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The Determinants of R&D Investment: A Survey of the Empirical Research.

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A Survey of the Empirical Research

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Abstract

This paper offers an extensive survey and a critical discussion of the empirical literature on the driving factors of R&D. These factors are subsumed under five broad types. The paper first summarises the key predictions from theory regarding each type's R&D effect. It then examines for which factors differences in the theoretical predictions can also be found in empirical studies, and for which factors the empirical evidence is more unanimous. As the focus is on the empirical literature, methodological issues are also highlighted. The major factor types identified in the literature are, individual firm or industry characteristics, particularly internal finance and sales; competition in product markets; R&D tax credits and subsidies; location and resource related factors, such as spillovers from university research within close geographic proximity, membership of a research joint venture and cooperation with research centres, and the human capital embodied in knowledge workers; and spillovers from foreign R&D. Although on balance there is a consensus regarding the R&D effects of most factors, there is also variation in results. Recent work suggests that accounting for non-linearities is one area of research that may explain and encompass contradictory findings.

Keywords: R&D; R&D policy; innovation policy; financial constraints; competition; public funding; knowledge spillovers.

JEL codes: F2; H3; O1; O3.

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1. INTRODUCTION

In the light of the importance of R&D investment in explaining economic growth, it comes as no surprise that analysis of the driving factors of R&D remains a subject of key methodological and empirical concern to economic researchers. The positive impact of R&D on growth and productivity has been predicted by a considerable number of theoretical contributions, and a broad corpus of empirical work has supported this result at the firm, industry and country level (see, inter alia, Arrow, 1962a; Romer, 1986, 1990; Grossman and Helpman, 1991; Aghion and Howitt, 1998; Proudman and Redding, 1998; for the theory and, inter alia, Coe and Helpman, 1995; Coe, Helpman and Hoffmaister, 1997, 2009; Griliches, 1998; Cameron, Proudman and Redding, 2005; Kafouros, 2005; O'Mahony and Vecchi, 2009; Bravo-Ortega and Marin, 2011; for empirical evidence).

Policies by modern governments increasingly recognise the benefits of supporting R&D investment. In part this is testimony to the importance of Nelson's (1959) and Arrow's (1962b) early insights into the motives underlying R&D investments. In essence, the argument proceeds from the observation that industrial R&D exhibits a classic public goods problem in that it is both non-rivalrous and not (completely) excludable. If the private rate of return thus is below the social rate of return, as firms cannot fully assimilate the returns from their R&D, private R&D investment has positive externalities and could be lower than socially optimal. The empirical evidence provided in Griliches (1979, 1998) confirms that the private rate of return to industry R&D typically is below the social rate of return. This mismatch of returns provides economic justification for government support of private R&D.[1]

There are a number of R&D driving factors that have been identified in the theoretical literature and subjected to empirical scrutiny. This paper offers an extensive survey and a critical discussion of the empirical literature on the R&D effects of these factors. The paper's main objective thus is to provide a concise account of where the literature stands currently in terms of knowledge of the driving factors of R&D, to identify remaining challenges for future research, and to indicate implications for policy. The factors are subsumed under five broad types. The paper first summarises the key predictions from theory regarding the R&D effect of each type. It then examines for which factors differences in the theoretical predictions can also be found in the results of empirical studies, and for which factors the empirical evidence

[1] For a review of the econometric literature on the measurement of the returns to R&D, see Hall, Mairesse and Mohnen (2010).

is more unanimous. This paper is addressed to both, the selective reader interested in only one or a few type(s) of R&D determinants and the reader interested in a broader overview.

In broad terms, the major types of factors include individual firm or industry characteristics, in particular internal finance and sales; competition in product markets; government policy measures such as R&D tax credits and direct subsidies; location and resource related factors, such as spillovers from university research within close geographic proximity, membership of a research joint venture and cooperation with research centres, and the human capital embodied in knowledge workers; and spillovers from foreign R&D. There are a number of early surveys of the R&D effects of firm characteristics and market structure (Kamien and Schwartz, 1982; Baldwin and Scott, 1987; Cohen and Levin, 1989; Acs and Audretsch, 1990; Cohen, 1995; Hall, 2002) as well as of the econometric evidence on the effect of R&D tax credits and subsidies (Hall and Van Reenen, 2000; David, Hall and Toole, 2000; García-Quevedo, 2004). However, there is no survey that encompasses and contrasts the substantial range of R&D determinants identified in the literature to date. Due to the large number of studies, reviewing the existing empirical literature must be a selective task, and given the earlier survey contributions and new research results since, this review focuses mainly on the post-2000 empirical work.[2]

The basic conclusions that can be drawn from the literature can be summarised as follows:

Internal finance, most notably cash flow, and sales generally have a positive effect on R&D investment, in support of Schumpeter's (1939, 1942) seminal work. Stronger sensitivity is found for small firms, for young firms and for firms in the US and UK compared with those in Continental Europe.

Competition is usually found to have a positive (linear) effect on R&D, consistent with the R&D rivalry argument proposed by the theoretical models from the trade and industrial organisation literatures. Recent work suggests that the effect of competition may have a non-linear inverted U-curve shape, with a positive effect on R&D by technologically advanced firms and a negative effect on R&D by laggard firms. This research is thus able to encompass the competing theoretical hypotheses as to the direction of the competition effect.

With respect to government R&D policies, the recent evidence suggests much more unanimously than concluded in earlier work that public subsidies and tax credits have a

[2] As the focus of this paper is on the empirical literature, the paper concentrates on the seminal thus typically early contributions in terms of the theoretical literature.

positive effect on private R&D investment. The additionality effect of public R&D funding has been shown to be particularly prevalent for small firms, which likely experience relatively more financial constraints. There is moreover some evidence that is indicative of a non-linear inverted U-curve subsidy effect and that suggests the effect of tax credits is quicker than the effect of direct subsidies.

The existing empirical literature predominantly concludes that private R&D benefits from geographically localised knowledge spillovers from university research, in line with the theoretical propositions. There is growing evidence that proximity matters in particular in high-tech sectors, suggesting that at least part of the spillovers are sector-specific and not just the diffuse effect of a large research university. There is substantial evidence that membership of a research joint venture to cooperate on R&D raises private R&D spending, and highly qualified human capital resources are also shown to have important effects.

The comparatively scarce evidence on spillover effects from foreign R&D to domestic R&D consistently does not find evidence of positive spillovers, but some evidence of crowding out. One reason may be that foreign firms are able to quickly appropriate any technological advance. An increasing number of studies suggests that technology sourcing is a fruitful source of foreign knowledge spillovers. This refers to locating R&D activity abroad in order to gain access to new 'tacit' foreign knowledge in the host country, which is then channelled back to the home country.

The paper is structured as follows. As the focus of this survey is on the empirical literature, section 2 provides an overview of the methodological issues involved in estimating models of R&D investment. Section 3 reviews the existing empirical literature on each of the broad types of R&D driving factors and links the results to the key predictions from theory. Section 4 discusses some remaining questions and challenges for future research. In concluding, section 5 summarises the main results.

2. METHODOLOGICAL ISSUES

2.1. Data and measurement of R&D

The first issue is how to measure and compare R&D across firms, industries and countries. Input measures, such as R&D expenditure or R&D intensity, as well as output measures, such as patents or innovation counts, have been used. One advantage of input measures is that their economic (monetary) value may be taken as homogenous, while the economic value of output measures such as patent counts is heterogeneous. Furthermore, the propensity to patent varies considerably across industries and countries, and even a high patent count need not imply a high level of innovation as some patents may never be implemented. However, because of its input character, higher R&D spending need not necessarily imply higher innovative output either. In practice, input and output measures appear to be correlated, as has been shown by a number of authors (see, e.g., Acs and Audretsch, 1988; Bound, Cummins, Griliches, Hall and Jaffe, 1984). As potential reasons for this correlation, Griliches, Hall and Pakes (1991) examine the relative importance of ‘demand pull’ and ‘technological push’ forces. They find little evidence of the technological push factor for a sample of US manufacturing firms, except for the pharmaceutical industry. They emphasise, however, that this lack of importance of this factor is due to the noisiness of patents as an indicator of the value of innovative output. Geroski and Walters (1995) obtain a similar result for the UK, using also output measures of innovation. In line with these findings, Jaffe (1988), using an input measure of innovation, R&D intensity, finds a significant and positive effect for both factors in a sample of US firms.

Most of the empirical work on the determinants of R&D focuses on R&D expenditures or R&D intensity. The comparability of the results from studies using different datasets may nonetheless be impeded by the difficulty in measuring the level of R&D expenditure accurately. Firms are given considerable latitude in what they choose to classify as R&D, and the definitions used may differ between datasets. Cohen and Mowery (1984), for instance, find that for the same US firms and years, Standard and Poor’s Compustat data reported an average of 12% more R&D than the Federal Trade Commission’s Line of Business Program data, with the difference resulting from the definitions used. The Frascati Manual publishes internationally agreed standards defined by the OECD (OECD, 2002). However, it is not always obvious from the literature whether the data definitions used follow the Frascati Manual. Hall (2006) provides a concise overview of the meaning of the term ‘R&D’, its economic analysis and its attribute as an investment.

2.2. The R&D equation

Most studies use as a starting point a simple panel data model of R&D investment of the form

$$r_{it} = a + \beta' X_{it} + \varepsilon_{it} \quad (1)$$

where *i* indexes the cross-section units, usually firms, industries or countries, and *t* indexes the units of time, usually years, *r* denotes R&D expenditure, *X* denotes the vector of explanatory variables, α is a constant, and ε_{it} is the error term. Other than as a convenient empirical starting point for an analysis of the determinants of R&D, (1) may be considered to be the stochastic form of the demand equation for R&D capital as derived from a CES production function where R&D and the flow of R&D investment are proportional to each other in steady state.

Unobserved heterogeneity between the cross-section units, as long as this is broadly stable over time and additive, can be controlled for by including fixed effects in the regression. Examples of these effects are managerial ability, language or culture. Model (1) can thus be re-written as the conventional within-groups or least squares dummy variables estimator:

$$r_{it} = \gamma' X_{it} + f_{it} + \varepsilon_{it} \quad (2)$$

where *f* denotes the fixed effects. Some studies capture common technology shocks and other time-variant common effects by including time dummies in (2).

There are a number of characteristics of R&D that suggest this type of investment should not be analysed in a static framework as in (2) but in a dynamic framework. One such characteristic is that R&D typically behaves as though it has high adjustment costs. Theory suggests these are important because of the high cost of temporary hiring and firing of highly skilled employees with firm-specific knowledge. Firms therefore tend to smooth their R&D investment over time (Hall, Griliches and Hausman, 1986; Lach and Schankerman, 1988). Hall (1993) reports that at least 50% of R&D budgets typically consist of the wages and salaries of highly qualified scientists and engineers, and the more recent figure of 60% reported in Bond, Harhoff and Van Reenen (2005) suggests that this share has risen somewhat over time.

Another characteristic of R&D that calls for a dynamic approach is that there is typically a high degree of uncertainty associated with the output of R&D investment, and sustained commitment to R&D is often required for projects to be successful. The role of uncertainty is implicit in the early adjustment costs literature in the context of capital investment (Eisner and Strotz, 1963; Lucas, 1967), which captures the role of backward-looking expectations formation through lagged variables. More recently, part of the growing literature on irreversible investment has criticised this essentially ad-hoc approach to the specification of adjustment cost functions. Tobin (1969) made explicit the role of future expectations in q-models of investment.

Most R&D studies use standard investment equation methodology to incorporate adjustment cost dynamics into the static R&D model (2), where the two main approaches are a neoclassical accelerator model with ad-hoc dynamics and an Euler equation as derived from forward-looking dynamic profit maximisation by firms.[3] As Euler equation respresentations of R&D investment tend to be little robust or informative (e.g., Hall, 1991; Bond, Harhoff and Van Reenen, 2005), most studies use the former approach to model dynamics by introducing a lagged dependent variable into (2):

$$r_{it} = \rho r_{i,t-1} + \delta' X_{it} + f_{it} + \varepsilon_{it} \quad (3)$$

The model is sometimes expressed in error correction form so as to take explicit account of short-run versus long-run effects (see, inter alia, Guellec and Van Pottelsberghe de la Potterie, 2001, 2003; Bond, Harhoff and Van Reenen, 2005; Becker and Pain, 2008; Becker and Hall, 2013).

2.3. Endogeneity

Inclusion of lagged R&D in (3) requires an instrumental variables estimator in order to avoid the downward bias that can result when using a fixed effects estimator in panels where the number of time periods is small (Nickell, 1981).[4] If the firm or industry responds to expectations of future technological shocks, this may also result in endogeneity bias. In general, strict exogeneity would imply that shocks to current R&D, ε_{it}, do not affect the future values of the explanatory variables, and this assumption clearly does not hold for a dynamic model that includes a lagged dependent variable.

Instrumental variables can further control for endogeneity or simultaneity bias that may plausibly arise from most types of R&D driving factors in X:

Individual firm characteristics such as sales, cash flow or output, for example, may be determined simultaneously with the firm’s R&D investment choice, as they are also under the

[3] Hall (1991) and Mairesse, Hall and Mulkay (1999) provide details on the econometric estimation of these models.

[4] The size of the bias decreases as the time dimension of the panel increases however (Nickell, 1981).

control of the firm. Given the output effect of R&D, there may also be reverse causality issues.

Measures of competition based on market structure may also be endogenous, as postulated in the endogenous sunk cost literature (e.g. Sutton, 1991). One example of this kind of measure is market share. This variable may also be subject to reverse causation effects in an R&D equation, as firms which invest more in R&D are likely to grow faster and thus assume a higher market share. Foreign competition measured by foreign firm entry can also be endogenous to innovation and R&D, the reason being that when considering entry into a new market, potential entrants are likely to take into account the innovative activity of local incumbents.

