for the agency costs of borrowing (Holmstrom and Tirole 1997; Jiménez et al. 2012) and determines the costs of funding i.e. lending on the interbank market (Adrian et al. 2018; Gambacorta and Shin 2018; Kapan and Minoiu 2018; Mingo 1975). Thus, higher bank

[8] In an economic downturn like the recent financial crisis, consumer demand falls (OECD 2009; Storm and Naastepad 2015). The decrease in demand likely affects R&D expenditures of firms negatively due to a reduction in internal means (Knudsen and Lien 2014). It is argued that a reduction in demand might have ambiguous effects on R&D expenditures of firms (Knudsen and Lien 2014). The resulting reduction in output decreases the opportunity costs of reallocating resources from manufacturing to R&D. Due to this opportunity cost effect, firms would rather invest counter-cyclically in R&D (Aghion and Saint-Paul 1998; Barlevy 2007). On the other hand, it is also argued that the decrease in demand might lead to reduced R&D spending, due to lower investment incentives (Schmookler 1966; Shleifer 1986). Thus, it is questionable whether the opportunity cost effect exerts any impact on R&D expenses. Following the argumentation of Knudsen and Lien (2014) the R&D-enhancing opportunity cost effect only predominates when the fall in demand is small. When the fall in demand is large enough, internal means decrease and the need for funding from external sources increases. In this case the opportunity cost effect is dominated by the consequences resulting from reductions in internal means and credit supply (Aghion et al. 2012; Knudsen and Lien 2014; López-Garcia et al. 2013).

capital is associated with higher bank lending in general (e.g. Berrospide and Edge 2010; Buch and Prieto 2014). Additionally, bank capital matters for the transmission of financial shocks to lending (Gambacorta and Mistrulli 2004; Peek and Rosengren 1997).[9] This is also observed in the recent financial crisis, as studies (e.g. Beltratti and Stulz 2012; di Patti and Sette 2016; Gambacorta and Shin 2018; Kapan and Minoiu 2018; Košak 2015) show that the contraction of lending by banks indeed depended on bank capitalization. Moreover, the enactment of the Basel II accord in 2007 was connected with minimum capital requirements for banks (e.g. Schindele and Szczesny 2016). These were intended to induce banks to make provisions for risks (e.g. Schindele and Szczesny 2016). Consequently, we expect that firms with higher financing constraints which are associated with a poorly capitalized bank would reduce their R&D expenditures to a greater extent than firms with lower financing constraints during the financial crisis. For firms associated with a more strongly capitalized bank, we assume that the sensitivity of R&D to financing constraints would not change remarkably during the crisis.

3 Data and methodology

3.1 Data and Variables

We use data for the years 2002 to 2012 from the Mannheim Innovation Panel (MIP). The MIP is the German part of the Community Innovation Survey (CIS).[10] It comprises data for firm-specific information concerning R&D-like innovation and R&D expenses on a yearly basis. Each firm in our sample is accompanied by bank account information. Consequently, we are able to combine the basis MIP data with bank balance sheet data from Bankscope which is compiled by Bureau van Dijk. By combining both data sets we are able to construct a yearly data set with repeated cross sections, since not all firms answer the questionnaire regularly. The firms in our sample stem from the high-tech and low-tech manufacturing sectors as well as knowledge-intensive services. These are roughly all industries sampled in the MIP and comprise the NACE Rev 2.0 codes from 5 to 39 and 58 to 66 as well as 69 to 73. Our final sample consists of 8,739 firm-years for 3,252 firms.

To test for the impact of financing constraints on R&D, we utilize the R&D expenditures of firms, as commonly applied in the literature (e.g. Brown et al. 2012; Czarnitzki and Hottenrott 2011b). To improve the distribution properties of the dependent variable, we use the

[9] See e.g. Kleff and Weber (2008) as well as Memmel and Raupach (2010) for analysis concerning bank capital in Germany.
[10] See Aschhoff et al. (2013) for more methodological details of the MIP for the survey waves 2006 to 2010.

logarithm of R&D expenses. Since some firms possibly perform no R&D and have no related expenses, we observe zero values. Simply applying the logarithm would lead to the drop of these zero value observations, which would result in a serious bias in our results. Thus, we apply the transformation ln(R&D+1).[11]

As an identifier of firms' financing constraints, we apply the firm's individual credit rating 'Rating' in accordance with the suggestion of Carreira and Silva (2010). The utilized rating index is calculated by the largest German credit rating agency, Creditreform. It is constructed utilizing several qualitative and quantitative factors and ranges from 100 (best rating) to 600 (worst rating). The construction of the rating index allows a characterization of the financial situation of a firm.[12] In that respect, Czarnitzki (2006), Czarnitzki and Hottenrott (2011a), Czarnitzki and Hottenrott (2011b) used the credit rating as a measure for access to external capital and for the internal financing situation of the firm[13], and Peters et al. (2017) applied it as indicator for the financial strength of a firm.[14] Our sample does not include firms with pre-crisis rating values larger or equal to 500 as these firms are close to bankruptcy.

Additionally, we use variables for firm characteristics that are common to the literature: Lagged employees in thousands 'Size' and its square 'Size squared' as well as firm age in years 'Age' and its square 'Age squared'. 'Group membership' is a dummy variable indicating whether the unit belongs to a firm group (unit value) or not (zero). Additionally, we use the lagged share of exports divided by sales 'Export share' to control for demand-related influences on the R&D expenditures.[15] Moreover, we utilize the lagged value of sales growth 'Sales growth' as an additional indicator for the financial situation of the firm.

Next, we use our bank balance sheet information from the Bankscope database to apply several measures as proxy for the bank's financial strength in terms of capital. For reasons of exogeneity, all variables are measured as of 2006 such that they are determined prior to the crisis[16] and before the Basel II guidelines became binding. One variable used is the ratio of

[11] Similar results are achieved if we apply the logarithm according to Cameron and Trivedi (2010) and use γ, a slightly smaller value than the minimum value as censoring point.
[12] The index is built from several items of firm information like liquidity, balance sheet structure, financing, legal form, ownership structure, industry, prior credit requests, ability to repay credits in time. See e.g. Czarnitzki and Hottenrott (2011a) for a detailed description of the construction of the rating index. We include federal state fixed effects to control for the possible regional variation in the index.
[13] Czarnitzki and Kraft (2007) show that a weaker firm rating is indeed correlated with higher interest rate payments.
[14] Moreover, we use the lagged rating value to verify the robustness of our results.
[15] See e.g. Bricongne et al. (2012) and Eaton et al. (2016) who show that the fall in demand during the financial crisis is correlated with exporting activity.
[16] See e.g. Beltratti and Stulz (2012) for a similar handling of variables.

equity to total assets, which corresponds to the inverse leverage ratio (Adrian et al. 2018; Berger and Bouwman 2013; Jiménez et al. 2012). However, we follow the literature (e.g. Anginer et al. 2016; Bayazitova and Shivdasani 2012; Bitar et al. 2018; Demirguc-Kunt et al. 2013; Kapan and Minoiu 2018, Tran et al. 2016) and take into account the quality of capital by using tangible common equity, which does not include intangible assets, goodwill and preferred stock (Bayazitova and Shivdasani 2012; Kapan and Minoiu 2018). Thus, we utilize the ratio of tangible common equity over tangible assets to create the variable 'Tangible common equity'.[17] A higher ratio implies a higher share of high-quality capital and therefore a better ability to absorb losses and to withstand shocks (Kapan and Minoiu 2018). Furthermore, investors prefer this ratio over regulatory ratios like the Tier 1 ratio (Kapan and Minoiu 2018).

We then apply the 'Capital funds' measure which is determined by the ratio of capital funds to total assets (Avdjiev et al. 2019; Nguyen 2012). Capital funds include equity, hybrid capital and subordinated debts (Avdjiev et al. 2019). Both subordinated debt and hybrid capital belong to Tier 2 capital (e.g. Brinkmann and Horvitz 1995; Demirguc-Kunt et al. 2013; Ito and Sasaki 2002; Llorens and Martin-Oliver 2017; Montgomery 2005) and have the ability to absorb losses (e.g. Llorens and Martin-Oliver 2017). Moreover, subordinated debt could be issued to increase the capital adequacy of banks (Ito and Sasaki 2002; Montgomery 2005). Thus, the ratio of capital funds to total assets is also used to proxy for the capital adequacy of banks (Avdjiev et al. 2019; Nguyen 2012). In additional robustness tests, we consider two further measures: first, the inverse of leverage calculated as equity over total assets 'Equity over total assets'; then, we employ the ratio of capital funds over net loans 'Capital funds over net loans'.

Descriptive statistics are shown in Table 1.[18] In about 25 percent of cases R&D expenses are equal to zero. Firm size is 344 employees on average, which is above the threshold normally assumed for a small and medium size enterprise of 250 employees. Nevertheless, more than 75% percent of the firms in our sample are SMEs. The average age of firms is about 31 years. The average credit rating is about 217 in our sample, which corresponds to a good rating according to the Creditreform index. The tangible common equity ratio amounts to a mean of about 4 percent. The size of capital funds is on average about 6% of bank assets.

[17] The ratio of tangible common equity over risk weight assets is a commonly applied ratio in the context of the Basel III requirements on bank capital (e.g. Yan et al. 2012).
[18] See Table A1 and A2 in Appendix A for the distribution of firms over industries and federal states.

