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DIRECTORATE FOR SCIENCE, TECHNOLOGY AND INNOVATION
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Working Party of National Experts on Science and Technology Indicators

The Impact of R&D Investment on Economic Performance: A Review of the Econometric Evidence

Paris, OECD, Headquarters, 27-28-29 April 2015

Delegates will find attached a survey of econometric research on the impact of R&D on productivity and economic performance. The review contributes to NESTI work on the "The role and impact of science and technology policies" (intermediate output result 1.3) foreseen under the CSTP Programme of Work and Budget for 2013-14.

NESTI delegates may wish to focus their attention on section 4, comprising an exploratory meta-analysis of the results in the literature. The meta-analysis approach is also relevant for the new OECD-NESTI distributed micro-data project on the incidence and impact of public support for business R&D as a means for pooling and investigating country-level estimates.

This report has been prepared by Silvia Appelt from the OECD secretariat with support from Antonio Zamorano-Gañán, and it is presented under Item 9 of the NESTI agenda. Delegates are invited to note the survey's findings and comment on its implications for future analytical work of NESTI. Delegates are also asked to approve the document before its submission to the CSTP for declassification.

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THE IMPACT OF R&D INVESTMENT ON ECONOMIC PERFORMANCE: A REVIEW OF THE ECONOMETRIC EVIDENCE

TABLE OF CONTENTS

EXECUTIVE SUMMARY 3
1. Introduction 5
1.1. Background and rationale for this study 5
1.2. Survey scope and methodology 5
2. Conceptual framework for estimating economic returns to R&D 6
2.1 Estimation approaches, measurement concepts and challenges 6
2.1.1 Production functions (primal approach) 7
Economic output and productivity 7
R&D flows and stocks 9
The stock of external knowledge and knowledge spillovers 10
2.1.2 Cost functions (dual approach) 12
2.2. Empirical implementation 13
2.2.1 Estimating R&D returns in the production function framework 13
2.2.2 Econometric challenges in measuring R&D returns 15
3. Review of main findings 16
3.1 R&D output elasticity 16
3.2 Private rates of return to R&D 17
3.3 Social rates of return to R&D 19
3.3.1 Domestic knowledge spillovers 20
3.3.2 International knowledge spillovers 21
4. Exploratory meta-analysis 22
4.1 Descriptive meta-analysis 22
4.1.1 Full set of econometric publications (1958-2014) 23
4.1.2 Selected set of econometric publications (2000-2010) 25
4.2 Exploratory meta-regression analysis 28
5. Concluding remarks 31
ANNEX 1: EMPRICIAL RESEARCH ON THE ECONOMIC IMPACT OF R&D – TIMELINE 32
ANNEX 2: META-ANALYSIS OF R&D RETURNS: DESCRIPTIVES 40
ANNEX 3: META-ANALYSIS: DEFINITION OF VARIABLES & SUMMARY STATISTICS 41
ANNEX 4: META-ANALYSIS: ROBUSTNESS TESTS 42
REFERENCES 45

EXECUTIVE SUMMARY

1. The pioneering work of Robert Solow (1956) highlighted the importance of R&D as a driver of technological change, innovation and economic growth, and gave a major impetus to theoretical and empirical research on the economic impacts of R&D investments. Governments across OECD countries and partner economies seek to encourage R&D induced innovation through various financial and non-financial instruments. Public support for business R&D through direct funding (R&D grants, loans and public procurement), and in some cases tax relief, constitutes a major policy instrument. In the OECD area, business accounts for approximately 68% of total R&D performed (OECD, 2015) – approximately 12% of which is government-financed as of 2012.[1] Securing empirical evidence on the magnitude of R&D impacts and channels through which R&D promotes economic growth is a necessary first step for assessing the likely impact of public support for R&D and other policies intended to encourage R&D and innovation.

2. This survey provides a comprehensive and up-to-date analysis of the economic impacts of R&D – business R&D more specifically. Following an introductory outline of the conceptual framework for estimating economic returns to R&D, the survey examines the magnitude of R&D impacts within the scope of a literature review and dedicated, exploratory meta-analysis of R&D return estimates. The literature review seeks to provide a synthesis of the main findings of econometric research assessing the economic impact of R&D at firm, industry and country levels. The descriptive a part of the meta-analysis sheds light on the scope of the econometric studies (e.g. country coverage) over time and on the magnitude and variability of R&D returns based on a hand-collected sample of recently published estimates. A meta-regression finally explores how the size of these estimates is related to measurement and estimation approach chosen, aside factors such as unit of analysis and time coverage. Both the literature review and meta-analysis draw upon a list of approximately 200 peer-reviewed articles and selected economic research papers, published over the time period 1958-2014.