Government funding provided to the private sector may be endogenous, as the success of an application for funding depends on the characteristics of the firm and the application. Tax competition also implies that government policy and R&D tax credits may be endogenous. The user cost of R&D, for example, is a function of both the tax system and a range of other economic variables, such as the economy's real interest rate.

When using a measure of highly qualified human capital as an explanatory variable in an R&D equation, estimations also need to take account of potential double counting. Indeed, R&D personnel and R&D spending have sometimes been used as alternative dependent variables of R&D regressions.

Estimates of spillover effects of foreign R&D on domestic R&D might be subject to reverse causality problems as well: For reasons of technology sourcing, multinationals may have an incentive to increase their R&D investment abroad as a result of an increase, or an expected increase, in the host country's R&D.

One instrumental variables technique that has been applied relatively widely in the R&D panel data literature is the first-differences generalised methods of moments (GMM) estimator, whereby the model is estimated in first differences and lagged levels are used as instruments (Anderson and Hsiao, 1982; Arellano and Bond, 1991). The first-differencing transformation eliminates the individual fixed effects from the model and in contrast to the fixed effects estimator does not rely on asymptotic consistency in the time dimension. However, this estimator may be subject to large finite sample bias in cases where the instruments available have weak predictive power. This applies in particular when a times series is highly persistent, as is R&D, because lags will be poor predictors of future outcomes.[5] Bloom, Griffith and Van Reenen (2002) experiment with both techniques and find that the point estimates are similar, but that the GMM estimates are much more imprecise. Blundell and Bond (1998) show that efficient GMM estimation in the case of very persistent series may be achieved by using the systems approach developed by the authors, where the model is estimated in levels as well as in first differences and where lagged first differences are used as instruments in the levels equations and lagged levels are used as instruments in the in first-differences equations. This approach is increasingly used in the more recent literature, for example in Bond, Harhoff and Van Reenen (2005), Griffith, Harrison and Van Reenen (2006), Brown and Petersen (2011) and Brown, Martinsson and Petersen (2012).[6]

2.4. Parameter heterogeneity

Although estimations have been conducted at different levels of aggregation in the R&D literature, the majority of existing work uses firm level (panel) datasets. The models typically assume, and constrain, the R&D effects of the factors under consideration to be homogeneous across the cross-section dimension of firms, industries or countries. Under this assumption, the estimated coefficients reflect average effects within the sample. While average effects reveal important information, they do not provide any information about potential cross-sectional differences of the R&D effects. Set against this possible lack of information is the disadvantage of a smaller sample size when estimating sub-samples of firms or industries. Sub-sample estimates may thus be less precise, and interpretation may need to be more cautious. However, relatively low degrees of freedom need not necessarily imply a lack of precision, and authors who have split their samples into such sub-samples have found important differences in the R&D effects of a number of factors: Lach (2002) and Bloch (2005), for instance, find that the R&D effects of government subsidies and of financial constraints, respectively, differ between small and large firms. Financial constraints are further found to matter much more for young than for mature firms (Brown, Fazzari, Petersen, 2009; Brown and Petersen, 2009, 2011; Brown, Martinsson, Petersen, 2012). Hall, Lotti and Mairesse (2009) and Becker and Hall (2013) identify differences between high-tech and low-tech industries with respect to the effect of international competition and of

[5] For extensive discussion of this issue, see, inter alia, Hall, Griliches and Pakes (1986); Lach and Schankerman (1989); Bound, Jaeger and Baker (1995); Blundell and Bond (1998); Blundell, Bond and Windmeijer (2000).

[6] For issues of potential biases of this estimator, see Arellano and Bond (1991) and Blundell and Bond (1998); for finite sample corrections, see Windmeijer (2005).

government funding, respectively. Differences between countries have been identified in multi-country studies by, inter alia, Mulkay, Hall and Mairesse (2001), Bond, Harhoff and Van Reenen (2005) and Coe, Helpman and Hoffmaister (2009). Considering full-sample as well as sub-sample estimates may thus bear useful conclusions for R&D policies.

2.5. Model uncertainty

Differences between studies may also result from the set of control variables included in the regressions. The extent to which the magnitude of cash flow and sales affects R&D varies across studies, for example, suggesting that the results may be sensitive to the other variables included in the model. Cash flow is, for instance, highly procyclical, so some studies which fail to include cash flow may instead find stronger procyclical effects from sales growth. Many alternative empirical equations have equal theoretical status, however, so that differences in results from models with different control variables need to be interpreted with care.

2.5. Non-linearities

Relatively little attention has so far been paid to potential non-linearities in the relationship between R&D and its driving factors. If non-linearities are present, then traditional linear models may be misspecified. A recent study using UK data provides compelling evidence of an inverted U-curve effect of competition (Aghion, Bloom, Blundell, Griffith and Howitt, 2005) and has stimulated a growing body of further research on this issue (see section 3.2). The authors find that an exponential quadratic model neatly fits the data. Their theoretical model and empirical results are hence able to encompass both of the competing theoretical predictions as to the impact of competition on R&D. This is similar for the effect of foreign firm entry at the technological frontier (Aghion, Blundell, Griffith, Howitt and Prantl, 2004, 2009). Guellec and Van Pottelsberghe de la Potterie (2003) find that the elasticity of private R&D with respect to a government subsidy has an inverted U-shape for a multi-country OECD sample, which enables them to identify threshold levels of subsidies at which the effect of the subsidy on private R&D changes sign, and Görg and Strobl (2007) provide similar evidence for Irish firms. Non-linear effects are conceivable for other factors of R&D as well: Positive externalities on private R&D from a research laboratory in close geographic proximity may have a significant impact only up to some threshold distance, for example.

Similarly, domestic R&D might experience positive spillovers from R&D investment by foreign subsidiaries up to some threshold market share of foreign R&D, beyond which the increased foreign competition may reduce the profitability of domestic R&D and hence act to reduce the host country's own R&D expenditure.

3. THE DRIVING FACTORS OF R&D INVESTMENT

3.1. Individual firm and industry characteristics

The literature identifies internal finance and sales as the two key firm characteristics that affect R&D. Cash flow in particular has been shown to be important in many empirical studies. A common argument is that, as a result of capital market imperfections, firms are not able to attract (sufficient) external funds to finance investment in R&D. Being thus financially constrained, they have to rely on internal funds. The theoretical argument that internal finance be an important determinant of R&D expenditures goes back at least to Schumpeter's (1939, 1942) analysis of the evolutionary dynamics of economic systems. The results of early empirical studies have been less clear cut: While most of the studies in the survey by Cohen (1995) point to a positive relationship, the earlier survey by Kamien and Schwartz (1982) concluded that there was only weak empirical evidence of a significant effect.[7]

The more recent empirical literature generally is more unanimous in finding that R&D investment is correlated with measures of internal finance, particularly cash flow. Differences in results are, however, observed in particular with respect to firm size, countries, and firm age.

Bloch (2005), for instance, examines the effect of cash flow on R&D investment in a sample of small and large firms in Denmark. The results for the full sample suggest important cash flow effects and indicate that R&D investment decisions are adversely affected by capital market imperfections. Sub-sample results show that the effect is significant for the small firms but not for the large firms, and the author concludes that this is at least in part due to greater credit constraints for small firms. These sub-sample results confirm earlier evidence on comparisons between small versus large firms (see, e.g., the survey in Hall,

[7] Other detailed early surveys on the impact of firm characteristics are provided by Baldwin and Scott (1987); Cohen and Levin (1989); Acs and Audretsch (1990); Hall (2002). The interested reader is referred to these surveys for the earlier literature, while this paper focuses on the post-2000 literature.

2002). Small firms may be more reliant on external finance because they have less collateral in terms of existing assets to be used for obtaining loans.[8]

In a study on manufacturing UK and German firms, Bond, Harhoff and Van Reenen (2005) find that cash flow or its lag do not impact significantly on the size of R&D expenditures of these firms. However, cash flow does affect the likelihood of whether high-tech firms in the UK will undertake any R&D at all. This is interpreted to mean that British firms face important financial constraints, with a higher sensitivity than German firms, but that the British firms that invest in R&D are a self-selected group that is subject to fewer constraints. Mulkay, Hall and Mairesse (2001) find that R&D is positively sensitive to cash flow for manufacturing firms, and much more highly so for US firms than for French firms in the same sector. Indeed, in her comprehensive survey, Hall (2002) concludes that R&D spending by firms in the US and in the UK is typically more sensitive to cash flow than R&D spending by Continental firms. Reasons may include institutional differences between the countries, a different structure of financial and capital markets and different corporate attitudes towards risk and uncertainty. Hillier, Pindado, De Queiroz and De La Torre (2011) find for a sample of nine European countries, Japan and the US that firm-level R&D is less sensitive to cash flow in countries with indicators of stronger corporate governance, in particular investor protection. This result is rationalised in that shareholders in countries that exhibit stronger protection are more willing to invest in activities where the potential private benefits of control are greater.[9]

Differentiating between young and mature high-tech US firms, Brown, Fazzari and Petersen (2009) find that cash flow as well as the issuance of public equity have an important effect on R&D investment by the former group of firms but only little effect on R&D by the latter group. The results are therefore consistent with the presence of binding financial constraints for young firms, which are often the most reliant on external funding sources. One reason is that outside investors do not yet have sufficient information to differentiate between better and poorer performers and so may be reluctant to provide funding. The increasing importance of the issuance of public equity as a means to finance R&D is supported in a

[8] Another reason may be that as a group they are likely to include more young firms, which is discussed below.

[9] See e.g. Driver and Guedes (2012), Hall and Lerner (2010) and the references therein for a discussion of the standard principal agency view that enhanced governance will increase R&D because investors will be assured that managers are not shirking, versus the view of a contradictory effect of governance on uncertain investments through discouraging autonomy, reducing managerial security or discouraging the build-up of hard-to-measure real options.

related paper by Brown and Petersen (2009). The authors argue that not controlling for public equity can lead to a downward bias of the estimated link between R&D and cash flow, because of the increasing fraction of publicly traded firms that report persistent negative cash flows and often heavily use public equity to expand investment when cash flow is particularly low.

Brown and Petersen (2011) examine whether firms use cash holdings to smooth their R&D expenditures from transitory shocks to finance in the face of adjustment costs. The results for US firms suggest that young firms extensively do so, while there is little such evidence for mature firms. The authors thus conclude that one way that liquidity can create value is by allowing financially constrained firms to maintain a relatively smooth flow of R&D expenditure in the face of shocks to finance, thereby reducing adjustment costs. Brown, Martinsson and Petersen (2012) argue that not controlling for such endogenous liquidity management may lead to downward bias of the R&D effect of internal and external finance in within-firm regressions and that this is particularly relevant in Europe, where labour laws can make adjustment costs for R&D especially large. For a sample of 16 European countries, the authors find little or no effects of finance in specifications that include only cash flow, but positive and important effects when controlling for public equity and for R&D smoothing through changes in cash holdings. The authors thus suggest that lack of control for the latter two variables may offer another reason why previous studies on Continental Europe have found few or no effects of cash flow. Consistent with the studies discussed above, these two variables have by far the strongest impact on R&D in the groups of firms most likely to face binding financing constraints, i.e. small firms and young firms.

In a related analysis, Brown and Floros (2012) examine the association between private equity inflows and new corporate R&D investment by publicly traded firms that raise external equity via private placements, i.e. private investments in public equity. The sample's typical firm that raises private equity this way is a small high-tech firm that cannot finance investment internally and has little or no access to public debt and equity markets. The results show that funds raised in private placements have a substantial effect on current and also on future R&D investment, whereby the latter effect works through the significant fraction of private placement inflows that are saved as cash reserves and used to fund future R&D. Using another novel measure of financing constraints, cash inflows generated by fixed asset sales, Borisova and Brown (2013) further corroborate the evidence of financing frictions for small high-tech firms and young high-tech firms.

Alternative measures of financial constraints are also used. In a study on Irish manufacturing firms, Bougheas, Görg and Strobl (2003) use the lagged ratio of net profits to capital rather than cash flow to measure liquidity and obtain a significant positive effect, thereby supporting the theoretical notion that internal finance be an important determinant of expenditure in R&D. They also find a positive effect of the lagged ratio of sales to capital, which they argue is a proxy for expected future revenues. A similar argument is made by Domadenik, Prasnikar and Svejnar (2008) for a panel of the largest firms in Slovenia, whereby the positive effect of current sales is interpreted as evidence that expected future profits are one motive for R&D expenditure. Cash flow is also shown to be important and interpreted as financing constraints in the economic environment of an underdeveloped financial system of a transition economy. A positive association between a country's R&D and domestic financial market development in a sample of 18 OECD countries is found in the study by Maskus, Neumann and Seidel (2012), using industry data: R&D intensity of a heavily on external funding reliant industry in a country with well-developed domestic financial markets is substantially higher than R&D intensity of a less on external funding dependent industry in a country with poorly developed financial markets.

Czarnitzki and Hottenrott (2011a) differentiate between a firm's price-cost margin as an indicator of internal financial constraints and a credit-rating index as a direct indicator of external financial constraints in credit markets. For a sample of small and medium-sized firms in Germany, the authors find that R&D spending depends significantly on both. Internal financial constraints are not found to be related to firm size, which may however be due to the fact that the sample does not include large firms, so that the size heterogeneity of the examined firms is limited. External constraints are nonetheless found to be more severe for the smaller firms, suggesting that the impact of these constraints varies substantially with firm size.