Table 1: Descriptive statistics for 8739 firm-years

	Mean	SD	P10	P25	Median	P75	P90
Firm variables							
Log of R&D	9.676	5.816	0	7.579	11.961	13.570	17.952
Size	0.344	2.050	0.004	0.021	0.058	0.178	4.043
Age	30.67	31.323	3	12	18	35	146
Group membership	0.493	0.500	0	0	0	1	1
Sales growth	0.064	0.258	−0.540	−0.053	0.044	0.150	1
Export share	0.242	0.264	0	0.003	0.140	0.423	0.922
Rating index as of 2006	216.756	41.552	116	193	215	243	314
Lagged rating index	215.121	42.594	115	192	213	237	325
Bank variables							
Tangible common equity	4.005	2.137	1.710	2.800	4.060	5.300	9.190
Capital funds	5.768	2.303	2.700	5.150	5.380	7.140	13.710
Equity over total assets	4.088	2.102	1.750	2.920	4.150	5.310	9.190
Capital funds over net loans	13.341	9.843	6.890	8.180	11.660	15.950	41.410

Note: The count for the Subsidy variable is 6148 as this information was not available in each survey year.

3.2 Identification of the effect of financing constraints on R&D

First, we want to investigate the sensitivity of R&D to financing constraints in a period of stress on financial markets (financial crisis) compared to times when market conditions are more stable. For this purpose, we analyze specific time periods before (2002-2006), during (2007-2009) and after (2010-2012) the financial crisis and perform tests applying difference-in-differences estimations. Accordingly, we establish a causal relationship between the change in R&D expenditures due to the crisis and financing constraints. The intention is to test whether firms with a high financial strength change their R&D expenditures during the crisis to a lesser extent than firms with a lower financial strength.

To perform our analysis, we use the rating measure described above as of 2006 as continuous treatment indicator.[19] Additionally, we construct several indicator variables that represent specific time periods during and after the crisis. The constructed dummy 'Crisis' covers the time period of considerable tensions on financial markets and therefore takes the value one for the years 2007 to 2009 and otherwise zero.[20] The dummy variable 'PostCrisis' comprises the time after the severe distress on financial markets and takes value one for the years 2010 to

[19] We take the measure as of 2006 such that our indicator is not affected by the financial crisis in 2008/2009 or the implementation of the Basel II guidelines in 2007. Another reason for fixing the measure in 2006 is that the Basel II guidelines took effect in 2007. These guidelines promote a stronger focus on credit risk. The borrower risk is evaluated either with an internal rating-based approach or an external credit rating.

[20] First effects of the financial crisis for the banking sector were evident in Germany in the third quarter of 2007 (e.g. Dietrich and Vollmer 2012; Puri et al. 2011). Additionally, Basel II took effect in 2007 and affected firms (credit rating) and banks (capital requirements). Robustness tests concerning the definition of the time periods are shown in Section 5.5.

2012 and zero for the period before (2002-2009). Accordingly, we apply the following specification with multiple treatment periods, based on Imbens and Wooldridge (2009):

$$\ln(\text{R\&D})_{it} = \beta_0 + \beta_1 \text{Rating}_i + \beta_2 \text{Rating}_i \times \text{Crisis}_t + \beta_3 \text{Rating}_i \times \text{PostCrisis}_t + \beta \text{X}' + \phi_i + \eta_i + \gamma_t + \varepsilon_{it} \quad (1)$$

Interacting 'Crisis' and 'PostCrisis' with the rating measure yields the change in R&D expenses conditional on the degree of financing constraints in the respective period compared to the period before 2007. The vector X' consists of additional control variables described above. In addition, we apply industry (φ), federal state (η) and year fixed effects (γ) in each regression.

As a relevant fraction of the dependent variable has zero values, we account for possible corner solutions by applying a Tobit model (Wooldridge 2010). Wald tests concerning the homoscedasticity assumption of the Tobit model led to a rejection of the homoscedasticity assumption. To cope with this problem, we use the heteroscedastic Tobit according to Greene (2003). As a result, the normal variance component σ is replaced by a functional form $\sigma_i = \sigma \times exp(Z'\alpha)$ which is obtained by inserting a set of size, age and industry dummies.

Second, our analysis sheds light on the question of how the supply side of external financing affects the impact of financing constraints in the financial crisis. Thus, we assume that the firm's sensitivity to financing constraints during and after the financial crisis depends on its main bank, as this is usually the most important source of external finance. We determine the level to which the bank is affected by the financial crisis if the capital endowment of the bank is in the lower quartile of the bank distribution of all German banks observed in the Bankscope database for the related bank variable.[21] This implies a ratio of tangible common equity of below 5.17 percent and a ratio of capital funds to total assets of below 5.97 percent. Thus, in a second step, we estimate Equation (1) separately for firms related to low and high capitalized banks.

4 Results

4.1 Sensitivity of R&D to financing constraints over time

We first test for the sensitivity of R&D to firm financing constraints in the financial crisis. Thus, we assume a homogeneous effect of the bank credit supply shock in the recent financial

[21] This allows us to infer from the distribution of all banks (1452) for which information is available from the Bankscope data set. Our sample covers 659 of these banks. The distribution of values for both bank capital measures are shown in Appendix A, Figures A1 and A2.

crisis on all firms. Results of the estimations of Equation (1) are shown in Table 2. Column (1) shows the results with discarded interaction terms. The coefficient of the rating variable is negative and highly significant at the one percent level. This indicates that firms with higher financing constraints (a poor rating value) invest less in R&D than their peers with greater financial strength.

Next, we analyze whether the sensitivity of R&D to the rating variable changes over time. We include a variable for the pre-crisis, crisis and post-crisis period interacted with the rating variable. It becomes evident that the rating exerts its highest influence in the crisis period from 2007 to 2009 (Column 2). This coincides with the idea that R&D expenditures react more sensitively to financing constraints in times of distress on financial markets. For the post crisis period, it is evident that the impact of constraints on R&D almost returns to the previous level (Column 2). With respect to the time-related differences of the impact of constraints, we find that the more highly constrained firms indeed invest less in R&D in times of financial crisis (Column 3). However, we do not find a significant difference between the post-crisis and pre-crisis period (Column 3). Thus, for the estimate in Column (6), we find that a rating one point weaker coincides with a reduction in R&D expenditures by about 0.9 percentage points compared to a firm with a rating value that is one point better. At the extensive margin the results show that a firm with a rating one point weaker is 0.03 percent less likely to report a non-zero value for R&D expenditures compared to a firm with a rating that is one point better (Column 9).

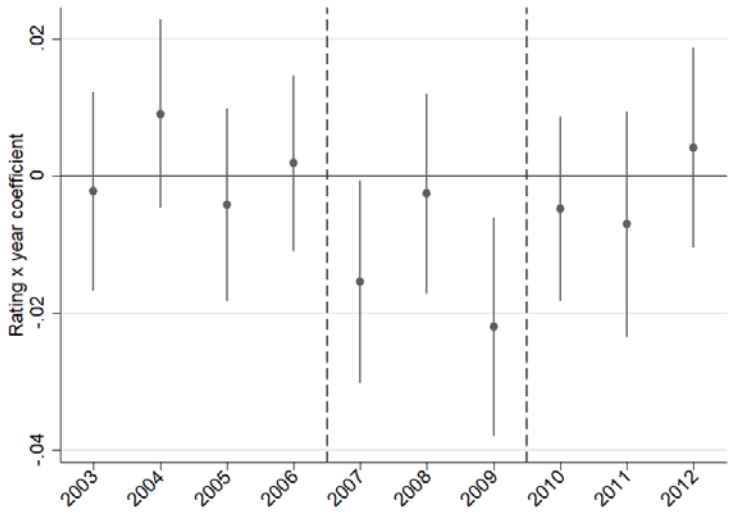
Table 2: Impact of firm financing constraints on R&D over time

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Tobit	Margin		Tobit	Margin		Tobit	Margin	
	Tobit	Intensive	Extensive	Tobit	Intensive	Extensive	Tobit	Intensive	Extensive
Rating	−0.016***	−0.012***	−0.000***				−0.011***	−0.008***	−0.0003***
	(0.003)	(0.002)	(0.000)				(0.003)	(0.003)	(0.0001)
Rating × PreCrisis				−0.011***	−0.008***	−0.000***			
				(0.003)	(0.003)	(0.000)			
Rating × Crisis				−0.024***	−0.018***	−0.001***	−0.013***	−0.009***	−0.0003***
				(0.004)	(0.003)	(0.000)	(0.004)	(0.003)	(0.0001)
Rating × PostCrisis				−0.016***	−0.011***	−0.000***	−0.004	−0.003	−0.0001
				(0.004)	(0.003)	(0.000)	(0.004)	(0.003)	(0.0001)
Size	0.896***	0.648***	0.020***	0.884***	0.640***	0.020***	0.884***	0.640***	0.020***
	(0.112)	(0.081)	(0.003)	(0.113)	(0.081)	(0.003)	(0.113)	(0.081)	(0.003)
Size squared	−0.017***	−0.012***	−0.000***	−0.016***	−0.012***	−0.000***	−0.016***	−0.012***	−0.000***
	(0.003)	(0.002)	(0.000)	(0.003)	(0.002)	(0.000)	(0.003)	(0.002)	(0.000)
Age	−0.033***	−0.024***	−0.001***	−0.034***	−0.024***	−0.001***	−0.034***	−0.024***	−0.001***
	(0.013)	(0.009)	(0.000)	(0.013)	(0.009)	(0.000)	(0.013)	(0.009)	(0.000)
Age squared	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Group membership	0.887***	0.642***	0.020***	0.895***	0.648***	0.020***	0.895***	0.648***	0.020***
	(0.244)	(0.177)	(0.005)	(0.243)	(0.176)	(0.005)	(0.243)	(0.176)	(0.005)
Sales growth	0.386	0.279	0.009	0.394	0.285	0.009	0.394	0.285	0.009
	(0.269)	(0.194)	(0.006)	(0.269)	(0.194)	(0.006)	(0.269)	(0.194)	(0.006)
Export share	0.047***	0.034***	0.001***	0.047***	0.034***	0.001***	0.047***	0.034***	0.001***
	(0.004)	(0.003)	(0.000)	(0.004)	(0.003)	(0.000)	(0.004)	(0.003)	(0.000)
Constant	7.660***			6.743***			6.743***		
	(1.346)			(1.398)			(1.398)		
H_0: Rating × $\text{year}_t = 0 \; \forall \; t < 2007$									
p-value							0.194		
Industry fixed effects		Yes			Yes			Yes	
Federal state fixed effects		Yes			Yes			Yes	
Year fixed effects		Yes			Yes			Yes	
Log likelihood		-23891.657			-23886.761			-23886.761	
Left-censored observations		2159			2159			2159	
Uncensored observations		6580			6580			6580	
Observations		8739			8739			8739	