3. Econometric studies predominately rely on the estimation of an augmented production function in order to gauge the economic returns to R&D. Such a function relates the physical output of a production process to a measure of R&D input and the standard factors of production, labour and physical capital. Through the expansion of a firm's stock of knowledge, R&D investments facilitate increases in the output and productivity of production. In the presence of knowledge spillovers, R&D investments also affect the economic performance of other firms not involved in the actual knowledge creating activity. This implies that the private return to R&D is likely to be smaller than the social return and that business likely underinvests in R&D from the social perspective (Arrow, 1962). Econometric analyses give rise to three measures of R&D impact: the elasticity of output with respect to R&D and the private and social rates of return to R&D, the latter accounting for the effects of own and external R&D capital via knowledge spillovers.[2] As an indicator of the potential degree of underinvestment in R&D by business, the relative gap between social and private returns provides a rationale for government funding of business R&D.

1. See OECD website on Measuring R&D tax incentives (http://www.oecd.org/sti/rd-tax-stats.htm) for information on the value of direct funding and tax incentive support for business R&D.

2. The R&D output elasticity specifies the percentage increase in output resulting from a 1-percent increase in R&D inputs, while rates of return denote the change in output caused by a one unit increase in R&D inputs.

4. The econometric evidence reviewed by this survey generally speaks in favour of positive and substantial impacts of R&D on productivity and economic growth at firm, industry and country levels. Private rates of return to R&D (gross of depreciation) usually outmatch those found for ordinary capital investments and the benefits that accrue to society as a result of R&D typically exceed private returns by far. At the same time, there is a substantial variation in the magnitude of estimated R&D impacts reflecting to some degree differences in the size of R&D impacts across different groups of firms, industries and countries. Recent firm-level evidence, for instance, suggests that firms in high-tech sectors enjoy higher returns to R&D (Kwon and Inui, 2003) and exhibit a higher R&D output elasticity (Kafourous, 2005). The link between output elasticity and firm size is less clear cut, by contrast (Wang and Tsai, 2004; Kafourous, 2005; Tsai, 2005 and Wang and Tsai, 2005). The elasticity of output with respect to external R&D in turn proves to be larger among firms that use advanced technologies and whose R&D intensity is in the medium range (Beneito, 2001) – this likely reflects the relatively high knowledge absorption capacity of these groups of firms. Country-level studies similarly point out to the role of knowledge absorption capacity in shaping the extent to which countries benefit from external R&D capital. The elasticity of output with respect to own and external R&D, for instance, is found to be higher among countries with a high ranking in terms of quality of tertiary education system and ease of doing business (Coe and Helpman, 2009).

5. Based on the results of our research, most of the empirical evidence on the economic impact of R&D stems from firm and industry level studies. Empirical research predominately focused on the United States and Canada up to the 1980s. In this period, economy-wide and multi-country studies, exploring the impact of internal knowledge spillovers, also began to arise. The latter now constitute an integral part of recent empirical research, accounting for approximately 40% of publications over 2000-2010. Exploiting R&D impact estimates from this more recent strand of the literature, the descriptive meta-analysis shows that output elasticities centre on 0.10 across the three units of analysis. Mean and median private returns to R&D (gross of depreciation) run in the order of 0.24 (0.39), looking at the median (mean) values from firm and industry level studies. Estimates based on economy-wide data in turn exceed the former both in terms of size and variability. Social rates of return to R&D generally prove to be significantly larger than private returns, the average (median) social return to R&D amounting to roughly 1.2 (0.8). On average, spillover benefits make up for approximately 61% (median 67%) of the social return to R&D.

6. These descriptive statistics are largely in line with the assessments made by preceding surveys. Complementing the descriptive evidence, an exploratory meta-regression finally examines how the size of output elasticity and private return estimates are related to various factors, including measurement and estimation approach. The meta-regression shows that output elasticity and private return estimates relying solely on the within-unit (temporal) variation in the data are generally smaller than their cross-sectional or pooled counterparts, the latter being based on both the cross and within unit variation in the data. This result is attributable to the relatively smaller variation of R&D investments in the cross-sectional vis-à-vis time dimension. As expected, correcting for R&D double counting proves to have a positive effect on the size of estimated private rates of return to R&D. One finding worth noting is the attenuating effect of controlling for human capital in empirical work. Both output elasticity and private return estimates turn out to be smaller once a measure of the stock of human capital is included in the econometric specification.