The effect of financial constraints may also vary with the type of R&D investment undertaken. For instance, theory suggests that financial constraints should be more binding for cutting-edge R&D than for routine R&D, due largely to the higher uncertainty involved in the former (Kamien and Schwartz, 1978). Czarnitzki and Hottenrott (2011b) conduct an empirical test of this proposition, using a panel of manufacturing firms in Germany and the credit rating index as an indicator for external financial constraints. The results support the theoretical argument, indicating that expenditure on cutting-edge R&D is adversely affected by credit constraints, while expenditure on routine R&D is not. The authors point out that this finding may have important implications for R&D policy, as due to the higher risk surrounding cutting-edge research this type of R&D may not be granted public R&D subsidies, while it is, however, cutting-edge R&D rather than routine R&D that can be assumed to provide the major impact on technological progress.[10]

Some studies also examine wider balance sheet effects. The existing evidence largely suggests that the firm's outstanding stock of debt does not have a significant effect on its R&D spending. However, Bond, Harhoff and Van Reenen (2005) find that a higher ratio of debt to capital does seem to prevent UK firms which do not currently invest in R&D from doing so in the next period. This result is consistent with the view that due to the persistence of R&D some firms do not find it worthwhile to initiate an R&D project, if they expect that it may have to be cut back in the future due to financial constraints.

Following Schumpeter (1939, 1942), several arguments have been put forward to support the hypothesis that R&D increases more than proportionately with firm size. These include economies of scale in R&D technology, more efficient implementation, higher returns from R&D and greater ability to secure funding for risky projects given capital market imperfections. Indeed, in the empirical work firm size, as measured by sales, is often found to have a significant positive impact on R&D expenditures. One recent example is the study by Coad and Rao (2010) which concludes for a US firm panel that growth in R&D expenditure is strongly associated with past sales growth. Sales also are often used as a control variable in studies that focus primarily on other factors of influence, which supports the importance attached to this variable as a driving factor of R&D. Related to the scale effect of the relationship between firm size and R&D is the effect of changes in output on R&D. Output changes mainly signal increases in demand or successful innovation and therefore signal that investment in R&D as an input to the innovation process is beneficial. A number of studies show that aggregate R&D growth tracks GDP growth for the US and G7 economies (e.g. Fatas, 2000; Rafferty, 2003; Wälde and Woitek, 2004; Comin and Gertler, 2006). Industry level R&D (e.g. Ouyang, 2011, for the US) and firm level R&D (e.g. Aghion, Askenazy, Berman, Cette, Eymard, 2012, for France; López-García, Montero, Moral-Benito, 2012, for Spain; Bovha-Padilla, Damijan, Konings, 2009, for Slovenia) are found to be procyclical in the presence of credit constraints. The interpretation is that whenever a firm is hit by a negative shock, its current earnings are reduced, and therefore so is the firm's ability to

[10] For more details on how the impact of financial constraints may differ across types of R&D projects, see Czarnitzki and Hottenrott (2010).

borrow in order to invest in R&D, hence R&D investments should be expected to be more procyclical in firms facing tighter credit constraints.

Concluding, the more recent empirical literature generally finds that R&D investment is positively correlated with measures of internal finance, particularly cash flow, and sales. Differences in results regarding the extent or the existence of the R&D effects of financial constraints are found particularly with respect to firm size, firm age and countries. Stronger sensitivity is found for small firms and for young firms. This is consistent with the growing evidence that private sector R&D tends to be more procyclical in firms facing tighter credit constraints. Stronger sensitivity is also found for firms in the US and UK than those in Continental Europe. Sample composition may thus account for differences in results found by studies that do not differentiate between these characteristics. Results may also be sensitive to the other variables included in the model. Given that cash flow is, for instance, highly procyclical, some studies which fail to include cash flow may instead find larger procyclical effects from sales growth. Recent evidence suggests that external finance through public equity also matters, as well as R&D smoothing through changes in cash holdings. Financial constraints may also differ between different types of R&D, but the evidence here is still scarce. Table 1 summarises the key features of a number of studies representing the main results from the literature.

3.2. Competition

Theory postulates that competition in product markets may have two distinct effects on R&D expenditures. One line of argument is that, for incumbent firms, especially ones with a degree of market power, greater competition reduces the incentive to invest in R&D because they are less able to extract the rents from innovation resulting from the R&D. This direction of the effect of competition is predicted by standard industrial organisation theory and early Schumpeterian growth models. As for industrial organisation models, Dixit and Stiglitz (1977), Salop (1977) as well as Dasgupta and Stiglitz (1980), for instance, show that ex-post competition drives out ex-ante competition by reducing post-entry rents and hence the equilibrium number of entrants.[11] Most early Schumpeterian growth models show that more

[11] Other theoretical industrial organisation models show that the finding that less intensive short-run competition may be associated with increased investment in the long-run strategic variable, such as R&D expenditure, in oligopoly may depend on the choice of functional form or the specification of the collusive technology (see, inter alia, Fershtman and Muller, 1986; Davidson and Deneckere, 1990; Fershtman and Pakes, 2000).

intense product market competition or a higher rate of imitation have a negative impact on productivity growth by reducing the monopoly rents that reward new innovation (e.g. Romer, 1990; Grossman and Helpman, 1991; Aghion and Howitt, 1992; Caballero and Jaffe, 1993).

Set against this view is the argument by another strand of literature which predicts that R&D may be used as a strategic variable to counter increased competition in order to defend the firm's market share. R&D rivalry in this context has been analysed in models from the trade and industrial organisation literatures. Spencer and Brander (1983), for example, show that the domestic firm, with the help of an R&D subsidy, will commit to an 'aggressive' output and R&D investment strategy in the face of international competition from a foreign firm. Clemenz (1990) suggests that investing in R&D may not be a profitable strategy in industries with a low competitive standing as there may be too much uncertainty about the expected payoff. Caves (1985) provides a survey of the major issues.

The theoretical debate has stimulated a growing body of empirical research. The recent study by Aghion, Bloom, Blundell, Griffith and Howitt (2005), for instance, encompasses both of the competing theoretical hypotheses. Using a panel of UK manufacturing industries and estimating an exponential quadratic model, the authors find empirical support for their theoretical model which predicts that the relationship between product market competition and measures of innovation may be an inverted U-shape: At low initial levels of competition, measured by the price-cost margin, the innovation-increasing effect of competition dominates, whereas at high levels of competition, the Schumpeterian effect is the dominant one.[12] The argument is that competition reduces the pre-innovation rents of efficient firms which therefore have an incentive to invest in R&D, as this enables them to escape competition and thus increase their post-innovation rents. Incumbents further behind the frontier cannot win against an entrant and have no incentive to invest in R&D, as competition reduces the post-innovation rents for these firms. When competition is low, there is a larger fraction of efficient or neck-and-neck incumbent firms and so the escape-competition effect is likely to dominate, whereas when competition is high, there is a larger fraction of laggard

[12] The model develops an extension of Harris and Vickers (1997) and Aghion, Harris, Howitt and Vickers (2001), who developed the 'escape-competition' effect. The non-linear effect of competition on innovation was first hinted at by Scherer (1967).

firms so the Schumpeterian effect is likely to dominate. The overall effect of competition therefore is non-linear and has an inverted U shape.[13]

Since the work by Aghion, Bloom, Blundell, Griffith and Howitt (2005) there has been an increasing number of studies that investigate the non-linear inverted U-curve effect. Applying the study's measure of distance to the technological frontier to an analysis of pooled cross-sections of Canadian manufacturing firms, Bérubé, Duhamel and Ershov (2012), for instance, find that a higher such distance substantially diminishes the significantly positive linear effect of competition on R&D expenditure. In other words, the further the majority of firms in an industry are from the technological frontier, the less they innovate. While the model does not directly test for the inverted U-curve effect, the authors note that its results are consistent with it. The results hold for all three measures of competition used, the industry and the firm level price-cost margins and an indicator of profit elasticity following Boone (2008a, b). Using data for the Netherlands, Polder and Veldhuizen (2012) directly test for, and find evidence of, an inverted U-curve effect at the industry level. At the firm level, the results suggest a non-linear effect with respect to the spread of technology within an industry; as this increases, the effect of competition R&D intensity, turns from positive to negative. Contrary to the study by Bérubé, Duhamel and Ershov (2012), the results are, however, sensitive to whether Boone's (2008a, b) profit elasticity or the industry or firm level price-cost margins are used to measure competition. In a cross-section study of manufacturing and service sector firms in Luxembourg, Peroni and Gomes Ferreira (2012) further identify a non-linear association between competition and R&D expenditure.[14] Using a dataset of Swedish manufacturing firms, Poldahl and Tingvall (2006) find evidence of the inverted U-shape relationship when competition is measured by the Herfindahl index, but not when the price-cost margin is used, in which case a negative effect is found. Tingvall and Karpaty (2011) report that evidence for Swedish service sector firms suggests an inverse U-shape effect for exporting firms and that this is usually the case for both, the profit elasticity measure of competition and the Herfindahl index. Two conclusions from this literature are that, first, on balance there seems

[13] In the study's empirical analysis this result holds regardless of whether patents or R&D expenditures are used to measure innovation; however the authors note that when using R&D expenditures the coefficients are not statistically significant due to a substantially smaller sample.

[14] Innovation effort is decreasing in the technology spread. Using estimated technology gaps directly as the measure of innovation in a study of the US banking sector, Bos, Kolari and Van Lamoen (2013) furthermore find evidence of an inverted U relationship.

to be growing evidence of an inverted U-curve relationship between competition and innovation, but that, second, results can be sensitive to the measurement of competition. [15]

Very recently, Askenazy, Cahn and Irac (2013) have extended the analysis in Aghion, Bloom, Blundell, Griffith and Howitt (2005) to take account of firm size and the cost of innovation. Using a panel of French firms, the study shows an inverted U-shape relationship that becomes flatter when the relative cost of R&D increases until it disappears for small firms. These results are consistent with the study's theoretical model which predicts that if innovations are large-scale and costly in the firm's sector or relative to the size of the firm, competitive shocks have to be sufficiently large to change innovation choices. Innovation is measured as the potential innovation flow, calculated as the square root of the ratio of annual R&D investment to the average innovation unit cost, with the latter being measured as sector level R&D divided by the number of patents in that sector. The results are robust to using the square root of a firm's R&D investment as an alternative measure of innovation. Competition is proxied by the Lerner index i.e. price-cost margin in the main analysis, whereby the results for firm size are robust to using the Boone (2008a) index, whereas most results for the absolute cost of innovation become insignificant with identical sign. With respect to competition policy, the authors conclude that in addition to taking account of the state of the industry as per the results by Aghion, Bloom, Blundell, Griffith and Howitt (2005), policy should also consider the firm size structure and probably the cost of innovation in the industry.

Griffith, Harrison and Simpson (2010) provide recent multi-country industry level evidence that the pro-competition reforms carried out under the European Union's Single Market Programme (SMP), measured by a reduction in average profitability, i.e. implying an increase in competition, led to an increase in R&D investment. The analysis focuses on a linear rather than non-linear effect of competition, as the aim of the SMP was to reduce non-tariff barriers to competition within the EU, which was expected to have a greater effect on countries and industries shielded from international competition ex ante. In line with the arguments in Aghion, Bloom, Blundell, Griffith and Howitt (2005), since more efficient neck-and-neck industries are expected to be prevalent at relatively low levels of competition, there would be an expectation that incentives to invest in R&D would increase as a result of the increased competition brought about by the SMP. The authors moreover point out that the

[15] See Boone (2008a, b) for a discussion of various measures of competition.

SMP itself was likely to make industries more neck-and-neck, e.g. by harmonising standards. The results thus confirm that in this kind of economic setting the escape-competition effect dominates.[16]

Another possibility is that competition may have different effects on the R&D activities of high-tech as compared with low-tech firms. Low-tech firms may invest less in R&D for the development of new products due to a higher degree of product standardisation in low-tech sectors. These firms may also find it more profitable to imitate new processes by high-tech firms rather than expend on R&D themselves. However, imitation is not costless either due to the 'tacit' nature of knowledge, and investing in some, if not much, R&D may still be profitable as it enhances absorptive capacity and the ability to imitate, which is also known as the 'second face of R&D'.[17] In line with these hypotheses, Hall, Lotti and Mairesse (2009), for instance, find in a recent study on Italian firms that international competition fosters R&D intensity particularly for high-tech firms.

Recently there is a growing literature examining the R&D and innovation effect of foreign competition through foreign firm entry at the technological frontier. Aghion, Blundell, Griffith, Howitt and Prantl (2004), for example, derive predictions from a multisector Schumpeterian growth model with entry from foreign firms at the technological frontier. The sectors of the economy differ in their initial state of technological development, measured by a sector's distance to the technological frontier. For incumbent firms in sectors that are initially close to the technological frontier, a higher foreign entry threat provides an incentive to escape entry by innovating. By contrast, innovation by firms in sectors initially far behind the frontier may be discouraged, as these firms cannot compete with the more efficient entrants and so an increased entry threat reduces their expected payoff from investing in R&D. The overall effect of foreign entry on R&D and innovation therefore is non-linear and has an inverted U-shape. The 'escape-entry' effect of foreign competition through entry is thus similar to the 'escape-competition' effect discussed above.

There is only relatively little empirical literature to date that tests these theoretical predictions. Aghion, Blundell, Griffith, Howitt and Prantl (2009) test for and detect a direct

[16] The authors also test for and detect an inverted U relationship, but note that they focus on the linear relationship in their results as there is insufficient variation in the data to identify the non-linear relationship precisely.