Notes: Standard errors clustered by firm are reported in parentheses. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

We test for the common trend assumption of the difference-in-differences approach and analyze the effect of heterogeneity by using a specification similar to Equation (1), but replace the dummy variables indicating the crisis or post-crisis periods by a set of year dummies for the years 2003 to 2012. This test serves as a test for the common trend assumption (Mora and Reggio 2015; Mora and Reggio 2019). Applying this approach, we follow recent applications (e.g. Hangoma et al. 2018; Miller 2018; Rowley et al. 2017). The common trend assumption holds if the joint test indicates that the interaction terms prior to 2007 are equal to zero. This is indeed the case, as shown by the relevant p-values of the test statistics at the bottom of Table 2, Column (7).[22] Moreover, Figure 3 plots the interaction effects and 95% confidence intervals. It becomes evident that there are no significant differences in the effects in the years 2003 to 2006 compared to the baseline period 2002. In the period of interest (2007 to 2009), a significant reduction in R&D occurs depending on the degree of financing constraints of firms in the years 2007 and 2009.

Figure 3: Impact of firm financing constraints on R&D over time



Notes: The figure shows the Tobit regression coefficients for the Rating×year interactions to obtain the *p*-values shown at the bottom of Table 2, Column (7). The reference year is 2002. Detailed regression results are shown in Table B1 in Appendix B.

[22] Detailed estimation results are shown in Table B1, Appendix B.

4.2 The effect of financing constraints dependent on the supply of external financing

The next set of tests analyzes the sensitivity of R&D to firm financing constraints conditional on the capitalization of the firm's main bank. Results of estimating Equation (1) separately for firms associated with banks with low or high capitalization are shown in Table 3. For firms which are related to a high capitalized bank, there is no difference in R&D spending during the financial crisis and the period observed immediately thereafter compared to the pre-crisis period. This follows as the statistical insignificant coefficients of the interaction terms (Rating × Crisis and Rating × PostCrisis) indicate that the effects in these time periods are not different from that of Rating. In contrast, firms which are related to a bank that has only a limited ability to absorb shocks due to a low ratio of tangible common equity to tangible assets likewise suffer in the financial crisis period (Column 1). Similar results are obtained for the capital funds ratio (Columns 3, 4).[23]

[23] Detailed estimation results are shown in Tables C1, C2 and C3 in Appendix C.

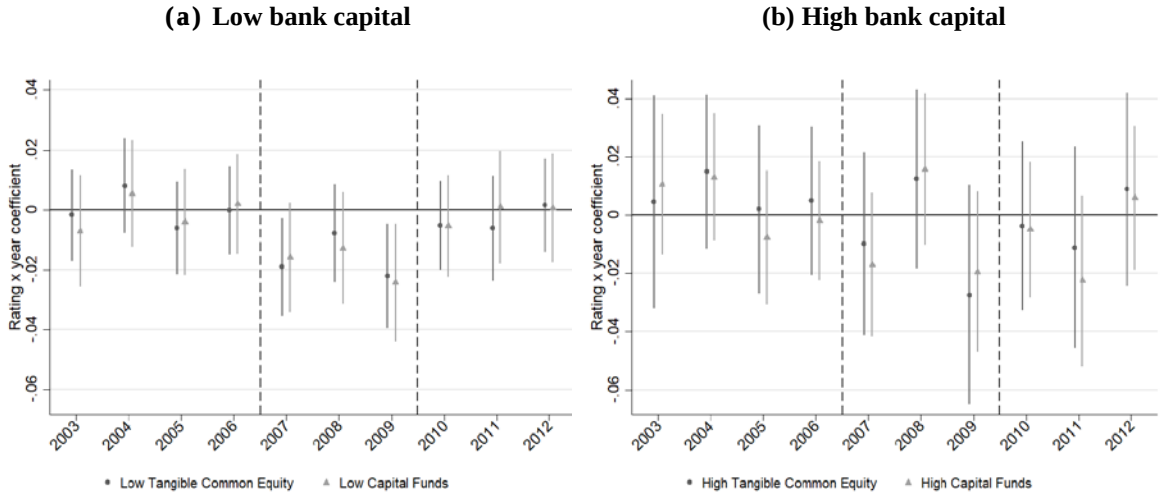
Table 3: Impact of firm financing constraints on R&D accounting for bank differences

	(1)	(2)	(3)	(4)	(5)	(6)
		Low			High	
	Tobit	Margin		Tobit	Margin	
		Intensive	Extensive		Intensive	Extensive
Panel A: Tangible common equity						
Rating	−0.011***	−0.008***	−0.0002***	−0.014**	−0.009**	−0.0003**
	(0.004)	(0.003)	(0.0001)	(0.007)	(0.004)	(0.0002)
Rating×Crisis	−0.015***	−0.011***	−0.0003***	−0.008	−0.006	−0.0002
	(0.005)	(0.004)	(0.0001)	(0.008)	(0.005)	(0.0002)
Rating×PostCrisis	−0.004	−0.003	−0.0001	−0.008	−0.005	−0.0002
	(0.005)	(0.004)	(0.0001)	(0.009)	(0.006)	(0.0002)
Constant	6.769***			6.773***		
	(1.790)			(2.446)		
H_0: Rating × $\text{year}_t = 0 \; \forall \; t < 2007$						
p-value	0.382			0.633		
Observations	6355	6355	6355	2384	2384	2384
Panel B: Capital funds						
Rating	−0.012***	−0.009***	−0.0002***	−0.010*	−0.007*	−0.0002*
	(0.004)	(0.003)	(0.0001)	(0.005)	(0.004)	(0.0001)
Rating×Crisis	−0.017***	−0.013***	−0.0003***	−0.005	−0.004	−0.0001
	(0.005)	(0.004)	(0.0001)	(0.007)	(0.005)	(0.0002)
Rating×PostCrisis	−0.002	−0.002	0.0000	−0.008	−0.005	−0.0002
	(0.005)	(0.004)	(0.0001)	(0.007)	(0.005)	(0.0002)
Constant	6.856***			6.123***		
	(1.843)			(2.181)		
H_0: Rating × $\text{year}_t = 0 \; \forall \; t < 2007$						
p-value	0.541			0.228		
Observations	5215	5215	5215	3524	3524	3524

Notes: All estimations include firm controls as described in Section 3.1. Moreover, industry, federal state and time fixed effects are included. Low indicates that the firm is related to a bank in the lower 25% of the variable's distribution of all German banks in the Bankscope data set. Cluster-robust standard errors in parentheses, clustered at the firm level. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

Again, we test for the common trend assumption by estimating Equation (1) but replacing the interaction terms by Rating×year interaction variables for the periods 2003 to 2012. The tests shown in the bottom row of Table 3 indicate that the common trend assumption holds as we cannot reject the null hypothesis that there is no joint significance of the pre-2007 interaction terms. This result is reinforced by the coefficient plots shown in Figure 4. We observe no difference in the effect in the period before 2007. However, in the time period of interest (2007 to 2009), we observe that the effect is different from the baseline period for firms which are related to a low-capitalized bank in the years 2007 and 2009. This relation does not hold for firms associated with high-capitalized banks.

Figure 4: Impact of financing constraints on R&D over time dependent on bank capital



Notes: The figure shows the Tobit regression coefficients for the Rating×year interactions estimated for firms related to a low or high capitalized bank to obtain the *p*-values shown at the bottom of Table 3, Panels A and B, Columns (1,4). The reference year is 2002. Detailed regression results are shown in Table C3 in Appendix C.

Consequently, we observe heterogeneity in the effect of the financial crisis on constrained firms. It becomes evident that constraints exert an effect on both groups of firms in the pre-crisis period. However, the interaction term shows that the increase in intensity of constraints during the crisis is significantly higher for this group of firms than for the group of firms associated with a high-capitalized bank. The differences in the effects between both groups of firms point towards an intensification of financing constraints due to the financial crisis rather than to an impact of the Basel II guidelines. This relation is assumed to hold as the Basel II regulations are expected to affect the importance of the ratings independently of the capital reserves of the banks.

5 Robustness and sensitivity tests

5.1 Endogenous firm-bank matching and sample selection

A possible problem of our empirical specification is that the affiliation of banks and firms may not be random. On the one hand, banks differ in terms of their risk policies (e.g. regarding orientation towards capital accumulation).[24] On the other hand, firms also pursue varying risk strategies, and an important factor here is the decision for or against R&D. A possible consequence of this would be the association of banks and companies with an affinity for risk (and vice versa), as risk-affine banks are prepared to finance risky projects. The possible endogenous matching process could affect the impact of the crisis on research-intensive companies. Consequently, a selectivity problem might exist.

To account for this selectivity problem, we use an inverse probability weighting (IPW) approach (e.g. Abadie and Cattaneo 2018; Imbens and Wooldridge 2009). First, we estimate the probability of each firm to be related to a low or high-capitalized bank by accounting for the impact of the firm's creditworthiness in each year. In the second step, we calculate the inverse probability weight from the obtained propensity score. Finally, we estimate Equation (1) and perform the regressions for firms related to high and low-capitalized banks separately and weight the observations by the generated weight. This has two advantages. Firstly, the re-weighting is supposed to eliminate potential differences between both types of firms by equalizing the explanatory variables. Secondly, the IPW approach is helpful in reducing the selection bias which results from the sample splitting approach in Section 4.2 (e.g. Wooldridge 2002; Wooldridge 2007).[25] The results for the Probit estimation, indicating whether firms are related to a high or low-capitalized bank, are shown in Appendix D, Table D1. The corresponding test on the difference in mean of the explanatory variables after re-weighting is shown in Table D2 of Appendix D. It becomes evident that there are no differences in means of the explanatory variables after the weighting. Table D3 shows the estimation results for the re-weighted regressions. The results look fairly similar to the estimates in Tables 2, 3.