7. The latter finding highlights the importance of accounting for other innovation inputs such as human capital, ICT and non-R&D related intangibles in empirical work in order to comprehensively assess the economic impact of business R&D investments and polices that seek to stimulate such investments. The survey's findings speak also in favour of a micro-data based approach in assessing the efficacy of public support for business R&D by type of firm given the notable variation in estimated economic returns to R&D across different groups of firms. The meta-analysis approach undertaken as part of this survey is also relevant for the new OECD-NESTI distributed micro-data project on the incidence and impact of public support for business R&D as a means for pooling and investigating country-level estimates.

1. Introduction

1.1. Background and rationale for this study

1. This report reviews the econometric evidence on the impact of research and experimental development (R&D) on productivity and economic growth. Securing empirical evidence on the magnitude of the impact and mechanisms by which R&D investments promote economic growth is a necessary first step for evaluating the likely impact of a large number of policies intended to promote innovation (OECD, 2010).[3] On a purchasing power parity basis, gross domestic expenditure on R&D (GERD) in the OECD area amounted to USD 1.14 trillion in 2013, the equivalent of 2.4% of total OECD GDP (OECD, 2015).

2. The analysis of the impact of business R&D investment on productivity and growth deserves particular attention from an economic policy perspective. Business R&D accounts for approximately 68% of total R&D performed in the OECD area (OECD, 2015). Governments worldwide provide significant levels of financial support for business R&D in various forms, through in kind support from government and other public institutions, but also through various instruments such as grants, loans, public procurement and in some cases, R&D tax incentives. Approximately 7.2% of business R&D is directly funded by governments as of 2012. R&D tax incentives account for the equivalent of an additional 4.8% of public funding of business R&D.[4] Other indirect or in-kind contributions remain to this date very difficult to estimate on a global basis. Other framework policies such as IP rights aim to allow firms to enjoy a return on their investments in R&D. To establish a rationale for these support policies, a fundamental policy question is to what extent do firms that invest in R&D benefit directly from such investments, relative to society as a whole.

3. This literature survey examines the magnitude and variability of R&D returns drawing upon a comprehensive examination of peer-reviewed journals and selected economic research papers. In addition, this paper reports on the results of a new meta-analysis of econometric estimates of R&D returns. Its objective is to investigate the channels through which R&D affects economic growth and give insights into the absolute and relative size of private and social returns to R&D based on recent empirical work. The relative size of the latter provides an indication of the possible extent of underinvestment in R&D by business from a social perspective (Arrow, 1962), and a rationale for government funding of R&D.[5] While noting the importance of other R&D impacts such as improvements in health outcomes and social well-being more generally, the scope of this survey is confined to the impact of business R&D on economic performance which as an imperfect measure of economic prosperity.

1.2. Survey scope and methodology

4. The survey adopts a three-staged approach in order to provide a comprehensive and up-to-date analysis of the econometric evidence on impacts of R&D investment. It comprises an introduction to the measurement and estimation of R&D returns, a review of findings on the economic impacts of R&D and an exploratory meta-analysis of R&D return estimates as collected from firm, industry and country level

3. For surveys of the evidence on the impact of direct and tax incentive support for R&D, see Cunningham et al. (2013), Mohnen (1999), Hall and van Reenen (2000) and Köhler et al. (2012), for instance.

4. See OECD website on Measuring R&D tax incentives (http://www.oecd.org/sti/rd-tax-stats.htm) for information on the value of direct funding and tax incentive support for business R&D and the design of expenditure-based R&D tax incentive provisions across OECD countries and partner economies.

5. The divergence of private and social returns to R&D constitutes only one possible market failure (Griffith et al., 1996) leading to an underinvestment of R&D by business. Other market failures, not explored within this survey, relate to the (short-term) undersupply of researchers and the supply of funds problem (Hall, 2002). The latter is connected to the high uncertainty of the R&D output and the information asymmetries between performers and investors which cannot perfectly verify the level and quality of R&D efforts.

studies. Both the literature review and meta-analysis draw upon a list of approximately 200 peer-reviewed articles and selected economic research papers, published between 1958 and 2014.