[17] Mansfield, Schwartz and Wagner (1981) find that an imitation incurs 65% of innovation costs, taking 70% of innovation time to complete. For the theoretical foundation of the second role of R&D, see, inter alia, Cohen and Levinthal (1989); for recent empirical evidence, see, inter alia, Griffith, Redding and Van Reenen (2004) and Blalock and Gertler (2009).

and positive effect of entry by frontier foreign firms on innovation by the more efficient incumbent firms in the UK and a negative effect on innovation by laggard firms, thus confirming the inverted U-curve effect. Sabirianova, Svejnar and Terrell (2005, 2012) suggest that foreign firm entry in the Czech Republic and Russia impacts positively on the efficiency of incumbent foreign firms, which are likely at or close to the technological frontier, and negatively on incumbent domestic firms, which likely are laggards. These results are consistent with underlying heterogeneous R&D and innovation effects. One implication of the research on foreign entry effects is that policies to decrease or remove barriers to foreign entry per se may not be sufficient to foster R&D investment of incumbent firms, and may even be counterproductive depending on the composition of efficient and laggard firms. Sector-specific competition policies may therefore be more appropriate.

Competition in foreign markets, as measured by a firm's or industry's exports, also tends to impact positively on R&D investment by the exporting firm at home, according to the literature to date. The main reason cited in the literature is that exporters must innovate rapidly to remain viable in competitive foreign markets. There is a large literature examining the R&D effects of exports indirectly, whereby learning from foreign markets through R&D and innovation or imitation is the presumed channel through which exporting raises firms' efficiency. There is much less empirical literature that examines the effects on R&D directly.[18] One recent study by Yang and Chen (2012), for instance, finds that exporting contributes to R&D of firms in Indonesia. Girma, Görg and Hanley (2008) conclude the same for Ireland, while they find no strong such evidence for Britain. Reasons suggested for the different results for Ireland and Britain include that firms in the smaller economy Ireland export at an earlier stage of their development when they have most to learn and that they export a greater output share to more advanced countries. In a study of Northern Ireland, Harris and Trainor (2011) conclude that encouraging more domestic firms to export is one way to boost their R&D activity. Criscuolo, Haskel and Slaughter (2010) find for the UK as a whole that exporters are significantly more likely to innovate than their domestic counterparts, whereby the majority of the innovation-output advantage of globally engaged firms is accounted for by their superior access to information from existing knowledge, with only a minority left explained by global engagement per se. For Slovenia and for a sample of

[18] While the superior performance of exporting firms compared with their domestic counterparts has been documented frequently, there is ongoing debate as to whether exporting boosts firm efficiency or whether highly efficient firms self-select themselves into export markets (see Greenaway and Kneller, 2007, and Wagner, 2007, for surveys). Accordingly, the causation between exports and R&D has also been shown to run both ways (see Harris and Moffat, 2011, for a survey).

27 emerging market countries, respectively, Damijan, Kostevc and Polanec (2010) and Gorodnichenko, Svejnar and Terrell (2010) further suggest that exporting positively influences firm level innovation. Taking a slightly different focus, Baum, Caglayan and Talavera (2012) show that a higher degree of geographical export market diversification increases R&D spending by UK firms.

Summarising, most of the empirical literature examining a linear effect concludes that competition has a positive effect on R&D. This is consistent with theoretical models that emphasise the extent to which R&D might be used as a defensive strategy in response to greater competition. There is some evidence that the positive effect is particularly pronounced in high-tech sectors compared with low-tech sectors. However, the evidence on the direct effect of competition on R&D as compared with some other measures of innovation is still relatively scarce. Recent research suggests that allowing for a non-linear effect, differentiating between more efficient versus laggard industries, is a way forward to encompass the different theoretical and sometimes different empirical results. There is a growing body of evidence emerging that suggests an inverted U-curve relationship between competition and R&D, however results can be sensitive to the measure of competition used. Very recent work moreover suggests that this effect may also depend on firm size and cost of innovation in the industry. The non-linear inverted U-curve effect has been found in particular also for competition through foreign firm entry at the technological frontier, differentiating between a positive effect on R&D by frontier incumbent firms and a negative effect on R&D by laggard firms. Competition in foreign markets, via exporting, is predominantly found to have positive effects on R&D and innovation at home. Table 2 summarises the key features from representative studies that reflect the main results and use a variety of measures of competition.

3.3. Government R&D policies

Market failures can provide a rationale for government intervention to support private R&D. As argued by a large number of authors, and first by Nelson (1959) and Arrow (1962), industrial R&D exhibits a classic public goods problem as it is both non-rivalrous and not (completely) excludable. If the private rate of return is below the social rate of return, as might be expected if firms are unable to fully appropriate the returns from their R&D, then private expenditure on R&D has positive externalities and may be lower than socially optimal. Equally, if firms experience significant external financial constraints, with agency costs limiting the funds available from external investors, then R&D expenditure may again be lower than optimal, especially by smaller and by younger firms. The empirical evidence in Griliches (1979, 1998), for example, confirms that the private rate of return to industry R&D typically is below the social rate of return.

The classical public finance solution would be to subsidise the economic activity which creates the positive externality, i.e. private R&D investment. Two policy tools available to governments are R&D tax credits and direct subsidies of private R&D projects. The former is a more market-oriented approach, leaving decisions on the level and timing of the investment to the private sector.[19] Indirect government support of private R&D may also be possible if there are spillovers from government-funded research in universities and publicly funded research centres.[20]

When assessing the response of private R&D spending to a change in its price, it is important to bear in mind the implications of what is known as the 'relabelling' problem (Hall and Van Reenen, 2000): The true impact of a change in the tax credit on companies' R&D expenditure may be overestimated when using reported R&D data, as in response to an introduction of or an increase in the tax credit, firms have an incentive to maximise the share of R&D qualifying for the credit. They may thus move expenses within their accounts so as to ensure correct classification, whereas before the preferential tax treatment indifference with respect to the labelling of R&D expenses may have led to incorrect classification of at least part of the R&D spending. Hall and Van Reenen (2000) review some evidence in favour of this hypothesis.

Overall Hall and Van Reenen (2000) conclude that tax credits have a significant positive effect on R&D expenditure, although there is considerable variation in the findings of different studies.[21] The more recent literature more unanimously finds a positive effect,

[19] Of course, even when effective, any judgement as to the desirability of a tax credit would need to be based on a cost-benefit analysis that included deadweight costs and the relabelling of activities as R&D within corporate accounts (see the survey by Hall and Van Reenen, 2000, and the references therein). For a detailed microeconomic evaluation of the effects of a tax credit, see Klette, Møen and Griliches (2000). See also Jaffe (2002). For an assessment of the efficiency of public R&D support at the macroeconomic level, see Cincera, Czarnitzki and Thorwarth (2011).

[20] These are considered in section 3.4.

[21] For a detailed assessment regarding the advantages and disadvantages of the methods typically employed by empirical studies to estimate the impact of a tax credit on R&D, such as usage of a dummy variable equal to one when a credit is available and zero otherwise, or a price variable, such as the user cost of R&D, that captures the R&D marginal cost, see Hall and Van Reenen (2000).

whereby the precise estimated elasticities vary depending on the data, estimation method and model specification.

In a panel data study on the manufacturing sector of nine OECD countries for 1979-1997, Bloom, Griffith and Van Reenen (2002), for instance, estimate a long-run elasticity of R&D with respect to its user cost of around -1.0. Using aggregate data for a panel of 20 OECD countries during 1982-2001, Jaumotte and Pain (2005) obtain a long-run elasticity of between -0.8 and -1.3, depending on the module specification and averaging -0.9 across specifications.[22] Applying a similar estimation approach as Bloom, Griffith and Van Reenen (2002), Harris, Li and Trainor (2009) find a long-run elasticity of around -1.4 for a panel of manufacturing plants in Northern Ireland for 1998-2003, and an elasticity of between -1.5 and -1.8 is reported in Parisi and Sembenelli (2003) for a panel of Italian firms for 1992-1997. Lokshin and Mohnen (2012) and Koga (2003), respectively, obtain somewhat lower elasticities of -0.8 for firms in the Netherlands during 1996-2004, and -0.7 for firms in Japan during 1989-1998. Mulkay and Mairesse (2013) report a long-run user cost elasticity of -0.4 for a recent 2000-2007 sample of French firms. For the US and the Canadian manufacturing sectors, respectively, Bernstein and Mamuneas (2005) find R&D own price elasticities of -0.8 and -0.14. The authors suggest that one reason why the latter elasticity is so low is that much of Canadian R&D is performed by foreign firms which are not as susceptible to changes in Canadian economic conditions as are domestic firms. Baghana and Mohnen (2009) confirm the long-run elasticity of -0.14 for firms in the Canadian province Québec. Using a non-parametric matching approach, Czarnitzki, Hanel and Rosa (2011) conclude that R&D tax credits also have a positive impact on Canadian firms' decision whether to conduct any R&D at all. In a rare study on a newly industrialised economy, Yang, Huang and Hou (2012) find for Taiwan that tax credits induce firms to increase R&D spending. One policy conclusion that can be drawn from all of these studies is that fiscal policy measures that reduce the user cost may be expected to increase private R&D expenditure, other things being equal.

Regarding the effect of direct R&D subsidies, the surveys of earlier studies conclude that the econometric evidence is ambivalent and that there are additionality effects of public R&D on private R&D as well as –out effects (David, Hall and Toole, 2000, and García-Quevedo, 2004). David, Hall and Toole (2000), for example, find that a third of the 33 studies under review report substitution effects. However, the more recent research much more

[22] The elasticity changes to about -0.4 when science indicators are included in the model.

unanimously rejects crowding out and tends to find additionality effects. One criticism of much of the earlier work has been that it neglects the problem of sample selection bias, in that R&D intensive firms may be more likely to apply for a subsidy (David, Hall and Toole, 2000). Since it is likely that these firms would have undertaken at least part of the R&D in the absence of the subsidy, the results may have been more prone to finding crowding-out effects. The availability of new econometric techniques that control for the selection bias is thus likely one reason for the shift away from finding crowding-out effects.

In this vein, applying a matching framework to samples of French and Italian firms, respectively, Duguet (2004) and Carboni (2011) reject crowding out and find that public subsidies on average increase private R&D. Czarnitzki and Hussinger (2004) confirm these results for the German business sector, and Aerts and Schmidt (2008) provide similar results for firms in Flanders and in Germany from a conditional difference-in-differences estimator with repeated cross-sections. Using parametric and semiparametric two-step selection models, Hussinger (2008) further finds evidence of additionality effects of publicly funded R&D on private R&D investment per employee for German manufacturing. Comparing the results of seven matching methods, a selection model and a difference-in-differences estimator for a dataset of Italian firms, Cerulli and Potì (2012) also reject full crowding out of private R&D on average. Conducting a treatment effects analysis for manufacturing firms in Turkey as a developing country, Özçelik and Taymaz (2008) further find additionality effects.

In terms of recent panel data regression analyses, the result of additionality effects from the treatment effects analysis in Özçelik and Taymaz (2008) holds also for the various regression analyses conducted in the study. Klette and Møen (2012) compare the results of two panel fixed effects studies on similar Norwegian firm data for pre-2000 and post-2000 time periods, 1982-1995 and 2001-2007. The authors conclude that the fact that their study on the earlier period does not find any significant degree of additionality, while the study by Henningsen, Haegeland and Møen (2012) on the later period does find additionality, suggests that the effectiveness of this policy tool has improved over time. Using a dynamic panel fixed effects instrumental variables estimator in an analysis of UK manufacturing industries for 1993-2000, Becker and Pain (2008) find a positive effect of the share of business R&D funded by the government on the level of R&D. The study thus indicates that the decline in the share of manufacturing R&D financed by the government between 1992 and 1997 plays an important role in the explanation of the comparatively poor R&D performance of the UK seen over the

1990s. In a further dynamic panel data regression analysis, Bloch and Graversen (2012) obtain additionality effects of public R&D funding for a 1995-2000 sample of Danish firms. For the business enterprise sector of 21 OECD countries, Falk (2006) does not find a significant effect in dynamic panel data models. Nonetheless, the general conclusion from the post-2000 empirical evidence must be that public R&D subsidies succeed in stimulating private R&D investment.

There is growing evidence that public subsidies are particularly effective in increasing R&D of small firms, which as discussed in section 3.1 are likely to be more financially constrained. Lach (2002), for instance, using a difference-in-difference estimator, finds for a sample of firms in Israel that subsidies for the small firms temporarily crowd out these firms' R&D, but have a strong stimulative effect after the first year of the subsidy. The author argues that this may reflect the fact that firms which receive the subsidy are committed to implement the subsidised project, but that this commitment may have led firms to temporarily scale down non-subsidised projects due to the serious skilled labour shortage that characterised the economic environment in Israel over the sample period 1990-1995. Subsidies for the large firms in the sample are statistically insignificant. Most subsidies are granted to the large firms, however, which may explain the result that the average effect for the pooled sample, while positive, also is insignificant. These findings are interpreted as indicating that large firms get subsidies for projects that would also have been undertaken in the absence of the subsidy, whereas small firms use the subsidy to finance additional projects. From a policy point of view, the subsidy funds should therefore be redirected to the smaller firms. Using Finnish data, Hyytinen and Toivanen (2005) further show that when there are economically significant capital market imperfections, small and medium-sized firms in industries that are more dependent on external finance invest relatively more in R&D when more public funding is (potentially) available. Overall these results suggest that, on the one hand, subsidies targeted at financially constrained firms may raise overall private R&D spending, and that, on the other hand, policies designed to improve these firms' access to external finance might reduce the need for R&D subsidies.[23]

[23] There is some first evidence that suggests that award of a government subsidy may moreover provide a positive signal about firm quality and thus help a firm attract additional private funding, and hence ease the adverse effect of capital market imperfections. Meuleman and De Maeseneire (2012) provide strong evidence that obtaining an R&D grant results in better access to long-term debt and to a lesser extent short-term debt for small and medium-size firms in Belgium. Feldman and Kelley (2006) find that R&D grants facilitate attracting venture capital for US firms that participate in the Advanced Technology Program.