[24] See e.g. Schwert (2018), Calem and Rob (1999), Furlong and Keeley (1989).

[25] Applying Heckman selection models to correct for the sample selection does not alter the results considerably. This holds for sample selection model with a linear model in the second step as well as with a Tobit model to account for corner solutions in the second step.

5.2 Model and dependent variable

We provide several robustness tests for our analysis. Results for these are shown in Appendix E. First, we provide general tests concerning the model dependence of our results. Thus, we re-estimate the results of Tables 2, 3 using homoscedastic Tobit and OLS. The results are comparable to the estimates in Tables 2, 3 as shown in Panels A and B of Table E1 in Appendix E. Moreover, we re-estimate our results using the logarithm of the share of R&D expenditures per employee (Table E1, Panel C, Appendix E). Again, we observe similar results (Appendix E, Table E1). Additionally, we perform tests concerning the variables included in the heteroscedasticity term. The results for these tests (e.g. adding the remainder control variables) are shown in Table E2, Panels B, C and D and are fairly similar to the baseline results in Tables 2, 3.

5.3 Changes to the rating variable

We also test for the robustness of specification of our proxy for firm financing constraints, the rating variable. For this purpose, we start by using the one period lagged rating value as it is common practice in the literature (e.g. Czarnitzki and Hottenrott 2011a; Czarnitzki and Hottenrott 2011b) to determine whether firms are financially constrained. In line with this strand of literature, we assume that the lagged rating measure is exogenously determined. The advantage of this modified rating variable is its variation over time. The results shown in Panel A of Table F1 are comparable to the benchmark results presented in Table 2 and the results for the bank capital differentiation in Table 3. Next, we use the mean value of the firm's ratings in the three years prior to the Basel II guidelines (2004 to 2006). Again, we observe similar results (Tables F1, Panel B, Appendix F). Last, we provide the results for an extended sample in which we re-add the firms which have rating values of 500 or above. As shown in Panel C of Table F1 in Appendix F, these results are comparable to the ones shown in Tables 2, 3.

5.4 Changes concerning bank-related information

In addition to the previous robustness checks, we provide tests for the heterogeneity of our results concerning the supplier of external financing – the main banks. In a first step, we apply two specifications with cut-off points at 10% and 50% of the distributions of all banks in the Bankscope data set that are observed in the year 2006. The results are shown in Table G1, Panel A and B in Appendix G and they are quite similar to the results presented in Table 3. A second test in this respect comprises the firm-bank relationship. Therefore, we drop firms

from our sample that switched their main bank in any year of the sample period. We use the remainder of 5765 observations and re-estimate our results. As shown in Panel C of Table G1 in Appendix G, the results of both estimations are comparable to the results presented in Tables 2, 3. Last, we use additional definitions for the capitalization of banks. First, we apply the alternative measure of equity to total assets, which is the inverse of the bank leverage ratio as described above. Second, we use the value of capital funds to net loans (Avdjiev et al. 2019). Results based on these variables and the cut-off point at 25% are shown in Table G2 of Appendix G. They are fairly similar to the estimates in Table 3.

In a further set of tests concerning the definition of our bank variables, we exploit the full bank account information of the firms. We have access to up to six banks to which the firm is related. This allows us to re-define the indicator which sorts the firms into those which are related to a low or a high capitalized bank. Results of these tests are shown in Appendix G, Table G3, Panel A and B. First, we sort firms into the 'Low' group if at least one of the six banks the firm is related to has a low capital base. Correspondingly, firms which are not related to any low capitalized bank are defined as 'High'. The results in Panel A of Table G3, Appendix G look quite similar to the results in Table 3. Second we define firms as 'Low' if all banks the firm is related to have a low capital endowment. These firms are likely to have no way of substituting external financing. Firms are defined as 'High' if at least one bank is non-low capitalized. The results in Appendix G, Table G3, Panel B again look fairly similar to those in Table 3.

5.5 Sample size and time period definition

We perform various tests which concern the definition of the crisis and pre-crisis periods. Table H1 in Appendix H shows the corresponding results. First, we replace the crisis dummy (years 2007 to 2009) by a Basel dummy (2007) and Crisis dummy (2008 and 2009). The results are shown in Table H1, Panel A and are similar to the baseline results. Next, we account for the early 2000s recession – a period for Germany that was characterized by decreasing GDP growth and a recession in 2003 (Dustmann et al. 2014). Thus, we include a dummy for this pre-crisis downturn. As the first year in our sample is 2002, the dummy takes unit value in the years 2002 and 2003. As the downturn was probably unrelated to financial market issues[26], no effect is found for the interaction with the Rating variable (Table H1, Panel B). In additional tests, which are shown in Table H2 of Appendix H, we deleted the

[26] See e.g. Cingano et al. (2016) who uses the early 2000s period as a placebo period for a shock to financial markets.

years 2002 and 2003 (Panel A) and 2002 to 2004 (Panel B). This does not affect our results either.

6 Conclusion

The impact of credit constraints for firms on R&D has been investigated for some time now (e.g. Czarnitzki and Hottenrott 2010; Hall et al. 2016; He and Tian 2018). We extend this topic by taking two kinds of differentiation into account: the role of economic conditions in general and the impact of constraints of banks themselves. Economic conditions are considered by comparing the time of the financial crisis, as then demand and supply of debt was drastically affected, with periods before and afterwards. The impact of constraints of banks is included by taking up their bank balance sheet strength in terms of bank capital.

Our results clearly indicate that financial constraints matter for R&D in general and become more relevant during the financial crisis.[27] Firms with financing constraints reduce their R&D spending to a larger extent than less constrained firms during the crisis period, compared to the period before. With respect to the most important supplier of debts, namely the banks, it becomes obvious that banks with weaker balance sheets transmit their problems to their corporate customers. Thus, firms related to a bank with a weak capital endowment reduce their R&D spending in the financial crisis in accordance with their financing constraints. This effect is not observed for firms related to a high-capitalized bank. The consideration of bank constraints indicates that the financial crisis, rather than the Basel II enactment, was responsible for the sharper reduction in R&D expenditures. Thus, our results clearly imply an impact of bank financing on R&D.

The results point to a need for more research on the risk attitudes of banks. Thus, in line with the recent development of capital buffers due to the Basel II and III guidelines, the importance of considering bank capital is underlined by our results. Consequently, an implication for policy makers which might be drawn from our results is that strengthening the bank balance sheet is an important device to achieve stability in times of turbulence on financial markets. As holding capital is costly, it might be difficult to find a balance between costs of capital in normal times and the benefits in times of downturn (Adrian et al. 2018; Thakor 2014).

[27] Our results coincide with findings of other work utilizing periods which do not include the financial crisis (e.g. Czarnitzki and Hottenrott 2010; Hall et al. 2016; He and Tian 2018). Moreover, our findings are related to literature which investigates the impact of the crisis on innovation utilizing German data (e.g. Hud and Hussinger 2015; Kulicke et al. 2010; Rammer 2011).

We can also draw from our analysis several policy implications at the firm level. The cumulative public and private expenditures for R&D are below the EU policy target level of 3% of GDP (OECD 2018). The European Commission (2010a) and European Commission (2010b) point to the importance of access to finance in order to realize innovation activities and, to this end, two additional sources of external finance must be considered: subsidies and venture capital. Firstly, as highlighted by the literature on R&D subsidies, due to their influence on the growth of an economy it is essential to provide financial support to innovative firms (e.g. Brautzsch et al. 2015; Hud and Hussinger 2015).[28] Secondly, it might be important to support firms especially during times of difficult financing conditions, when banks are particularly cautious and will minimize their risks by reducing lending to innovative firms. In such periods public subsidies are especially valuable. Thirdly, another implication is the strengthening of venture capital financing. Even if this type of financing might be the least preferred by established firms, it is a valuable source of funding for younger firms (Brown et al. 2012; Hochberg et al. 2018). However, in Germany, the opportunities for venture capital financing are sparse. Fourthly, another option would be that firms make use of equity issuance to finance innovation (Brown et al. 2009; Lerner et al. 2011). However, like bank financing, equity financing contracted during the crisis (Kahle and Stulz 2013).

[28] See e.g. Hottenrott and Lopes-Bento (2014) for an evaluation of the effectivity of a targeted subsidy program.