5. This list of articles rest upon on a literature search involving Elsevier's Scopus scientific publication database and google scholar searches carried out from September to December 2014. Search terms included, for instance, "return", "R&D" and "productivity". The resulting list of publications was finally compared and reconciled with the literature listings reported by preceding literature surveys (Nadiri, 1993; CBO, 2005; Fraumeni and Okubo, 2005; Wieser, 2005; Sveikauskas, 2007; Mc Morrow and Röger, 2009 and Hall et al., 2010).[6] The final list of publications may not be fully exhaustive and capture all relevant econometric studies in this area, yet the survey's coverage, building upon the publication listings of previous literature reviews, is perhaps one of the most comprehensive and detailed currently available.

6. The literature review seeks to provide a synthesis of the main results from the vast body of econometric research on the economic impact of R&D as found for business R&D and common dichotomies of R&D investment (e.g. industry vs. publicly financed R&D, basic vs. applied research). This includes some initial findings on the economic impact of R&D aside other intangibles, human capital and ICT. The descriptive part of the meta-analysis examines the scope of the empirical literature – data vintage, unit of analysis and country coverage – over time and the size of estimated R&D returns at firm, industry and country levels. Doing so, the meta-analysis exploits recent, hand-collected estimates of R&D output elasticity, private and social rates of return to R&D and contrasts those with the assessments of previous surveys. To help guide future research, a meta-regression finally explores to what extent the size of output elasticity and private return to R&D estimates can be related to differences in measurement and estimation approaches. Drawing upon estimates from firm, industry and country-level studies, the meta-analysis extends the existing meta-regression evidence on firm-level R&D returns (Wieser, 2005).

7. The structure of the paper is as follows: Section 2 introduces the conceptual framework for estimating economic returns to R&D, describing measurement concepts and estimation approaches as well as existing challenges in measuring and estimating R&D returns. Section 3 reviews the empirical literature. Section 4 presents the descriptive and econometric results of a meta-analysis of R&D returns. Section 5 concludes with a summary of the main survey findings and an outlook on avenues for future research.

2. Conceptual framework for estimating economic returns to R&D

2.1 Estimation approaches, measurement concepts and challenges

8. The production and cost function approach, which are closely related and can be derived from one another (Diewert, 1971), are commonly used in the literature to estimate economic returns to R&D. The majority of studies rely on the production function framework which relates economic output to a set of inputs, including R&D. The use of the production function framework is significantly more widespread because it is simpler and entails less data requirements. The cost function approach, by contrast, facilitates the more flexible accounting for factors such as price-mark ups due to imperfect competition or adjustment costs (e.g. R&D project set up costs) incurred in altering the use of R&D, labour or capital inputs.

6. Another literature survey was recently carried out by Frontier Economics (2014). We did not include this survey among the set of preceding surveys considered for the reconciliation of relevant publications as it contains no list of articles feeding into their analysis of rates of return to R&D.

9. Because of the prominence of the production function (primal) vis-à-vis cost function (dual) approach, the survey focusses on the estimation of production functions and sketches only the principle elements of the dual approach[7]. The underlying measurement concepts and existing challenges in measuring economic output, R&D and standard inputs as well as R&D related knowledge spillovers are hence also presented and discussed in the context of the production function framework.

2.1.1 Production functions (primal approach)

10. A production function specifies the physical output of a production process as a function of factors of production and represents the maximum level of output that can be generated with a given combination of physical inputs, labour and capital inputs (L, C), for instance. R&D investments of firms in a given industry or country may affect economic output through multiple channels. Contributing to the expansion of firms' knowledge stock, R&D facilitates efficiency improvements in production and output growth. Some of this newly created knowledge may also leak out and benefit other firms not involved in the actual knowledge creating activity, possibly stimulating further R&D, innovation and economic growth. To estimate these direct and indirect economic effects of R&D, production functions are typically augmented by a measure of the existing knowledge stock created by own (K) and external (K') R&D.

$$\text{Output} := F(L, C, K, K') \tag{1}$$

Economic output and productivity

11. Output[8] as an indicator of economic performance can be measured by gross output, gross value-added (GVA) and gross domestic product (GDP), as shown in **Box 1**, or sales (revenue).