These conclusions are also compatible with evidence found by Almus and Czarnitzki (2003) for a transition economy, for which capital market imperfections may a priori also be expected to be relatively more pronounced. Applying a non-parametric matching approach to post-reunification cross-sections from the 1990s for East Germany, the study finds additionality effects of all public R&D subsidies on average. Czarnitzki and Licht (2006) moreover find that the additionality effect on firms' R&D and innovation input was more pronounced in Eastern Germany during the transition period than in Western Germany. One conclusion drawn by Czarnitzki (2006), however, is that while the subsidies were initially intended to accelerate the transformation process of East Germany from a planned to a market economy, the continuing high level of subsidisation may imply inefficiencies as market forces are weakened.[24]

González, Jaumandreu and Pazó (2005) model firms' decisions about performing R&D when some government support can be expected. Applying a semistructural framework to Spanish firm data, the authors find that public subsidies stimulate private R&D spending. However, there is only a very slight increase for those firms that would perform R&D anyway, whereas some small firms would not perform any R&D in the absence of (expected) public funding. Similarly to Lach (2002) the authors point out that subsidies are mainly awarded to firms that would have performed the R&D anyway, and that this suggests that public policy tends to neglect the inducing dimension of public funding. In a cross-country analysis, Czarnitzki and Lopes Bento (2012) conclude that private R&D in Belgium, Germany, Luxembourg and Spain would benefit from an extension of public R&D subsidies to currently non-subsidised firms. Applying a matching approach to the same dataset as González, Jaumandreu and Pazó (2005), González and Pazó (2008) moreover find that, similarly as for small firms, R&D subsidies are more effective for firms operating in low-tech sectors, which the authors argue is probably also due to the inducement effect. In a study of UK manufacturing industries, Becker and Hall (2013) find that a higher share of government-funded R&D has a positive effect only for the low-tech industry group while being insignificant for the high-tech industry group. These results also suggest that high-tech firms substitute incremental public funding for internal funding.

[24] One novelty of this study is that it takes into account non-R&D performing firms and the endogeneity of their decision as to whether or not to invest in R&D. The study thereby explicitly considers the fact that a large share of small firms do not invest in R&D due to a lack of financial resources, which has also been pointed out by Bond, Harhoff and Van Reenen (2005), for instance.

Comparing the private R&D effects of EU versus national grants, using a sample of German firms, Czarnitzki and Lopes Bento (2011) conclude that the former yield higher effects than the latter, if funding is received from only one of the two sources. Two reasons are suggested: First, EU grants may on average distribute larger subsidies, or, second, their requirements might be such that only those firms that are most likely to top up the grant with private funding more substantially comply. The largest R&D effects are obtained through simultaneous funding from both sources, and Czarnitzki and Lopes Bento (2013) confirm that simultaneous receipt of multiple grants does not cause crowding-out.

First evidence on the relationship between subsidies for individual research, research cooperation, and subsidies for cooperative research is provided by Czarnitzki, Ebersberger and Fier (2007). The study's results for a sample of West German and Finnish firms show that in both countries firms that either receive public subsidies or cooperate on research would increase their R&D spending if they combined the two. One policy interpretation is that public subsidies for R&D cooperation may be another means of raising private R&D.[25]

There is both early and recent evidence of a different time pattern of the effects of tax credits and direct subsidies. Tax credits have a significant effect on R&D expenditure mainly in the short run, but only little in the long run, whereas subsidies have a substantial positive effect in the medium to long run, but less so in the short run. Hence the effect of tax credits is quicker than that of direct subsidies (David, Hall and Toole, 2000; Guellec and Van Pottelsberghe de la Potterie, 2003). The earlier study suggests that this time pattern at least in part likely reflects the fact that the tax offsets against earnings occur for R&D projects chosen by firms, the incentives of which probably favour projects that will generate greater private profits in the short run. By contrast, subsidies apply to projects selected by the government, which may be of a long-term nature and create new opportunities that may induce firms to start further projects with internal funding at a later stage, as pointed out in the more recent study. That study further suggests that tax credits and direct subsidies are substitutes in that an increase in one dampens the effect of the other on business R&D. These results indicate that the design and implementation of the two policy tools may be more effective if performed in a coordinated way.

There is some first evidence that the effect of a public subsidy on private R&D may have an inverted U-shape. Guellec and Van Pottelsberghe de la Potterie (2003), for example,

[25] See section 3.4 for a review of the R&D effects of R&D cooperation.

obtain the strongest private R&D effects for medium average subsidisation rates of 4-11%, while rates above 20% are found to be associated with the substitution of government funds for private funds. Görg and Strobl (2007) find an inverted U-curve effect for indigenous Irish manufacturing firms. These studies thus suggest that large grants may more likely act to finance private R&D activity that would have been undertaken anyway. From a policy point of view, the non-linear effect suggests that for any given public R&D budget, it may be more effective to grant some intermediate level of support to a larger number of firms than to provide a large amount of support to fewer firms.

With respect to the potential importance of international tax differences, Bloom and Griffith (2001) conclude in a cross-country analysis of eight OECD countries that R&D in one country responds to a change in the R&D tax credit in another country. This result suggests that at least part of the reason for the international mobility of R&D may be related to the increasing tax subsidies to R&D offered in many countries. One implication for R&D tax policy then is that the positive R&D effect of tax credits may be higher than previously estimated and increasing over time. Foreign tax competition may moreover become increasingly important as impediments to capital mobility come down. With regard to direct government subsidies, Becker and Hall (2009) show that an increase in the share of business R&D funded by the government is associated with an increase in the volume of foreign R&D invested in the UK. Similarly to the findings for an R&D tax credit, these results indicate that public R&D subsidies may help attract foreign R&D into the domestic economy.

Economists have generally been sceptical regarding the efficacy of tax credits, one reason being the view that R&D was not very sensitive to changes in its price. The recent evidence suggests much more unanimously than concluded in surveys of the earlier work that R&D tax credits have a positive effect on private R&D investment, whereby the precise estimated elasticities vary depending on the data, estimation method and model specification. Generally, the negative demand elasticity of R&D with respect to its own tax price is estimated to be broadly around unity, at least in countries with a tax credit. The recent evidence predominantly also suggests that public R&D subsidies succeed in stimulating private R&D. The additionality effect has been shown to be particularly prevalent for small firms, which are more likely to experience external financial constraints. On the one hand, these results provide strong support of government funding schemes. On the other hand, a number of studies report that most of the funding is awarded to larger firms that would have performed the R&D also in the absence of the public subsidy, which suggests that in these cases subsidies could be targeted more effectively. Indeed, Czarnitzki and Ebersberger (2010) report that governments in general predominantly prefer to grant R&D subsidies to larger firms and that this is a common general criticism of the distribution of subsidies. The reason is that this kind of distribution may contribute to a higher concentration of R&D, the persistence of leadership in markets and higher barriers to entry, and thus eventually reduce competition. It may also be the case that a tax credit rather than a subsidy could be the more effective public policy instrument for firms that are likely to simply substitute incremental public funding for internal funding, as the tax credit supports the private R&D that is actually expended by the firms. There is some evidence that both policy tools may be more effective if performed in a coordinated way. There is also some indication that the effect of a subsidy may have an inverted U-shape, so that subsidy levels that are too high or too low crowd out private R&D, while intermediate levels stimulate R&D. To date there are, however, only very few studies that investigate the relative effect of both tools or allow for a potential non-linear effect. Other forms of government policy may also matter, for instance general support to the science base and the strength of intellectual property protection (Kanwar and Evenson, 2003). Table 3 summarises the key features of studies that represent the main results from the literature.

3.4. Location and resource related factors

A growing body of evidence indicates that a firm's location and human capital resources are important factors affecting the pattern of R&D across countries, regions and industries. These factors include geographic proximity to universities, membership of research joint ventures and cooperation with research centres, and the availability of highly qualified human capital.

The notion that knowledge spillovers be localised goes back at least to Marshall's (1920) concept of the external economies. He illustrates this with the example of industry localisation and identifies three reasons for localisation, which can also be found in most of the more recent literature on regional economics and economic geography: A pooled market for workers with industry-specific skills, support of the production of non-tradable specialised inputs, and informational spillovers between firms that give clustered firms a better production function than isolated firms. The theoretical foundation of the geography of innovation is provided in Krugman (1991a, b) who shows how a country can endogenously develop into an industrialised 'core' region and an agricultural 'periphery' region.

An early case study which indicates that knowledge spillovers may be a driving factor of firms' choice of location was provided by Dorfman (1983). Her results indicate that high-technology firms sought to locate close to universities, pointing to the importance of the MIT for the development of Boston's 'high technology' Route 128 and of Stanford University for the location of 'Silicon Valley'. Related to this, Nelson (1986) argues in the first formal indication of localised knowledge spillovers from universities to firms, that university research rarely in itself generates new technology, it rather enhances technological opportunities and the productivity of private R&D. In accordance with this, the much-cited study by Jaffe (1989) provides evidence of a large significant positive effect of university research on industry R&D spending within US states and concludes that a state that improves its university research system will increase local innovation by attracting industrial R&D. In support of Dorfman's (1983) early results, Woodward, Figueiredo and Guimaraes (2006) more recently find for the US that R&D expenditures at universities positively affect the location decision of new high-tech plants in a county. This positive effect extends up to a maxiumum distance of approximately 145 miles between the university and the new plant.[26]

More recently there has been a growing number of studies using data for countries other than the US. Applying a modified version of Jaffe's (1989) R&D model to French data, Autant-Bernard (2001), for instance, finds positive externalities from public research to private R&D expenditures, and moreover that these externalities are strongest within the same geographical area. Karlsson and Andersson (2009) provide evidence that industrial R&D in Sweden tends to increase in locations that offer high accessibility to university R&D. Abramovsky, Harrison and Simpson (2007) examine the relationship between the location of the average number of private sector R&D firms and university research departments in 111 postcode areas in the UK. The authors match data for R&D labs in six product groups with data from the Research Assessment Exercise on the quality of university research. The strongest evidence for co-location is found for pharmaceutical business R&D and the most highly ranked chemistry university departments.[27] Overall the results raise the possibility that

[26] After controlling for other determinants of high-tech start-ups, university R&D is found to have only a small marginal effect on county location probabilities. This result might at least in part be due to the high-technology boom of the 1990s sample period, which exhibited its own specific start-up dynamics.

[27] This relationship is stronger for foreign-owned than for domestic R&D labs, which is consistent with the notion of international technology sourcing by multinational firms (see section 3.5).

private sector R&D may benefit from proximity to both, frontier basic university research and also more applied university research. The authors note that while the latter may be considered as low-quality research in terms of the Research Assessment Exercise and consequent university funding allocations, it may be relevant in some areas of technology transfer and in attracting foreign-owned R&D. In a related analysis, Abramovsky and Simpson (2011) confirm that pharmaceutical firms locate their R&D facilities close to frontier chemistry university departments. In addition, the results for the chemicals and vehicles industries potentially indicate the presence of knowledge flows between R&D activity and production activity. Conditional on location, the evidence for these latter two industries is again consistent with geographic proximity facilitating knowledge flows from universities. Rosa and Mohnen (2008) measure knowledge transfers from universities to firms by the amount of R&D payments made by firms to universities. The authors' empirical results for Canadian data corroborate the mounting evidence that an increase in distance decreases spillovers.

All these studies' results suggest that private R&D benefits from geographically localised knowledge spillovers from university research. This has important implications for regional economic policy. Improving the university research system and facilitating spillovers to the private sector may raise local private R&D spending. The transmission channels of these knowledge spillovers as identified in the literature include direct personal interactions, university spin-off firms, formal collaboration agreements, consultancy and university supply of a pool of highly-trained graduates for employment in industry. The evidence that proximity matters especially in high-tech sectors suggests that at least part of the spillovers are sector-specific and not just the diffuse effect of a large research university.

A firm's membership of a research joint venture has the obvious advantage that it may enable the firm to overcome a cost-of-development barrier that may otherwise prevent R&D investment, if R&D requires a minimum threshold investment to be effective at all. Another benefit is the reduction of wasteful duplication of R&D. These benefits are set against the potential adverse outcome that participants will tend to free-ride on each other's R&D investments in case of sufficient positive externalities from each firm's R&D efforts, or curtail competition in other stages of the firms' interaction, as emphasised in the theoretical contribution by Kamien, Mueller and Zang (1992).[28] Imperfect ability to assimilate the

[28] Dixit (1988) provides an analysis within the framework of international competition.

returns from R&D and innovation increases the incentive to free-ride (Shapiro and Willig, 1990; Kesteloot and Veugelers, 1995). In their pioneering work on cooperative and noncooperative R&D in duopoly, D'Aspremont and Jacquemin (1988) show that in the presence of large spillovers, R&D cooperation leads to higher R&D spending by duopolists compared to the competitive case. A symmetric result is that for small spillovers, R&D cooperation reduces R&D spending by the firms. In terms of empirical testing and public policy, these results ascribe a central role to the degree of R&D externalities in the industry. When attempting to assess the welfare effects of R&D cooperation, one challenge for research is to take into account the factors that affect the level of spillovers through time. In an extension of the model by D'Aspremont and Jacquemin (1988), Kamien, Mueller and Zang (1992) show that if firms create a research joint venture and also share information in that they cooperate on their R&D expenditure to maximise combined profits, i.e. they are cartelised in the R&D stage, consumer plus producer surplus are maximised. Cassiman and Veugelers (2002) point out that little is known today about the complementarities between a firm's own R&D programmes, cooperative agreements in R&D, and external technology acquisitions, and that a better understanding of these issues may enhance firms' ability to appropriate potential spillovers from R&D cooperation. R&D cooperation has played an increasing role in firms' innovative activities (Hagedoorn, 2002). Surveys of the industrial organisation and strategic management literatures on partner motives and outcomes of research joint ventures, or more generally on the theory of R&D cooperation, are provided by Hagedoorn and Narula (1996), Hagedoorn, Link and Vonortas (2000), Caloghirou, Ioannides and Vonortas (2003) and Sena (2004).