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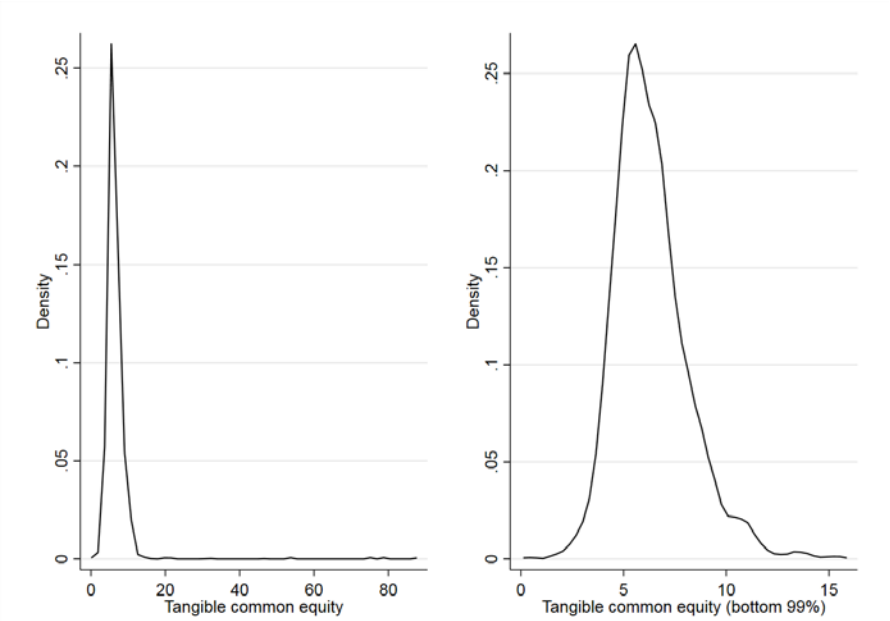
Appendix

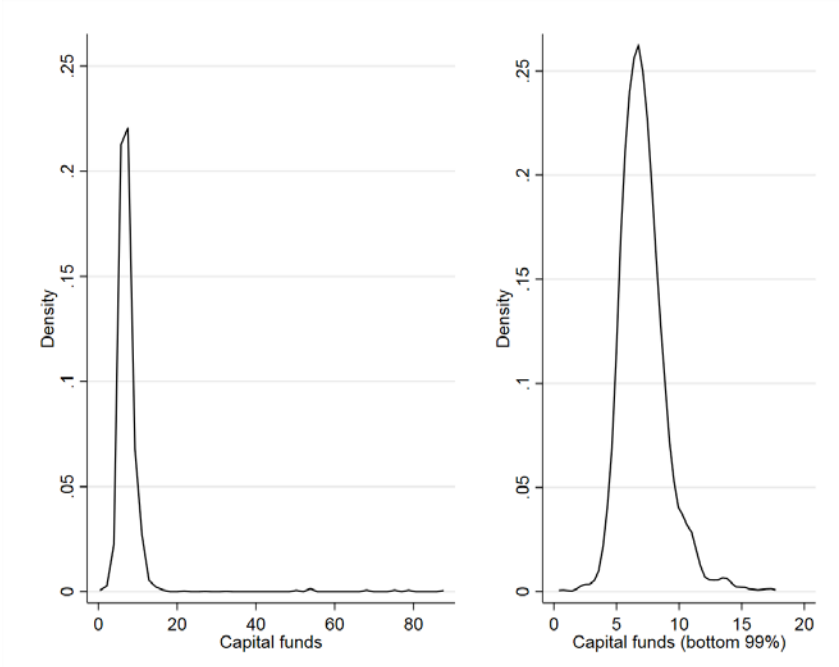
A Descriptive statistics

Figure A1: Distribution of the tangible common equity ratio



Notes: The figure shows the distribution of the tangible common equity ratio over 1452 banks (left) from the Bankscope data set. The right diagram shows the distribution for the bottom 99% of the banks.

Figure A2: Distribution of the capital funds ratio



Notes: The figure shows the distribution of the capital funds ratio over 1452 banks (left) from the Bankscope data set. The right diagram shows the distribution for the bottom 99% of the banks.

Table A1: Distribution of firms over industries

Name	NACE Rev. 2.0 code	Firms	Percentage share
Mining	5-9, 19, 35	96	2.952
Food/Tobacco	10-12	120	3.690
Textiles	13-15	132	4.059
Wood/Paper	16-17	110	3.383
Chemicals	20-21	218	6.704
Plastics	22	157	4.828
Glass/Ceramics	23	93	2.860
Metals	24-25	296	9.102
Electrical equipment	26-27	489	15.037
Machinery	28	374	11.501
Retail/Automobile	29-30	129	3.967
Furniture/Toys/Medical technology/Maintenance	31-33	235	7.226
Energy / Water	36-39	66	2.030
Media services	18, 58-60	98	3.014
IT/Telecommunications	61-63	256	7.872
Technical services/R&D services	71-72	288	8.856
Consulting/advertising	69, 70.2, 73	95	2.921
Total		3252	100.000

Table A2: Distribution of firms over federal states

Name	Firms	Percentage share
Baden-Wuerttemberg	496	15.252
Bavaria	457	14.053
Berlin	122	3.752
Brandenburg	120	3.690
Bremen	53	1.630
Hamburg	57	1.753
Hesse	195	5.996
Lower Saxony	230	7.073
Mecklenburg-Vorpommern	58	1.784
North Rhine-Westphalia	558	17.159
Rhineland-Palatinate	109	3.352
Saarland	31	0.953
Saxony	355	10.916
Saxony-Anhalt	145	4.459
Schleswig-Holstein	62	1.907
Thuringia	204	6.273
Total	3252	100.000

B Additional results and marginal effects for the baseline estimation

Table B1: Common trend test and effect heterogeneity

	(1)	(2)	(3)	(4)
Rating	-0.023***	-0.020***	-0.013**	-0.011***
	(0.006)	(0.004)	(0.006)	(0.003)
Rating × 2003	-0.003		-0.002	
	(0.008)		(0.007)	
Rating × 2004	0.012		0.009	
	(0.007)		(0.007)	
Rating × 2005	-0.002		-0.004	
	(0.008)		(0.007)	
Rating × 2006	0.002		0.002	
	(0.007)		(0.007)	
Rating × 2007	-0.014*	-0.017***	-0.015**	-0.017***
	(0.008)	(0.006)	(0.008)	(0.006)
Rating × 2008	-0.003	-0.005	-0.003	-0.004
	(0.008)	(0.006)	(0.007)	(0.006)
Rating × 2009	-0.020**	-0.023***	-0.022***	-0.024***
	(0.009)	(0.007)	(0.008)	(0.007)
Rating × 2010	-0.003	-0.006	-0.005	-0.006
	(0.007)	(0.005)	(0.007)	(0.005)
Rating × 2011	-0.009	-0.011	-0.007	-0.009
	(0.009)	(0.007)	(0.008)	(0.007)
Rating × 2012	0.002	-0.000	0.004	0.003
	(0.008)	(0.006)	(0.007)	(0.006)
Constant	10.195***	9.596***	7.096***	6.736***
	(1.815)	(1.449)	(1.718)	(1.397)
H_0: Rating × $\text{year}_t = 0 \; \forall \; t < 2007$				
p-value	0.107		0.194	
H_0: Rating × $\text{year}_t = 0 \; \forall \; t \leq 2012$				
p-value	0.006		0.003	
Firm controls	-	-	Yes	Yes
Industry fixed effects	Yes	Yes	Yes	Yes
Federal state fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Log Likelihood	-24177.002	-24179.376	-23880.642	-23882.502
Left censored obs.	2159	2159	2159	2159
Uncensored obs.	6580	6580	6580	6580
Obs.	8739	8739	8739	8739

Notes: Cluster-robust standard errors in parentheses, clustered at the firm level. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

C Detailed and additional results for the estimations with bank splits

Table C1: Estimation results with all variables included based on tangible common equity splitting

	(1)	(2)	(3)	(4)	(5)	(6)
	Low			High		
Rating	-0.016***		-0.011***	-0.018***		-0.014**
	(0.003)		(0.004)	(0.006)		(0.007)
Rating × Pre-Crisis		-0.011***			-0.014**	
		(0.004)			(0.007)	
Rating × Crisis		-0.026***	-0.015***		-0.022***	-0.008
		(0.005)	(0.005)		(0.008)	(0.008)
Rating × PostCrisis		-0.014***	-0.004		-0.022**	-0.008
		(0.004)	(0.005)		(0.009)	(0.009)
Size	0.849***	0.837***	0.837***	1.202***	1.194***	1.194***
	(0.111)	(0.112)	(0.112)	(0.351)	(0.362)	(0.362)
Size squared	-0.015***	-0.015***	-0.015***	-0.032***	-0.032***	-0.032***
	(0.003)	(0.003)	(0.003)	(0.010)	(0.011)	(0.011)
Age	-0.024	-0.024*	-0.024*	-0.052**	-0.053**	-0.053**
	(0.015)	(0.015)	(0.015)	(0.024)	(0.024)	(0.024)
Age squared	0.000*	0.000*	0.000*	0.000**	0.000**	0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Group	0.740***	0.751***	0.751***	1.080**	1.079**	1.079**
	(0.280)	(0.280)	(0.280)	(0.474)	(0.473)	(0.473)
Sales growth	0.319	0.317	0.317	0.635	0.675	0.675
	(0.295)	(0.295)	(0.295)	(0.682)	(0.680)	(0.680)
Export share	0.043***	0.043***	0.043***	0.054***	0.054***	0.054***
	(0.005)	(0.005)	(0.005)	(0.008)	(0.008)	(0.008)
Constant	7.796***	6.769***	6.769***	7.648***	6.773***	6.773***
	(1.731)	(1.790)	(1.790)	(2.350)	(2.446)	(2.446)
Industry fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Federal state fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Log Likelihood	-17487.261	-17481.776	-17481.776	-6332.266	-6331.509	-6331.509
Left censored obs.	1466	1466	1466	693	693	693
Uncensored obs.	4889	4889	4889	1691	1691	1691
Obs.	6355	6355	6355	2384	2384	2384

Notes: Cluster-robust standard errors in parentheses, clustered at the firm level. Low indicates that the firm is related to a bank in the lower 25% of the variable's distribution of all German banks in the Bankscope data set. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

Table C2: Estimation results with all variables included based on capital funds splitting