Box 1. Measuring economic output

The following concepts of economic output, as defined in the System of National Accounts, can be utilised to measure the link between R&D, productivity and economic growth using industry or economy-wide data:

- **Gross output** reflects the value of sales from production, the change in inventories and finished goods, and the value of capital assets created on own account, i.e. for internal use.
- **Gross value added (GVA)** is a measure of the value of goods and services produced in an economy which is obtained by subtracting from gross output the value of intermediate consumption (purchased intermediate inputs such as materials and services used in production). GVA is used to remunerate labour inputs (employment compensation) and capital (gross operating surplus).
- **Gross domestic product (GDP)** is equal to the value of GVA across all sectors, plus taxes and less subsidies on products. Net domestic product equals GDP less consumption of fixed capital, a measure of the use of capital assets in production, including their obsolescence.

Relative to gross output, the benefit of GDP and GVA as economic output measures is that a summing up of values from lower to higher levels or aggregation is possible as transaction flows within producing units are netted out.

A distinction is to be made between nominal and real values of economic output. The latter comprise price changes, e.g. due to inflation, and thus reflect changes in the actual volume of economic output.

These National Account concepts draw upon and have close counterparts in accounting measures typically used by firms, such as sales and profits.

Source: SNA (2008).

7. For a detailed description of the cost function approach, see Nadiri (1993) and Nadiri and Prucha (2001).

8. For an outline of work on the relationship between R&D and intellectual property as an inventive output measure, see Scotchmer (2004).

12. The choice of the output measure usually depends, among other factors, on the unit of analysis (firm, industry or country), data availability and the given measurement and estimation strategy. Studies based on economy or industry-wide data rely for the most part on GDP or GVA as a measure of output, whereas firm-level studies tend to measure output by sales deflated by some price index. Alternative firm-level measures reflecting economic outcomes can in principle be constructed based on company accounting data. This includes, for instance, gross margin (sales less cost of goods sold), operating margin (gross margin less cost of R&D expenditures) and Tobin's q which as a measure of the market capitalisation-to-book ratio reflects a forward-looking evaluation of stock listed firms' R&D investments.[9] By nature of the data the use of such outcome measures is confined to firm-level studies.

13. The knowledge created through R&D investments can lead to an increase in the efficiency of production, facilitating the production of a given amount of output using fewer resources, as well as to a quality improvement in the given output without necessarily changing the quantity of output produced. If the prices of inputs and outputs are appropriately deflated and adjusted for quality differences, quality improvements can in principle be distinguished from productivity increases. Measures of productivity feature in empirical work as an outcome variable of interest alongside the aforementioned output measures. Productivity indicators reflect the ratio of an output volume index to an input volume index. Labour productivity as a partial productivity measure is typically defined as total output (real GVA or GDP) per unit of labour (e.g. persons employed, hours worked). In contrast, multifactor (total factor) productivity (MFP or TFP) reflects the output per unit of some combined set of inputs, namely labour (L) and physical capital (C). TFP (T) essentially accounts for changes in total output not accounted for by these two standard factor inputs.

14. One way to construct an input index, a so-called Divisia-type index, is to aggregate individual inputs using their respective shares in total income (input cost as a percentage of output) as weights. TFP in turn can be calculated as output growth minus the growth in the input index, i.e. growth in labour ($\dot{L}$) and capital ($\dot{C}$) inputs multiplied by the output elasticity of the input (i $\in \{C, L\}$). As aforementioned, the latter is typically approximated by the income share s_i of the respective input:[10]

$$T = \dot{Q} - s_L \dot{L} - s_c \dot{C} \qquad (2)$$

15. TFP, as unexplained residual in growth regressions, often referred to as "Solow residual", can be related to R&D spending as a driver of technical change.[11] To measure the relationship between R&D, productivity and output, empirical studies include R&D input measures in addition to the standard inputs labour and physical capital. Labour is typically measured as person hours worked or number of employees and physical capital as total value of productive assets (e.g. structures and equipment).

16. The estimation of economic returns to R&D relies on the availability of reliable measures of economic output and productivity. As detailed below, challenges in the measurement of economic output and productivity mainly relate to the identification of real output (i.e. volume) increases vis-à-vis quality improvements across different sectors, industries and possibly groups of firms. Depending on the

9. This survey does not address the issues that arise in using accounting data to estimate the returns to corporate R&D. Hall et al. (2009) provide a comprehensive overview. For a survey of empirical work using the Tobin's q measure, see e.g. Hall (2000) and Grandi et al. (2009).