In an empirical analysis, Irwin and Klenow (1996) conclude that among firms who participated in Sematech, a joint R&D consortium of US semiconductor producers that was formed to develop new technologies for the production of computer chips, there was a drop in the total level of R&D expenditure. They interpret this as supporting the 'sharing' hypothesis, with information flows reducing duplicative R&D, allowing members to spend less on R&D than before. This is contrasted with the 'commitment' hypothesis of higher joint R&D expenditure on high-spillover types of R&D. Adams, Chiang and Jensen (2003) find that cooperation between federal laboratories and firms has a positive impact on private R&D expenditures and that no other channel of technology transfer from federal laboratories exerts a comparable effect. The authors point out that arrangements that strive to ensure effort by both, firms and federal laboratories, are required for technology transfer to be successful.

A first empirical insight into the potential effect of industry-university cooperative research centres on industry R&D expenditure is provided by Adams, Chiang and Starkey (2001) for the US. These centres are defined as "…small academic centers to foster technology transfer between universities and firms" (op. cit. p. 73). The results suggest that the development of these centres has fostered knowledge spillovers between member firms and universities. When the authors differentiate between National Science Foundation cooperative research centres and others, the effect is significant only for the former. However, the authors note that the coefficient may be biased upward as the centres are matched to larger and more productive laboratories. Two interpretions given by the authors are, first, that industry-university cooperative research centres provide new projects and stimulate industrial research, and, second, that larger laboratories are attracted to them. Hall, Link and Scott (2003) examine the performance of 54 industry-university projects funded by the US Advanced Technology Program which combines public funds with private investments for the creation and application of generic technology needed to commercialise new technology rapidly. The study finds that projects with university involvement are more likely to be in new technological fields where R&D is closer to science and that, therefore, such projects experience more difficulty and delay, but are more likely not to be aborted prematurely. The authors' interpretation is that universities are contributing to basic research awareness and insight among partners in the funded projects. With respect to geographic proximity, Ponds, Van Oort and Frenken (2007), using a sample of science-based industries in the Netherlands, find that proximity matters more when cooperating partners have different institutional backgrounds, such as firms and universities, than for organisations with similar institutional backgrounds. Geographic proximity may thus help overcome institutional differences between collaborators.

Recent research indicates that spillover effects may also be mediated. Using a sample of Belgian manufacturing firms, Cassiman and Veugelers (2002), for example, provide evidence that firms are more likely to cooperate on R&D if they believe that external information flows, i.e. incoming knowledge spillovers, are probably important. This also holds for firms with more effective appropriation of the returns from their R&D, i.e. with lower outgoing spillovers. The results also suggest different effects of incoming spillovers on the one hand and of appropriability on the other hand. Incoming spillovers positively affect the probability that firms will cooperate with research institutes, such as universities and public or private research laboratories. This suggests that those firms which find the publicly available pool of knowledge more important as an input to their innovation process have a higher probability of benefiting from cooperative R&D agreements with research institutes. Appropriability has no significant impact on this type of cooperation, which is supported in Veugelers and Cassiman (2005) who argue that the more generic and uncertain nature of these R&D projects involves less intellectual property issues. Hall, Link and Scott (2001) further note that when research results are uncertain, neither party is able to define meaningful boundaries for any resulting intellectual property issues, and so it is then less likely that appropriability is an insurmountable issue. In contrast, appropriability positively affects the probability of firms' cooperation with customers and suppliers (Cassiman and Veugelers, 2002). The authors argue that this result suggests that only firms which can sufficiently protect their proprietary information are willing to engage in cooperative agreements with downstream and upstream firms, because the outcome of these more applied research projects, that is commercially sensitive information, often leaks out to competitors through common suppliers or customers.

There is a growing number of studies that apply the ideas in Cassiman and Veuglers (2002) to data for other countries. Schmidt (2005), for instance, finds that incoming spillovers and in particular appropriability matter for the decision by German manufacturing firms' to cooperate on R&D. For a sample of Spanish firms, Lopez (2008) in addition finds that strategic methods to protect the returns from R&D are particularly important for firms' R&D cooperation with direct competitor firms. This observation is consistent with the results of the multicountry study of France, Germany, Spain and the UK by Abramovsky, Kremp, Lopez, Schmidt and Simpson (2009). While cooperation among competitor firms is not investigated in Cassiman and Veugelers (2002) due to a lack of data, the result is nonetheless consistent with this study's conclusion of the importance of protection from the leakage of commercially sensitive information to competitors. The free-rider problem may thus be more serious within direct competitor agreements. The results in Belderbos, Carree, Diederen, Lokshin and Veugelers (2004) for the Netherlands further reflect greater appropriability concerns for cooperation between firms. The study moreover shows that firms tend to gravitate to the cooperation type that has the highest value in terms of source-specific incoming knowledge. Spillovers from universities and research institutes have a positive effect on all types of cooperation, i.e. cooperation with direct competitors, customers, suppliers, and research institutions. The authors argue that this finding indicates that knowledge from universities and research institutes is more generic in nature and improves the technological opportunities and general effectiveness of a firm's own R&D and its R&D cooperation strategies.

Consistent with the theoretical argument presented above, most empirical studies that examine the importance of cost-sharing conclude that this is important for the decision to cooperate on R&D (see e.g. Abramovsky, Kremp, Lopez, Schmidt, Simpson, 2009, and the references therein).[29] There is also some evidence that suggests that public subsidies can stimulate R&D cooperation of firms with research institutions and with customers and suppliers.[30] Taken together, these results suggest that governments may increase private R&D spending by facilitating and incentivising R&D cooperation, for instance through providing direct funding and appropriate intellectual property protection mechanisms.

Adams (2002) analyses to what extent publicly and privately generated knowledge spillovers differ in their effects on private (individual firm) R&D. The results from US data indicate that university spillovers are more localised than industrial spillovers. The author suggests that this, on the one hand, reflects the dissemination of normal science and the industry-university cooperative movement, both of which encourage firms to work with nearby universities, so that geographic localisation coincides with the public goods nature of academic research. On the other hand, in relations with other firms contractual arrangements are often required to access proprietary information, and often at considerable distance. The results further indicate that nearby stocks of R&D increase localisation, while laboratory and firm size reduce localisation. This latter effect suggests that research by smaller laboratories and firms depends more on localised spillovers, other things being equal. Furman, Kyle, Cockburn and Henderson (2006) conclude that if competition between firms has a negative effect on R&D, there may be a trade-off between, on the one hand, a firm's incentive to locate close to for example universities in order to benefit from their locally generated public knowledge, and, on the other hand, the incentive to avoid geographically close competition with rival private firms which may choose the same near-university location. One way around this trade-off may be the formation of cooperative R&D centres so as to turn competitors into

[29] Similarly to the positive signal of the award of a government subsidy, that may attenuate financial constraints for R&D investments by enabling a firm to attract additional private funding (see previous section), recent research suggests that being a partner in horizontal R&D collaboration may also alleviate liquidity constraints by acting as a positive signal about firm quality and expected success of a project (see Czarnitzki and Hottenrott, 2012, and the references therein).

[30] There are, of course, a number of other determinants of R&D cooperation, an exploration of which is beyond the scope of this paper. The interested reader is referred to the discussed empirical studies and the surveys, and the references therein.

collaborators. This again suggests a potential role for government policy in terms of providing appropriate incentive structures.

As for potential effects of highly qualified human capital resources, several studies suggest that these have important R&D effects. The empirical proxies used in the literature include the number of highly qualified scientists and engineers (Adams, Chiang, Starkey, 2001; Adams, Chiang, Jensen, 2003; Becker and Pain, 2008), the share of the number of workers with higher education in the total number of workers (García and Mohnen, 2010), years of formal schooling (Kanwar and Evenson, 2003) and at country level the share of scientific researchers in the population as well as the share of the population with tertiary education in the population aged 24-65 (Wang, 2010).

Summarising, the existing literature on the US and a variety of other countries predominantly concludes that private R&D benefits from geographically localised knowledge spillovers from university research. This could have important implications for regional development policies and the evaluation and funding of university research. Improving the university research system and facilitating spillovers to the private sector may raise local private R&D spending. The transmission channels of these knowledge spillovers as identified in the literature include direct personal interactions, university spin-off firms, formal collaboration agreements, consultancy, and university supply of a pool of highly-trained graduates for employment in industry. There is some evidence that proximity matters especially in high-tech sectors, which suggests that at least part of the spillovers are sector-specific and not just the diffuse effect of a large research university. Similarly, available evidence on the quality of university research suggests this matters in particular for the location of pharmaceutical business R&D. Membership of a research joint venture and R&D collaboration with a variety of partner institutions have also been shown to impact positively on private R&D spending, whereby geographic proximity may help to overcome institutional differences between collaborators. Highly qualified human capital resources also have important effects on private R&D. Taken together, the results in the literature to date indicate several roles for government policy. One role lies in strengthening university research, another in facilitating spillovers to the private sector, in particular in relevant high-tech industries. Other roles lie in the provision of appropriate intellectual property protection mechanisms and of direct subsidies in order to raise private R&D spending through R&D cooperation. Table 4 summarises the key features of studies that represent the main results from the literature.

3.5. Spillovers from foreign R&D

A relatively small number of papers examines the issue of potential knowledge spillovers from foreign-owned multinational firms to domestic firms' R&D.

The eclectic theory on multinational enterprises (e.g. Dunning, 1979, 1988; Caves, 1996) provides theoretical insights into the reasons why foreign subsidiaries, first, are likely to be more technologically advanced than domestic firms and, second, may transfer technology to firms in the host country. Much of the argument related to the first issue is based on the concept of ownership advantages of the foreign multinational firm, which it can exploit in markets abroad through foreign direct investment, so that there will be know-how transfers from the parent firm to the subsidiary abroad. Regarding the second issue, technology transfer from foreign multinational firms to domestic firms can occur directly, for example through licensing out or R&D contracting with local firms, or indirectly as knowledge becomes public and spillovers are assimilated by the domestic firms. Griliches (1992) provides a key survey of the literature on technology spillovers.

Most of the empirical work to date focuses on the impact of foreign multinational firms on local productivity (see, inter alia, Blomström and Kokko, 1998; Mohnen, 2001, for surveys). Less attention has been paid to the potential impact of foreign multinational firms on domestic R&D, which may, in turn, affect productivity (see, e.g., Griliches, 1998, for a survey on the productivity effects).

In a recent study, Veugelers and Cassiman (2004) find that foreign firms in Belgium are less likely to transfer technology to domestic firms than innovative domestic firms are, once the foreign firms' superior access to the international technology market is controlled for. The authors suggest that this result can be related to a higher appropriation of knowledge within the foreign firms, which may prefer foreign direct investment to licensing to a local firm, as this allows for a better control of knowledge flows. Moreover, the incentives of foreign subsidiaries to transfer technology locally may be lower, in particular when the host market is not an attractive candidate for potential reciprocal access to knowledge.[31] Foreign firms have a positive compositional effect on R&D in the host country however, other things equal, as they have a higher probability of having an R&D base and of investing in R&D. Driffield, Love and Menghinello (2010) use a dataset on Italian firms that directly identifies technology flows from a foreign parent company to its affiliates abroad and from the affiliate to domestic

[31] See the discussion on technology sourcing below.

firms in the host country. The study finds that the more profitable affiliates exploit technology from the parent company, but do not transfer this technology to domestic firms. Hence the authors suggest that those affiliates that are best able to prevent the leakage to domestic firms of knowledge transferred from the parent company are in turn the most profitable.

Driffield (2001) examines the impact of R&D expenditures by foreign firms in the UK on the R&D expenditures by domestic firms at the industry level. His results provide evidence of intra-industry crowding-out effects from foreign R&D. He suggests that one explanation may be that domestic firms conduct less R&D as a result of knowledge gained by interacting with superior inward foreign investors.