	(1)	(2)	(3)	(4)	(5)	(6)
	Low			High		
Rating	-0.017***		-0.012***	-0.014***		-0.010*
	(0.003)		(0.004)	(0.005)		(0.005)
Rating × Pre-Crisis		-0.012***			-0.010*	
		(0.004)			(0.005)	
Rating × Crisis		-0.028***	-0.017***		-0.015**	-0.005
		(0.005)	(0.005)		(0.007)	(0.007)
Rating × PostCrisis		-0.014***	-0.002		-0.018***	-0.008
		(0.004)	(0.005)		(0.007)	(0.007)
Size	0.766***	0.757***	0.757***	1.409***	1.406***	1.406***
	(0.105)	(0.105)	(0.105)	(0.324)	(0.329)	(0.329)
Size squared	-0.014***	-0.013***	-0.013***	-0.035***	-0.035***	-0.035***
	(0.002)	(0.002)	(0.002)	(0.009)	(0.009)	(0.009)
Age	-0.014	-0.015	-0.015	-0.056***	-0.056***	-0.056***
	(0.016)	(0.016)	(0.016)	(0.020)	(0.020)	(0.020)
Age squared	0.000	0.000	0.000	0.000***	0.000***	0.000***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Group	0.909***	0.925***	0.925***	0.694*	0.702*	0.702*
	(0.315)	(0.315)	(0.315)	(0.363)	(0.362)	(0.362)
Sales growth	0.156	0.164	0.164	0.740	0.755*	0.755*
	(0.332)	(0.332)	(0.332)	(0.456)	(0.455)	(0.455)
Export share	0.041***	0.041***	0.041***	0.052***	0.052***	0.052***
	(0.005)	(0.005)	(0.005)	(0.007)	(0.007)	(0.007)
Constant	7.813***	6.856***	6.856***	6.904***	6.123***	6.123***
	(1.766)	(1.843)	(1.843)	(2.126)	(2.181)	(2.181)
Industry fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Federal state fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Log Likelihood	-17487.261	-17481.776	-17481.776	-6332.266	-6331.509	-6331.509
Left censored obs.	1166	1166	1166	993	993	993
Uncensored obs.	4049	4049	4049	2531	2531	2531
Obs.	5215	5215	5215	3524	3524	3524

Notes: Cluster-robust standard errors in parentheses, clustered at the firm level. Low indicates that the firm is related to a bank in the lower 25% of the variable's distribution of all German banks in the Bankscope data set. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

Table C3: Common trend test and effect heterogeneity

	Tangible common equity		Capital funds	
	Low	High	Low	High
	(1)	(2)	(3)	(4)
Rating	-0.011*	-0.020	-0.012	-0.013
	(0.006)	(0.012)	(0.008)	(0.010)
Rating × 2003	-0.002	0.004	-0.007	0.011
	(0.008)	(0.019)	(0.010)	(0.012)
Rating × 2004	0.008	0.015	0.005	0.013
	(0.008)	(0.013)	(0.009)	(0.011)
Rating × 2005	-0.006	0.002	-0.004	-0.008
	(0.008)	(0.015)	(0.009)	(0.012)
Rating × 2006	-0.000	0.005	0.002	-0.002
	(0.007)	(0.013)	(0.008)	(0.010)
Rating × 2007	-0.019**	-0.010	-0.016*	-0.017
	(0.008)	(0.016)	(0.009)	(0.013)
Rating × 2008	-0.008	0.012	-0.013	0.016
	(0.008)	(0.016)	(0.010)	(0.013)
Rating × 2009	-0.022**	-0.027	-0.024**	-0.019
	(0.009)	(0.019)	(0.010)	(0.014)
Rating × 2010	-0.005	-0.004	-0.005	-0.005
	(0.008)	(0.015)	(0.009)	(0.012)
Rating × 2011	-0.006	-0.011	0.001	-0.023
	(0.009)	(0.018)	(0.010)	(0.015)
Rating × 2012	0.001	0.009	0.001	0.006
	(0.008)	(0.017)	(0.009)	(0.013)
Constant	6.900***	8.173**	6.884***	6.690**
	(2.056)	(3.357)	(2.229)	(2.899)
H_0: Rating × $\text{year}_t = 0 \; \forall \; t < 2007$				
p-value	0.382	0.633	0.541	0.228
H_0: Rating × $\text{year}_t = 0 \; \forall \; t \leq 2012$				
p-value	0.026	0.425	0.050	0.048
Firm controls	Yes	Yes	Yes	Yes
Industry fixed effects	Yes	Yes	Yes	Yes
Federal state fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Log Likelihood	-17478.411	-6327.529	-14401.005	-9385.943
Left censored obs.	1466	693	1166	993
Uncensored obs.	4889	1691	4049	2531
Obs.	6355	2384	5215	3524

Notes: Cluster-robust standard errors in parentheses, clustered at the firm level. Low indicates that the firm is related to a bank in the lower 25% of the variable's distribution of all German banks in the Bankscope data set. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

D Endogenous firm-bank matching and sample selection

Table D1: Matching results to obtain the propensity score for the construction of the inverse probability weights

	(1)	(2)
Dependent variable	Low Tangible Common Equity	Low Capital Funds
Rating	−0.003**	−0.005***
	(0.001)	(0.001)
Rating × 2003	0.000	0.002
	(0.002)	(0.002)
Rating × 2004	0.002	0.003*
	(0.002)	(0.002)
Rating × 2005	0.000	0.003*
	(0.002)	(0.002)
Rating × 2006	0.001	0.004**
	(0.002)	(0.002)
Rating × 2007	0.002	0.002
	(0.002)	(0.002)
Rating × 2008	0.000	0.003
	(0.002)	(0.002)
Rating × 2009	0.002	0.003*
	(0.002)	(0.002)
Rating × 2010	0.001	0.004**
	(0.002)	(0.002)
Rating × 2011	0.002	0.003
	(0.002)	(0.002)
Rating × 2012	0.002	0.003
	(0.002)	(0.002)
Size	0.108***	0.106***
	(0.033)	(0.027)
Size squared	−0.002***	−0.002***
	(0.001)	(0.001)
Age	0.002	0.000
	(0.002)	(0.002)
Age squared	0.000	0.000
	(0.000)	(0.000)
Group membership	0.417***	0.396***
	(0.035)	(0.032)
Sales growth	−0.008	−0.081
	(0.064)	(0.060)
Export share	0.005***	0.004***
	(0.001)	(0.001)
Constant	0.501	0.952***
	(0.337)	(0.324)
Log likelihood	-4197.067	-5125.850
Observations	8739	8739

Notes: Treatment status is defined as being related to a low capitalized bank. Each regression includes industry times federal state fixed effects. Standard errors in parentheses. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

Table D2: Mean comparison after matching – Means calculated using inverse probability weights

	Mean		Difference	p-value
Variable	Control	Treated		
Panel A: Tangible Common Equity				
Rating	217.559	216.401	−1.157	0.505
Rating × 2003	9.253	10.954	1.701	0.199
Rating × 2004	19.229	20.683	1.454	0.542
Rating × 2005	18.494	18.487	−0.007	0.998
Rating × 2006	24.281	23.999	−0.282	0.918
Rating × 2007	18.882	21.027	2.145	0.281
Rating × 2008	24.863	25.850	0.986	0.675
Rating × 2009	12.759	14.504	1.745	0.285
Rating × 2010	37.092	27.729	−9.363	0.120
Rating × 2011	15.625	16.303	0.678	0.722
Rating × 2012	20.532	21.404	0.872	0.704
Size	0.470	0.342	−0.128	0.493
Size Squared	7.408	4.284	−3.125	0.615
Age	30.359	31.011	0.652	0.546
Age squared	1878.887	1959.242	80.355	0.519
Group membership	0.498	0.492	−0.007	0.777
Sales growth	0.060	0.063	0.004	0.829
Export share	24.057	24.016	−0.041	0.970
Panel B: Capital Funds				
Rating	216.636	217.214	0.577	0.641
Rating × 2003	11.388	11.118	−0.270	0.865
Rating × 2004	21.206	20.763	−0.443	0.813
Rating × 2005	18.200	18.445	0.245	0.876
Rating × 2006	23.132	23.863	0.732	0.690
Rating × 2007	19.612	20.879	1.267	0.410
Rating × 2008	24.670	25.864	1.194	0.495
Rating × 2009	13.432	14.364	0.932	0.474
Rating × 2010	28.383	27.946	−0.437	0.830
Rating × 2011	16.372	16.549	0.177	0.909
Rating × 2012	22.763	21.866	−0.897	0.718
Size	0.484	0.347	−0.137	0.258
Size squared	7.796	4.445	−3.350	0.368
Age	30.643	30.741	0.099	0.904
Age squared	1926.061	1945.922	19.861	0.855
Group membership	0.506	0.491	−0.015	0.285
Sales growth	0.073	0.065	−0.008	0.330
Export share	24.150	24.027	−0.124	0.870

Table D3: Weighted estimations for the impact of firm financing constraints on R&D accounting for bank differences

	(1)	(2)	(3)
	Baseline	Tangible common equity	
		Low	High
Panel A: Tangible Common Equity			
Rating	−0.016***	−0.012***	−0.025***
	(0.004)	(0.004)	(0.007)
Rating × Crisis	−0.013**	−0.012**	−0.014
	(0.005)	(0.005)	(0.009)
Rating × PostCrisis	−0.008	−0.002	−0.008
	(0.007)	(0.005)	(0.012)
Constant	8.067***	6.494***	9.305***
	(1.412)	(1.916)	(2.115)
Observations	8613	6229	2384
Panel B: Capital Funds			
	Baseline	Capital Funds	
		Low	High
Rating	−0.014***	−0.013***	−0.017***
	(0.003)	(0.005)	(0.005)
Rating × Crisis	−0.012**	−0.014**	−0.007
	(0.005)	(0.006)	(0.008)
Rating × PostCrisis	−0.002	0.002	−0.003
	(0.005)	(0.006)	(0.008)
Constant	8.143***	6.796***	9.338***
	(1.344)	(1.919)	(1.852)
Observations	8693	5169	3524

Notes: All estimations include firm controls as described in Section 3.1. Moreover, industry, federal state and time fixed effects are included. Baseline refers to the estimation of Equation (1) with the changes highlighted in the respective heading of each panel. Low indicates that the firm is related to a bank in the lower 25% of the variable's distribution of all German banks in the Bankscope data set. Cluster-robust standard errors in parentheses, clustered at the firm level. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