Most of the work on international R&D spillovers focuses on the effects on the recipient country of inward foreign R&D. Recently however there has been evidence of knowledge spillovers associated with technology sourcing. This refers to investing in R&D abroad in order to gain access to spillovers of new 'tacit' foreign knowledge from other foreign firms or from indigenous firms in the host country. This knowledge is then channelled back to the home country and contributes to its productivity. Thus 'listening posts' are established in areas of technological expertise around the world (e.g. Gassmann and Von Zedtwitz, 1999; Serapio and Dalton, 1999; Von Zedtwitz and Gassmann, 2002; Ito and Wakasugi, 2007). In one recent study, Driffield and Love (2005) show that the positive effects for foreign subsidiaries in the UK of (productivity) spillovers from other foreign investors are largely restricted to R&D intensive industries. A related result is found by Cantwell and Immarino (2000) who identify the UK's South East as the country's core region of technological expertise, in which research by foreign-owned firms is even more locationally concentrated than research by domestically-owned firms. The study concludes that this region attracts foreign-owned firms' R&D for reasons other than its existing indigenous technological specialisation. Griffith, Harrison and Van Reenen (2006) investigate technology sourcing by UK manufacturing firms that invest in R&D in the US and were listed on the London Stock Exchange in 1985. The authors estimate that the 33% increase in the US R&D stock in the manufacturing sector between 1990 and 2000 was associated with an average increase of 5% in the level of total factor productivity of UK manufacturing firms in 2000. Crucially, the authors find that the majority of the benefits from the US spillovers accrued to UK firms conducting R&D in the US, strongly supporting the technology sourcing hypothesis. Consistent with these results for the UK are those for Japan by Branstetter (2006) who suggests that knowledge spillovers received by Japanese firms investing in the US tend to be largest via R&D and product development facilities. Griffith, Harrison and Van Reenen (2006) conclude that government policies designed to attract foreign R&D investment away from the US and towards the home country may be counterproductive, as this may reduce the scope of the benefits for indigenous firms from US based R&D spillovers. Rather, to reap the full benefits from US R&D, firms must undertake R&D in the US.

Concluding, the comparatively scarce recent evidence on the impact of foreign R&D on domestic R&D consistently does not find evidence of positive spillovers, but some evidence of crowding out.[32] One reason may be that domestic firms carry out less R&D as a result of knowledge gained by interacting with foreign firms. An increasing number of studies suggest that technology sourcing is a fruitful source of positive knowledge spillovers from abroad to the home country. The precise mechanisms underlying technology transfer through international R&D spillovers are not yet well understood, however (Keller, 2004). Table 5 summarises the key features of studies that use a variety of spillover measures.

4. QUESTIONS AND CHALLENGES FOR FUTURE RESEARCH

The extensive literature on the determinants of R&D allows for a number of conclusions to be drawn about what drives private R&D investment and what policies are likely to be conducive to incentivising further private R&D. Likewise, there are important issues that remain unresolved, and others that have not been considered in research to date. A few of these issues are discussed in the following.

The precise measurement of the returns to R&D, for instance, suffers from the central unsolved problem of how to measure the depreciation rate of R&D assets. In extension of Griliches (2000), Hall (2005) explores in detail the consequences of unknown private depreciation rates. Two major conclusions are, that private depreciation likely is more variable and higher than the 15 percent usually assumed, and that the rate of return to R&D is the complex outcome of a moving equilibrium, rather than a parameter. Hence further research is needed in order to obtain more accurate estimates of the R&D depreciation rate and consequently the rate of return than available to date.

[32] The rare pre-2000 studies also come to this conclusion, see e.g. Veugelers and Vanden Houte (1990) for Belgium and Van Reenen (1997) for the UK.

Regarding individual firm and industry characteristics, more evidence on the differences in financial constraints of small versus large firms and young versus mature firms could raise the effectiveness of government policies designed to reduce the cost of financing R&D and to increase access to external finance. There also appear to be important country-specific differences in the sensitivity of R&D to cash flow between the US and the UK versus Continental European economies, and further exploration of the underlying reasons would be useful.

Future research may also usefully explore further the effect of product market competition on the relative incentives of high-tech versus low-tech firms to conduct R&D. The growing evidence for an inverted U-curve effect of competition can be sensitive to the measurement of competition, whereby there does not seem to be a systematic difference between different measures, however, and so further exploration of the measurement issues seems useful. Very recent work suggests that the effect of competition on R&D and innovation may also differ with firm size and cost of innovation, and more research is needed in order to obtain a more comprehensive picture of these issues. Regarding the inverted U-shape effect of competition through foreign firm entry, with a positive R&D effect in technologically advanced sectors and a negative R&D effect in laggard sectors, research suggests there may be a need for labour and capital market institutions that complement policies aimed at decreasing or removing product market barriers to entry and that facilitate the reallocation of factors and resources from less to more advanced sectors (Aghion, Blundell, Griffith, Howitt and Prantl, 2009).

Government R&D policy usually is assumed to be exogenous, but tax competition implies that it may be endogenous. In this regard, Hall and Van Reenen (2000) point out that understanding the process by which different policies are conceived, for instance why and when governments introduce tax breaks, is as important as evaluating their effect. Furthermore, there has been little research to date on the way that award of public funding could be a signal about firm quality that helps a firm attract additional private funding and that hence potentially eases the effect of capital market imperfections. Further utilisation of international panel data seems another promising way forward: Identification of public policy effects on private R&D is difficult for studies of single countries, as R&D policies are correlated with other policies aimed at increasing the appropriability of research benefits to firms that invest in areas of new technological opportunity.

The mounting empirical evidence which suggests that geographic proximity is important for knowledge spillovers from university research to private research says relatively little about the actual mechanisms of this knowledge transfer, albeit some have been identified more generally. It is therefore difficult to suggest specific policy recommendations, as for each transmission mechanism there is varying potential for market failures, as pointed out in Abramovsky, Harrison and Simpson (2007). The mechanisms of knowledge transfer may also differ across industries. Future research to identify the precise mechanisms at work could be highly informative. Furthermore, it would be useful to analyse whether geographic proximity has any impact not just on the quantity but also on the quality of the transferred knowledge (Rosa and Mohnen, 2008). Developing in more detail the importance of distinguishing between incoming and outgoing spillover measures for a firm's R&D cooperation decisions also ought to be part of the future research agenda, as emphasised in Cassiman and Veugelers (2002). Finally, more explicit modelling of the endogeneity of the location of research and any impact this may have on research findings also is of importance.

It remains to be seen whether future research will support the lack of positive spillovers from foreign knowledge on domestic R&D, as suggested in much of this comparatively scarce literature. The mechanisms underlying technology transfer through international R&D spillovers are not well understood, and future microeconometric research is required to shed more light on the quantitative importance of such spillovers. Research that further explored the relative importance of technology sourcing abroad versus acquiring spillovers from foreign technology at home could also usefully inform policy.

Concluding, the overriding motivation for future research needs to be the search for appropriate policy design so as to increase private investment in R&D and generate positive returns for economic growth.

5. CONCLUSIONS

This paper has surveyed the literature on the driving factors of R&D investment. The major types of factors are, individual firm or industry characteristics, most notably internal finance and sales; competition in product markets; government policy measures such as R&D tax credits and direct subsidies; location and resource related factors, such as spillovers from university research within close geographic proximity, membership of a research joint venture and cooperation with research centres, and the human capital embodied in knowledge workers; and spillovers from foreign R&D.

Summarising, the main conclusions from the literature on each of the five types of R&D driving factors are reiterated in the following.

In support of Schumpeter's (1939, 1942) seminal work, internal finance, most notably cash flow, and sales emerge as the two key firm- or industry-specific determinants of R&D. The recent empirical literature generally finds that R&D investment is positively correlated with either. Differences in the extent or existence of the R&D effects are found with respect to firm size, firm age and countries. Stronger sensitivity is found for small firms and for young firms. This is consistent with the growing evidence that private sector R&D tends to be more procyclical in firms that face tighter credit constraints. Stronger sensitivity is also found for firms in the US and UK than those in Continental Europe. Sample composition may thus account for differences in results found by studies that do not differentiate between these characteristics. Results may also be sensitive to the other variables included in the model. As cash flow is, for instance, highly procyclical, some studies which fail to include cash flow may instead find larger procyclical effects from sales growth. Recent evidence suggests that external finance through public equity also matters, as well as R&D smoothing through changes in cash holdings; for firms in both the US and Europe, and again more strongly so for smaller firms and for younger firms. Financial constraints may also differ between different types of R&D, but the evidence here is still scarce. Recent evidence moreover suggests that award of an R&D subsidy, and partnership in horizontal R&D cooperation, may act as positive signals about the quality of a firm and the expected success of a project and thus enable a firm to attract additional private funding, hence easing the adverse effect of capital market imperfections.

Most of the empirical literature examining a linear effect of competition concludes that it has a positive effect on R&D. This is consistent with theoretical models that emphasise the extent to which R&D might be used as a defensive strategy in response to greater competition. There is some evidence that the positive effect is particularly pronounced for high-tech sectors as compared with low-tech sectors. However, the evidence on the direct effect of competition on R&D as compared with other measures of innovation is still relatively scarce. Recent research suggests that allowing for a non-linear effect is a way forward to encompass the different theoretical and sometimes different empirical results, and there is a growing body of evidence that suggests an inverted U-curve relationship between competition and R&D. However results can be sensitive to the measure of competition used. Very recent work moreover suggests that this effect may also depend on firm size and cost of innovation in the industry. The non-linear inverted U-curve effect has been found in particular for competition through foreign firm entry at the technological frontier, differentiating between a positive effect on R&D by frontier incumbent firms and a negative effect on R&D by laggard firms. One implication of the different effects on heterogeneous industries and firms is that policies to decrease or remove barriers to competition per se may not be sufficient to foster R&D investment, and may even be counterproductive depending on the composition of efficient and laggard firms. Sector-specific competition policies may therefore be more appropriate. Competition in foreign markets, via exporting, is predominantly found to have positive effects on R&D and innovation at home.

With respect to R&D tax credits and direct subsidies, the recent evidence suggests much more unanimously than concluded in surveys of the earlier work that these policy tools have positive effects on private R&D investment. The precise estimated elasticities of tax credits vary depending on the data, estimation method and model specification. The additionality effect of public R&D funding has been shown to be particularly prevalent for small firms, which are likely to experience relatively more external financial constraints. On the one hand, these results provide strong support of government funding schemes. On the other hand, a number of studies report that most of the funding is awarded to larger firms that would have performed the R&D also in the absence of the public subsidy, which suggests that in these cases subsidies could be targeted more effectively. It may also suggest that a tax credit rather than a subsidy could be the more effective public policy instrument for firms that may simply substitute incremental public funding for internal funding, as the tax credit supports the private R&D that is actually expended by the firms. There is some evidence that both policy tools may be more effective if performed in a coordinated way. There is also some indication that the effect of a subsidy may be non-linear and have an inverted U-shape, so that subsidy levels that are too high or too low crowd out private R&D, while intermediate levels stimulate R&D. To date there are, however, only very few studies that investigate the relative effect of both tools or allow for a potential non-linear effect.

The existing literature on the US and a variety of other countries predominantly concludes that private R&D benefits from geographically localised knowledge spillovers from university research. This could have important implications for regional development policies and the evaluation and funding of university research. Improving the university research system and facilitating spillovers to the private sector may raise local private R&D spending. The transmission channels of these spillovers as identified in the literature include direct personal interactions, university spin-off firms, formal collaboration agreements, consultancy, and university supply of a pool of highly-trained graduates for employment in industry. There is some evidence that proximity matters especially in high-tech sectors, which suggests that at least part of the spillovers are sector-specific and not just the diffuse effect of a large research university. Available evidence on the quality of university research suggests this matters in particular for the location of pharmaceutical business R&D. There is strong empirical evidence that membership of a research joint venture and R&D collaboration with a variety of partner institutions impact positively on private R&D spending, whereby some first evidence suggests that geographic proximity may overcome institutional differences between collaborators. Highly qualified human capital resources also have important effects on private R&D. Taken together, the results in the literature to date indicate several roles for government policy. One role lies in strengthening university research, another in facilitating spillovers to the private sector, in particular in relevant high-tech industries. Other roles lie in the provision of appropriate intellectual property protection mechanisms and of direct subsidies in order to raise private R&D spending through R&D cooperation.

Empirical testing of the theoretical benefits from foreign knowledge on host-country R&D is a comparatively under-researched area, and the evidence to date consistently does not find evidence of positive spillovers, but some evidence of crowding out. One reason suggested in the literature is that domestic firms carry out less R&D as a result of knowledge gained by interacting with foreign firms. An increasing number of studies suggest that technology sourcing is a fruitful source of knowledge spillovers from abroad. This refers to spillovers from other foreign firms and from indigenous firms in the host country, which are then channelled back to the home economy.

The advances as well as the gaps in the literature to date point to avenues of research the pursuit of which seems interesting and valuable to fully understand the many facets of the incentives that drive private R&D investment. While much work remains to be done, recent progress has been rapid and very productive. The improved insights look certain to improve further in future work, and the subject is set to remain prominent in the academic and policy debate for some time to come.

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Table 1. Studies on firm / industry characteristics

Study / Estimation Methodology	Country/ies	Level of Aggregation	Firm / Industry Characteristics	Effect	Control Variables	Effect	Period
BROWN, FAZZARI, PETERSON (2009) *IV (first-difference GMM, one-step)* - All variables are scaled by the book value of total assets at beginning of period in question. - The results reported are those with industry-specific rather than aggregate time dummies, which have a higher Sargan statistic. - High-tech firms.	US	firms (panel data)		all firms | mature firms | young firms		all | m | y	1990-2004
			cash flow$_t$ (gross, = *net cash flow* [= *after-tax income plus depreciation allowances*] plus R&D expenditure)	s | ns(-) | s	ldv ldv squared	s | s | s s(-) | s(-) | ns(-) (10%s)	
			cash flow$_{t-1}$ (gross)	ns | s | ns			
			net cash raised from stock issues$_t$ (= sale minus purchase of common and preferred stock)	s | ns | s			
			net cash raised from stock issues$_{t-1}$	s(-) | ns(-) | s(-)			
			net sales$_t$	ns(-) | s | ns(-)			
			net sales$_{t-1}$	s(-) | s(-) | s(-)			
BLOCH (2005) *OLS fixed effects* - All variables are scaled by the book value of total assets at beginning of period in question.	Denmark	firms (panel data)		all firms | small firms | large firms		all | s | l	1989-2001
			cash flow$_t$ (net, *see above for definition*)	s < s | ns	Tobin's q (= market value of equity plus book value of long-term debt) firm dummies time dummies	s | s | ns	
			sales$_t$	s | ns | s			
BOND, HARHOFF, VAN REENEN (2005) *ECM: IV (systems GMM)* - Dv: Δ_t R&D expenditure (log) - All firms.	Britain, Germany	firms (panel data)	*ECM:*	UK | Germany	*ECM:*	UK | Germany	1985-94
			cash flow$_t$ (net, *see above for definition*) / capital stock$_{t-1}$	ns | ns	ldv EC term$_{t-2}$ (log)	s(-) | s(-) s(-) | ns(-)	
			cash flow$_{t-1}$ (net) / capital stock$_{t-2}$	ns | ns(-)	time dummies		
			Δ_t sales (log, deflated by an aggregate producer price index for UK, by GDP deflator for GE)	ns | s			
			Δ_{t-1} sales (log, deflated)	s | s			
R&D participation model: Probit ML - Dv: dummy – conduct R&D yes or no - High-tech firms.		(cross-section data)	*Participation model:*		*Participation model:* industry dummies		1992
			cash flow$_{t-1}$ (net) / capital stock$_{t-2}$	s | ns			
			sales$_{t-1}$ (log, deflated)	s | s			

MULKAY, MAIRESSE, HALL (2001) *OLS fixed effects, ECM* - Dv: R&D expenditure$_t$ (deflated by an overall price index for R&D in manufacturing industries) / net R&D capital stock at end of year$_{t-1}$ - The results are reported from the authors' preferred specification in which all s/r coefficients, but only the l/r coefficients for cash flow, are allowed to vary by country.	France, US	firms (panel data)	 **cash flow$_t$** (**net**, *see above for definition*) / net total capital stock (= fixed plus R&D) at end of year$_{t-1}$; deflated as for sales) **cash flow$_{t-1}$** (**net**) / net total capital stock$_{t-2}$ **cash flow$_{t-2}$** (**net**) / net total capital stock$_{t-3}$ Δ_t **sales** (deflated by production price indices at 2-digit level) Δ_{t-1} **sales** (deflated) **sales$_{t-2}$** (deflated)	US ns s s(-) s s s(-)	France ns(-) ns(10%s) ns s s s(-)	 ldv EC term$_{t-2}$ firm dummies time dummies	US s s(-)	France s s(-)	1982-1993

Note: The dependent variable is R&D expenditure unless mentioned otherwise. *Dv* and *ldv* denote dependent variable and lagged dependent variable, respectively. *S* (*ns*) denotes significance (insignificance) of the coefficient at the 5% or higher level. *S/r (l/r)* denote short-run (long-run) coefficient. (-) denotes negative coefficient. Δ_t is first difference. *EC* is error correction term. The abbreviations *ECM*, *GMM*, *IV*, *(FI)ML*, *OLS*, *3SLS* and *SURE* follow the conventional ways to denote error correction model, generalised method of moments, instrumental variables, (full information) maximum likelihood, ordinary least squares, three stage least squares and seemingly unrelated regression estimation models. *Gov't* denotes government, *log* denotes logarithm or natural logarithm, *av* denotes average, *regr* denotes regression. Dummy variables distinguishing between a 'yes' or 'no' answer to a question were set equal to 1 (0) when the answer was 'yes' ('no'), unless mentioned otherwise.

Table 2. Studies on competition

Study / Estimation Methodology	Country/ ies	Level of Aggregation	Effect	Competition Proxies and Control Variables	Period
GRIFFITH, HARRISON, SIMPSON (2010)	Belgium, Denmark	industries (panel data)	non-linear specification / linear specification	**Competition proxies**:	1987-2000
IV (OLS for non-linear specification)	France, UK,		ns(-) / s(-)	average profitability$_{ijt}$ (= value added / (labour costs + capital costs) for industry i, country j, year t)	
- Dv: R&D / value added - IV results are reported from the 2nd-stage regr. with supportive Hansen test. (A regr. of the reforms on profitability is the 1st-stage regr.) - A non-linear inverted U-curve effect is identified qualitatively, but not statistically significant.	Nether-lands (affected by SMP); Canada, Finland, Norway, US (not affected)		s(-)	European Union Single Market Programme (SMP) variable for high-tech, public procurement markets (= 0 for t < 1992 when all SMP reform measures were supposed to have been implemented; for t ≥ 1992 = employment share in 3-digit industry k within total employment in corresponding 2-digit industry i in 1985-1987, i.e. prior to SMP implementation, if k was expected to be affected by SMP, summed up over all k per i)	
			ns	average profitability squared	
				Control variables: country-year dummies, industry-year dummies	
HALL, LOTTI, MAIRESSE (2009)	Italy	firms (pooled cross-section data)	all / high-tech / low-tech	**Competition proxies**:	1995-2003
OLS			ns / ns / ns(-)	dummy: firm declares to have large firms as competitors	
			ns / ns / ns(-)	dummy: firm declares to have regional competitors	
- Dv: R&D expenditures / number of employees (log, real terms)			ns / ns(10%s) / ns(-)	dummy: firm declares to have national competitors	
			s / s / ns(10%s)	dummy: firm declares to have European competitors	
			s / s / ns	dummy: firm declares to have international competitors	
				Control variables:	
			s / s / ns(10%s)	dummy if firm received subsidy over years of survey	
			ns(10%s) / s / s	dummy if firm is member of an industrial group	
			s(-) / ns(-) / s(-)	size class (21-50 employees)	
			ns(-,10%s) / ns(-) / s(-)	size class (51-250 employees)	
			ns(-) / ns / ns(-)	age class (15-25 years)	
			ns(-) / ns(-) / ns(-)	age class (> 25 years)	
				industry dummies, time dummies, survey wave dummies	
AGHION, BLUNDELL, GRIFFITH, HOWITT, PRANTL (2009)	UK	firms (panel data)		**Competition proxies:**	1987-1993
IV, Zero-Inflated Poisson model			s(-)	interaction term of foreign entry$_{t-1}$ x distance to technological frontier$_{t-1}$	
			s	foreign entry$_{t-1}$	
			s	import penetration$_{t-1}$	
- Dv: Innovation (measured as number of patents by UK firms taken out in US Patent Office)			s(-)	import penetration$_{t-1}$ squared	
			ns(10%s)	competition$_{t-1}$ (measured as an index of av. profitability in incumbent firms, = 0 no competition, = 1 perfect competition)	

- The results reported are from the IV regression that uses all IVs, allowing for endogeneity of the linear and interaction terms.				ns(-10%) s s s	competition$_{t-1}$ squared Control variables: distance to technological frontier$_{t-1}$ patent stock pre-sample dummy patent stock pre-sample (> 0 if there was pre-sample patent activity) year effects industry effects	

Note: See Table 1 for the abbreviations and further notes.

Table 3. Studies on government R&D policies

Study / Estimation Methodology	Tax Credit or Subsidy	Country/ies	Level of Aggregation	R&D Policy Variables	Effect	Control Variables	Effect	Period
Bloom, Griffith, Van Reenen (2002) *IV (log-log)* - Dv: (industry-funded) R&D expenditure / output - The results are reported from the authors' preferred dynamic specification which imposes constant returns.	**tax credit**	Australia, G7, Spain	countries (panel data)	user cost of R&D	s(-) (s/r and l/r)	ldv country dummies time dummies	s	1979-97
Lach (2002) *Pooled difference-in-difference estimator* - The results are reported from the final specification.	**subsidy**	Israel	firms (panel data)	subsidy subsidy$_{t-1}$	<u>all firms</u> / <u>small firms</u> / <u>large firms</u> s(-) / s(-) / ns(-) ns / s / ns	employment$_t$ industry dummies time dummies	<u>all</u> / <u>s</u> / <u>l</u> s / ns / ns	1991-95
Guellec, Van Pottelsberghe De La Potterie (2003) *IV (3SLS, log-log, first-differences)* - The results are reported from the regression that tests directly for (and finds) a non-linear inverted U-curve subsidy effect.	**tax credit and subsidy**	Australia, Belgium, Denmark, Finland, G7, Ireland, Netherlands, Norway, Spain, Sweden, Switzerland	countries (business sector aggregates; panel data)	B-index of fiscal generosity towards R&D$_{t-1}$ = (after-tax cost of a 1$ R&D investment) / (1– corporate income tax rate) interaction term of subsidy$_{t-1}$ and share of subsidy in total business-performed R&D$_{t-1}$ interaction term of subsidy$_{t-1}$ and squared share of subsidy in total business-performed R&D$_{t-1}$	s(-) s s(-)	ldv value added$_t$ gov't intramural R&D$_{t-1}$ higher education R&D$_{t-1}$ time dummies	ns(10%s) s s(-) ns(-)	1981-1996

Note: See Table 1 for the abbreviations and further notes.

Table 4. Studies on location and resource related variables

Study / Estimation Methodology	Country/ ies	Level of Aggregation	Location / Resources Variables	Effect	Control Variables	Effect	Period
JAFFE (1989) *IV (3 SLS, log-log)* - The results are reported from the all-areas industry R&D equation.	US	28 states (pooled cross-section data)	**university research: spending by departments** (technical areas: drugs, chemicals, electronics, mechanical arts, all other)	s	population value added	ns s	1972-77, 1979, 1981
ABRAMOVSKY, HARRISON, SIMPSON (2007) *Negative binomial regression* - Dv: average number of firms carrying out intramural R&D - The results are reported from the all-firms regression for the *pharmaceuticals* product group.	UK	postcode areas (cross-section data)	presence of university, dummy: yes or no number of universities average university quality **number of univ. departments rated 1-4** [maximum quality: 5*]: biology chemistry medical **number of univ. dept's rated 5 and 5***: biology chemistry medical no. of research students in 1-4 dept's no. of research students in 5, 5* dept's	ns(-) ns (-) ns ns s ns s(-) s ns ns ns	total manufacturing employment (log) diversification index (= (1-H) x 100, where H= sum of squared share of employment in 4-digit industry i in total manufacturing employment in the postcode area) [index increasing in extent of diversification] % of total manufacturing employment that is in pharmaceuticals industry % of economically active population that is qualified to degree equivalent or above	s ns s s	2000
ADAMS, CHIANG, JENSEN (2003) *OLS* - Dv: company-financed laboratory R&D net of expenditures on federal laboratories (log)	US	firms (cross-section data)	**member of Cooperative R&D Agreement between firms and federal labs**, dummy: yes or no **number of PhD scientists in the laboratory** (log)	s s	stock of sales over the last 12 years (log) R&D in rest of firm (log) dummies for lab characteristics gov't contractor dummy: yes or no value of procurement near the lab (log) value of procurement in rest of firm (log) industry dummies year dummies	s s(-) vary ns(-) ns ns	1991 and 1996 (average)

Note: See Table 1 for the abbreviations and further notes.

Table 5. Studies on foreign R&D spillovers

Study / Estimation Methodology	Country/ies	Level of Aggregation	Foreign Spillover Variables	Effect	Control Variables	Effect	Period
VEUGELERS, CASSIMAN (2004) *Heckman Probit* - Dv: dummy: innovative firm transferring technology to Belgium - The results are reported from the structural equation for this dv, which identifies the direct effect of the foreign spillover measure.	Belgium	firms (cross-section data)	**dummy: firm is a subsidiary with foreign headquarters**	s(-)	size (= sales) size squared effectiveness of protecting new products and processes (= average of scores (from 1 = unimportant, to 5 = crucial) for following methods of protection: patents; registration of brands, copyright; secrecy; complexity; lead time (rescaled between 0 and 1)) dummy: innovative firm acquiring technology from outside Belgium generalised residual from structural equation with acquiring technology dummy as dv industry dummies	ns(-) ns ns s s(-)	1992
DRIFFIELD (2001) *IV, FIML SURE* (*log-log*, simultaneous equation system with a productivity growth equation) - Dv: Δ_t domestic R&D stock - The results are reported from the R&D equation of the system. - All monetary variables are in real terms.	UK	industries (cross-section data)	Δ_t **stock of foreign-owned R&D expenditure**	s(-)	Δ_t domestic R&D in other 3-digit industries within the same 2-digit sector domestic capital labour ratio (to measure the technological capability to assimilate the output from R&D) advertising intensity at start of period (= advertising expenditure / sales) growth of sales over the three years up to start of period past profits (to measure the availability of funds for R&D)	ns s s s s	1989 and 1992 (difference)
GRIFFITH, HARRISON, VAN REENEN (2006) *IV (systems GMM)* - Dv: value added / capital stock (log)	UK	firms (panel data)	**interaction term of share of a firm's innovative activity in US** (= proportion of a firm's total patents applied for between 1975-1989 that cited at least one other patent whose lead inventor was	s	number of employees / capital stock R&D stock interaction term of share of a firm's innovative activity in UK (= proportion of a firm's total patents applied for between 1975-1989 that	s s ns	1990-2000

- The results are reported from the regression that uses the most refined measure of location of innovative activity, which is the variable that captures technology sourcing behaviour by firms.			located in the US and which was applied for within the previous three years) **and R&D stock in firm's industry in US** (log) [= *technology sourcing variable*] **R&D stock in firm's industry in US** (log) **share of a firm's innovative activity in US** (measured as above)	 ns s(-)	cited at least one other patent whose lead inventor was located in the UK and which was applied for within the previous three years) and R&D stock in firm's industry in UK (log) R&D stock in firm's industry in UK (log) share of a firm's innovative activity in UK (measured as above) industry dummies year dummies	 s ns(-)	

Note: See Table 1 for the abbreviations and further notes.