E Model and dependent variable

Table E1: Model and dependent variable

	(1)	(2)	(3)	(4)	(5)
	Baseline	Tangible common equity		Capital Funds	
		Low	High	Low	High
Panel A: Homoscedastic Tobit					
Rating	-0.013***	-0.013***	-0.012*	-0.012**	-0.012*
	(0.004)	(0.005)	(0.007)	(0.005)	(0.006)
Rating × Crisis	-0.012***	-0.013**	-0.011	-0.015***	-0.009
	(0.005)	(0.005)	(0.009)	(0.006)	(0.007)
Rating × PostCrisis	0.000	0.001	-0.007	-0.001	-0.003
	(0.005)	(0.006)	(0.009)	(0.006)	(0.007)
Constant	7.612***	8.114***	6.727***	7.455***	6.837***
	(1.187)	(1.453)	(2.190)	(1.504)	(1.909)
Observations	8739	6355	2384	5215	3254
Panel B: OLS					
Rating	−0.012***	−0.011***	−0.011**	−0.011***	−0.010**
	(0.003)	(0.004)	(0.005)	(0.004)	(0.004)
Rating × Crisis	−0.008**	−0.009**	−0.007	−0.011**	−0.005
	(0.003)	(0.004)	(0.006)	(0.004)	(0.005)
Rating × PostCrisis	0.000	0.001	−0.005	−0.001	−0.003
	(0.004)	(0.004)	(0.007)	(0.005)	(0.005)
Constant	8.888***	9.240***	8.305***	8.737***	8.321***
	(0.891)	(1.112)	(1.581)	(1.169)	(1.360)
Observations	8739	6355	2384	5215	3254
Panel C: Heteroscedastic Tobit with scaled dependent variable					
Rating	−0.003	−0.002	−0.006	−0.002	−0.003
	(0.002)	(0.003)	(0.004)	(0.003)	(0.004)
Rating × Crisis	−0.009***	−0.011***	−0.007	−0.011***	−0.005
	(0.003)	(0.003)	(0.005)	(0.004)	(0.005)
Rating × PostCrisis	−0.004	−0.004	−0.004	−0.003	−0.004
	(0.003)	(0.003)	(0.006)	(0.004)	(0.005)
Constant	4.005***	4.009***	4.557***	3.967***	4.052***
	(0.882)	(1.149)	(1.482)	(1.171)	(1.370)
Observations	8713	6334	2379	5199	3514

Notes: All estimations include firm controls as described in Section 3.1. Moreover, industry, federal state and time fixed effects are included. Baseline refers to the estimation of Equation (1) with the changes highlighted in the respective heading of each panel. Low indicates that the firm is related to a bank in the lower 25% of the variable's distribution of all German banks in the Bankscope data set. Cluster-robust standard errors in parentheses, clustered at the firm level. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

Table E2: Changes to the heteroscedasticity term

	(1)	(2)	(3)	(4)	(5)
	Baseline	Tangible common equity		Capital funds	
		Low	High	Low	High
Panel A: Baseline – Three size dummies, two age dummies, industry dummies					
Rating	−0.011***	−0.011***	−0.014**	−0.012***	−0.010*
	(0.003)	(0.004)	(0.007)	(0.004)	(0.005)
Rating × Crisis	−0.013***	−0.015***	−0.008	−0.017***	−0.005
	(0.004)	(0.005)	(0.008)	(0.005)	(0.007)
Rating × PostCrisis	−0.004	−0.004	−0.008	−0.002	−0.008
	(0.004)	(0.005)	(0.009)	(0.005)	(0.007)
Constant	6.743***	6.769***	6.773***	6.856***	6.123***
	(1.398)	(1.790)	(2.446)	(1.843)	(2.181)
Observations	8739	6355	2384	5215	3254
Panel B: Three size dummies, two age dummies					
Rating	−0.013***	−0.012***	−0.013*	−0.011**	−0.011*
	(0.004)	(0.004)	(0.007)	(0.005)	(0.006)
Rating × Crisis	−0.011**	−0.012**	−0.012	−0.014**	−0.008
	(0.005)	(0.005)	(0.008)	(0.006)	(0.007)
Rating × PostCrisis	−0.001	0.000	−0.008	−0.002	−0.005
	(0.005)	(0.006)	(0.009)	(0.006)	(0.007)
Constant	7.546***	8.177***	6.872***	7.501***	6.597***
	(1.183)	(1.453)	(2.183)	(1.511)	(1.916)
Observations	8739	6355	2384	5215	3254
Panel C: Only industry dummies					
Rating	−0.012***	−0.011***	−0.013*	−0.012***	−0.010*
	(0.003)	(0.004)	(0.007)	(0.004)	(0.005)
Rating × Crisis	−0.012***	−0.016***	−0.007	−0.017***	−0.006
	(0.004)	(0.005)	(0.008)	(0.005)	(0.007)
Rating × PostCrisis	−0.003	−0.003	−0.007	−0.002	−0.007
	(0.004)	(0.005)	(0.009)	(0.005)	(0.007)
Constant	6.865***	6.763***	6.742***	6.870***	6.185***
	(1.397)	(1.784)	(2.492)	(1.821)	(2.189)
Observations	8739	6355	2384	5215	3254
Panel D: Baseline variables and Group, Sales growth, Export share					
Rating	−0.011***	−0.011***	−0.013**	−0.012***	−0.009*
	(0.003)	(0.004)	(0.006)	(0.004)	(0.005)
Rating × Crisis	−0.012***	−0.013***	−0.010	−0.016***	−0.003
	(0.004)	(0.005)	(0.008)	(0.005)	(0.007)
Rating × PostCrisis	−0.004	−0.005	−0.006	−0.003	−0.007
	(0.004)	(0.005)	(0.009)	(0.005)	(0.007)
Constant	6.735***	6.599***	6.818***	6.796***	5.977***
	(1.371)	(1.813)	(2.354)	(1.872)	(2.058)
Observations	8739	6355	2384	5215	3254

Notes: All estimations include firm controls as described in Section 3.1. Moreover, industry, federal state and time fixed effects are included. Baseline refers to the estimation of Equation (1) with the changes highlighted in the respective heading of each panel. Low indicates that the firm is related to a bank in the lower 25% of the variable's distribution of all German banks in the Bankscope data set. Cluster-robust standard errors in parentheses, clustered at the firm level. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

F Changes to the rating variable

Table F1: Changes of the rating variable

	(1)	(2)	(3)	(4)	(5)
	Baseline	Tangible common equity		Capital funds	
		Low	High	Low	High
Panel A: Lagged rating index					
Rating	−0.011***	−0.010***	−0.013**	−0.012***	−0.008
	(0.003)	(0.004)	(0.006)	(0.004)	(0.005)
Rating × Crisis	−0.010**	−0.012**	−0.005	−0.014***	−0.002
	(0.004)	(0.005)	(0.008)	(0.005)	(0.007)
Rating × PostCrisis	−0.004	−0.003	−0.010	−0.001	−0.010
	(0.004)	(0.005)	(0.009)	(0.005)	(0.007)
Constant	6.629***	6.659***	6.677***	6.905***	5.581***
	(1.367)	(1.773)	(2.359)	(1.808)	(2.144)
Observations	8739	6355	2384	5215	3254
Panel B: Mean of rating over the period 2004 to 2006					
Rating	−0.013***	−0.011**	−0.022***	−0.012**	−0.014**
	(0.004)	(0.004)	(0.008)	(0.005)	(0.006)
Rating × Crisis	−0.017***	−0.018***	−0.014	−0.016***	−0.017**
	(0.005)	(0.005)	(0.009)	(0.006)	(0.008)
Rating × PostCrisis	−0.005	−0.007	−0.001	−0.004	−0.009
	(0.005)	(0.006)	(0.011)	(0.006)	(0.008)
Constant	7.371***	7.195***	8.683***	7.104***	7.201***
	(1.496)	(1.873)	(2.742)	(1.968)	(2.328)
Observations	7564	5540	2024	4598	2966
Panel C: Adding observations with ratings equal or above 500					
Rating	−0.007***	−0.005**	−0.015**	−0.005*	−0.012***
	(0.002)	(0.002)	(0.007)	(0.003)	(0.004)
Rating × Crisis	−0.011**	−0.012**	−0.009	−0.013**	−0.005
	(0.004)	(0.005)	(0.007)	(0.006)	(0.006)
Rating × PostCrisis	−0.005	−0.007*	0.002	−0.008*	0.001
	(0.004)	(0.004)	(0.010)	(0.005)	(0.007)
Constant	5.741***	5.660***	6.962***	5.444***	6.510***
	(1.293)	(1.661)	(2.422)	(1.690)	(2.053)
Observations	8806	6405	2401	5263	3543

Notes: All estimations include firm controls as described in Section 3.1. Moreover, industry, federal state and time fixed effects are included. Baseline refers to the estimation of Equation (1) with the changes highlighted in the respective heading of each panel. Low indicates that the firm is related to a bank in the lower 25% of the variable's distribution of all German banks in the Bankscope data set. Cluster-robust standard errors in parentheses, clustered at the firm level. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

G Changes concerning bank-related information

Table G1: Changes concerning bank-related information

	(1)	(2)	(3)	(4)	(5)
	Baseline	Tangible common equity		Capital funds	
		Low	High	Low	High
Panel A: Cut point for bank variables at 10%					
Rating	−0.011***	−0.008**	−0.013**	−0.011*	−0.011**
	(0.003)	(0.004)	(0.006)	(0.006)	(0.004)
Rating × Crisis	−0.013***	−0.015***	−0.009	−0.017**	−0.011**
	(0.004)	(0.005)	(0.007)	(0.007)	(0.005)
Rating × PostCrisis	−0.004	−0.005	−0.010	−0.005	−0.007
	(0.004)	(0.005)	(0.008)	(0.008)	(0.005)
Constant	6.743***	6.689***	6.279***	7.411***	5.839***
	(1.398)	(1.877)	(2.310)	(2.624)	(1.613)
Observations	8739	5432	3307	2409	6330
Panel B: Cut point for bank variables at 50%					
Rating	−0.011***	−0.011***	−0.016*	−0.013***	−0.007
	(0.003)	(0.004)	(0.009)	(0.004)	(0.007)
Rating × Crisis	−0.013***	−0.015***	−0.001	−0.015***	−0.002
	(0.004)	(0.005)	(0.011)	(0.005)	(0.009)
Rating × PostCrisis	−0.004	−0.005	−0.007	−0.003	−0.006
	(0.004)	(0.005)	(0.015)	(0.005)	(0.009)
Constant	6.743***	6.253***	9.206***	7.059***	4.768*
	(1.398)	(1.596)	(3.137)	(1.587)	(2.697)
Observations	8739	7615	1124	6339	2400
Panel C: Without bank switching firms					
Rating	−0.012***	−0.011**	−0.016	−0.015***	−0.005
	(0.005)	(0.005)	(0.011)	(0.005)	(0.008)
Rating × Crisis	−0.014**	−0.019***	0.006	−0.019***	−0.006
	(0.005)	(0.006)	(0.012)	(0.006)	(0.010)
Rating × PostCrisis	−0.005	−0.004	−0.005	0.001	−0.011
	(0.006)	(0.006)	(0.013)	(0.006)	(0.010)
Constant	7.443***	8.316***	5.900*	9.425***	3.678
	(1.687)	(2.020)	(3.421)	(2.006)	(2.946)
Observations	5765	4212	1553	3468	2297

Notes: All estimations include firm controls as described in Section 3.1. Moreover, industry, federal state and time fixed effects are included. Baseline refers to the estimation of Equation (1) with the changes highlighted in the respective heading of each panel. Low indicates that the firm is related to a bank in the lower 10% (Panel A), 25% (Panel C) or 50% (Panel B) of the variable's distribution of all German banks in the Bankscope data set. Cluster-robust standard errors in parentheses, clustered at the firm level. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

Table G2: Results based on different variables for bank capitalization

	(1) Baseline	(2) Equity over total assets	(3)	(4) Capital funds over net loans	(5)
		Low	High	Low	High
Rating	−0.011***	−0.011***	−0.014**	-0.007	−0.012***
	(0.003)	(0.004)	(0.007)	(0.005)	(0.004)
Rating × Crisis	−0.013**	−0.016***	−0.007	−0.023***	−0.008
	(0.004)	(0.005)	(0.008)	(0.006)	(0.006)
Rating × PostCrisis	−0.004	−0.004	−0.008	−0.006	−0.007
	(0.004)	(0.005)	(0.009)	(0.007)	(0.006)
Constant	6.743***	6.698***	6.807***	6.728***	6.210***
	(1.398)	(1.772)	(2.472)	(2.048)	(1.783)
Observations	8739	6371	2368	3130	5609

Notes: All estimations include firm controls as described in Section 3.1. Moreover, industry, federal state and time fixed effects are included. Baseline refers to the estimation of Equation (1) with the changes highlighted in the respective heading of each panel. Low indicates that the firm is related to a bank in the lower 25% of the variable's distribution of all German banks in the Bankscope data set. Cluster-robust standard errors in parentheses, clustered at the firm level. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

Table G3: Using the full set of bank information

	(1) Baseline	(2) Tangible common equity	(3)	(4) Capital funds	(5)
		Low	High	Low	High
Panel A: Low: at least one bank low capitalized; High: no bank low capitalized					
Rating	−0.011***	−0.012***	0.012	−0.013***	0.006
	(0.003)	(0.004)	(0.010)	(0.004)	(0.007)
Rating × Crisis	−0.013***	−0.013***	−0.017	−0.012**	−0.016
	(0.004)	(0.005)	(0.015)	(0.005)	(0.010)
Rating × PostCrisis	−0.004	−0.003	−0.026	−0.001	−0.024**
	(0.004)	(0.005)	(0.017)	(0.005)	(0.011)
Constant	6.743***	7.567***	−1.845	7.199***	2.927
	(1.398)	(1.491)	(4.266)	(1.589)	(3.012)
Observations	8739	7734	1005	6883	1856
Panel B: Low: all banks low capitalized; High: at least one bank high capitalized					
Rating	−0.011***	−0.006	−0.023***	−0.016**	−0.011**
	(0.003)	(0.004)	(0.006)	(0.007)	(0.004)
Rating × Crisis	−0.013***	−0.019***	−0.003	−0.015*	−0.013**
	(0.004)	(0.006)	(0.007)	(0.009)	(0.006)
Rating × PostCrisis	−0.004	−0.005	−0.002	0.014	−0.008
	(0.004)	(0.005)	(0.008)	(0.009)	(0.006)
Constant	6.743***	5.958***	10.136***	7.816***	6.485***
	(1.398)	(1.989)	(2.308)	(2.532)	(2.068)
Observations	8739	4992	2742	2876	4007

Notes: All estimations include firm controls as described in Section 3.1. Moreover, industry, federal state and time fixed effects are included. Baseline refers to the estimation of Equation (1) with the changes highlighted in the respective heading of each panel. Low indicates that the firm is related to a bank in the lower 25% of the variable's distribution of all German banks in the Bankscope data set. Cluster-robust standard errors in parentheses, clustered at the firm level. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

H Sample size and time period definition

Table H1: Changes to time period definition

	(1)	(2)	(3)	(4)	(5)
	Baseline	Tangible common equity		Capital funds	
		Low	High	Low	High
Panel A: Differentiate Basel introduction and Crisis period					
Rating	−0.011***	−0.011***	−0.014**	−0.012***	−0.010*
	(0.003)	(0.004)	(0.007)	(0.004)	(0.005)
Rating × Basel	−0.017***	−0.020***	−0.016	−0.016**	−0.020**
	(0.006)	(0.007)	(0.011)	(0.007)	(0.009)
Rating × Crisis	−0.011**	−0.013**	−0.004	−0.017***	0.003
	(0.005)	(0.006)	(0.010)	(0.006)	(0.009)
Rating × PostCrisis	−0.004	−0.004	−0.008	−0.002	−0.008
	(0.004)	(0.005)	(0.009)	(0.005)	(0.007)
Constant	6.745***	6.772***	6.788***	6.855***	6.136***
	(1.396)	(1.788)	(2.447)	(1.843)	(2.181)
Observations	8739	6355	2384	5215	3254
Panel B: With pre-crisis downturn (2002 and 2003)					
Rating	−0.010***	−0.010**	−0.012*	−0.010**	−0.011*
	(0.004)	(0.004)	(0.007)	(0.005)	(0.006)
Rating × Early2000	−0.004	−0.002	−0.005	−0.004	0.003
	(0.005)	(0.006)	(0.011)	(0.007)	(0.008)
Rating × Crisis	−0.014***	−0.016***	−0.010	−0.018***	−0.004
	(0.005)	(0.006)	(0.008)	(0.006)	(0.007)
Rating × PostCrisis	−0.005	−0.004	−0.010	−0.003	−0.007
	(0.005)	(0.005)	(0.010)	(0.006)	(0.007)
Constant	7.288***	7.048***	7.662**	7.502***	5.602**
	(1.579)	(1.927)	(3.037)	(2.054)	(2.555)
Observations	8739	6355	2384	5215	3254

Notes: All estimations include firm controls as described in Section 3.1. Moreover, industry, federal state and time fixed effects are included. Baseline refers to the estimation of Equation (1) with the changes highlighted in the respective heading of each panel. Low indicates that the firm is related to a bank in the lower 25% of the variable's distribution of all German banks in the Bankscope data set. Cluster-robust standard errors in parentheses, clustered at the firm level. Significance: $*$ significant at the 10% level, $**$ significant at the 5% level, $***$ significant at the 1% level.

Table H2: Changes to sample size

	(1)	(2)	(3)	(4)	(5)
	Baseline	Tangible common equity		Capital funds	
		Low	High	Low	High
Panel A: Without the years 2002 and 2003					
Rating	−0.010***	−0.009**	−0.013*	−0.010**	−0.011*
	(0.004)	(0.004)	(0.007)	(0.005)	(0.006)
Rating × Crisis	−0.014***	−0.016***	−0.010	−0.017***	−0.005
	(0.005)	(0.006)	(0.008)	(0.006)	(0.007)
Rating × PostCrisis	−0.005	−0.004	−0.008	−0.003	−0.006
	(0.005)	(0.005)	(0.010)	(0.006)	(0.007)
Constant	7.103***	7.224***	7.432***	6.792***	7.500***
	(1.473)	(1.901)	(2.535)	(1.996)	(2.233)
Observations	7617	5504	2113	4483	3134
Panel B: Without the years 2002, 2003 and 2004					
Rating	−0.014***	−0.013**	−0.019**	−0.012**	−0.018***
	(0.005)	(0.005)	(0.008)	(0.006)	(0.007)
Rating × Crisis	−0.011**	−0.012**	−0.006	−0.016**	0.001
	(0.005)	(0.006)	(0.009)	(0.006)	(0.008)
Rating × PostCrisis	−0.002	−0.001	−0.004	−0.001	0.000
	(0.005)	(0.006)	(0.010)	(0.006)	(0.008)
Constant	7.818***	7.891***	8.681***	7.102***	8.779***
	(1.691)	(2.209)	(2.696)	(2.332)	(2.361)
Observations	6770	4876	1894	3960	2810

Notes: All estimations include firm controls as described in Section 3.1. Moreover, industry, federal state and time fixed effects are included. Baseline refers to the estimation of Equation (1) with the changes highlighted in the respective heading of each panel. Low indicates that the firm is related to a bank in the lower 25% of the variable's distribution of all German banks in the Bankscope data set. Cluster-robust standard errors in parentheses, clustered at the firm level. Significance: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

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