10. This definition is based on the assumption of perfect competition and constant returns to scale with respect to labour and capital inputs (α+β=1), following which the output elasticities with respect to labour (α) and capital (β) can be interpreted as factor shares s_L and s_C respectively. For an overview of TFP calculation methodologies, see Nadiri and Prucha (2001), Lipsey and Carlaw (2004) and OECD (2001; 2013).

11. To apportion the contribution of R&D to growth, as captured by TFP, growth accounting studies need to assign an income share to R&D which can be based on empirical estimates of the rate of return to R&D.

availability of suitable, quality-adjusted price deflators, it may be more (e.g. manufacturing vs. services) or less (e.g. new products) straightforward to identify the real output and productivity impacts of R&D.

- *Quality adjustments for output*: a large portion of R&D involves quality improvements that may or may not go in hand with output and productivity increases. If output price deflators do not account for quality adjustments, the relative price of R&D intensive products will be overstated and actual changes in output not correctly identified. In the case of new products, difficulties in the measurement of prices arise if no comparable products exist that would help establish a representative quality level so that meaningful price deflators can be derived.
- *Quality adjustment of final and intermediate outputs*: a misattribution of productivity effects can arise when only the economic output of some selected industries is quality-adjusted. For instance, if quality adjustments are applied only to the prices of final outputs, but not to intermediates, overall productivity effects will be attributed exclusively to the final output producing sector. If quality adjustments differ across groups of firms or industries, the use of common industry or economy-wide output deflators can in principle have the same misleading effect.
- *Measuring Total factor productivity (TFP):* conventional measures of productivity reflect not only technical advances but also economies of scale and price mark-ups due to imperfect competition (Bernard et al., 2003) which can blur the estimated relationship between R&D and productivity. The measurement of TFP is further directly affected by the challenges encountered in measuring economic output and standard and R&D inputs (Griliches, 1987, 1994 and 1995).

R&D flows and stocks

17. The 6th edition of the OECD Frascati Manual defines research and experimental development (R&D) as comprising "creative work undertaken on a systematic basis in order to increase the stock of knowledge, including knowledge of man, culture and society, and the use of this stock of knowledge to devise new applications" (OECD, 2002). R&D includes three activities: basic research, applied research and experimental development. Econometric studies use for the most part R&D expenditure rather than R&D personnel data to construct a measure of R&D input. Measures of intramural R&D expenditures provide a flow measure that captures gross additions to the stock of knowledge created by R&D. Because R&D can be done on behalf of other parties, some adjustments that take into account funding flows are required to arrive at a measure of investment by a firm.

18. As R&D generates a stock of knowledge which as an intangible asset is likely to entail long term economic benefits to the investing company, it is inappropriate to rely solely on the investment flow as measure of R&D input when explaining current production. In order to reflect the inter-temporal benefits of R&D investments (R_{it}), econometric studies typically incorporate a measure of the knowledge stock K_{it} created by R&D[12]. If R&D has an impact on innovation and economic growth, then it will be through the expansion of this stock of knowledge that a company can draw upon.

$$K_{it} = (1 - \delta)K_{i,t-1} + R_{it} \tag{3}$$

19. The stock of knowledge (K_{it}) created by the R&D of a firm, industry or country (i) in period (t) can be modelled in line with the perpetual inventory method as the sum of the net R&D investment (R_{it}) and the past knowledge stock depreciated at rate δ in account of the obsolescence of knowledge.

12. Another stream of the literature models productivity as a function of innovation output, using measures such as patents per employee or share of innovative sales (e.g. Geroski, 1991 and Crépon et al., 1998). See Scotchmer (2004) for a review of empirical work on the impact of R&D, patent and patent citation counts on firm value (e.g. Cockburn and Griliches, 1988; Harhoff et al., 1999 and Hall, et al. 2005).

20. Equation (4) presents a derived, normalised R&D input measure – the R&D intensity indicator (RDI_{it}) can be defined as the ratio of R&D investment (R_{it}) – net or gross of depreciation – to output (Q_{it}).

$$RDI_{it} = \frac{R_{it}}{Q_{it}} \quad (4)$$

21. Alike the measurement of economic output and productivity, estimating the impact of R&D on output entails a number of challenges.

- *Double counting of R&D:* labour and physical capital inputs used for R&D will be counted twice if the R&D components of conventional inputs are not removed (Schankerman, 1981). Human and material resources may be dedicated to the production of R&D rather than to the goods and services that typically account for most of the firm's measured output. This double-counting of R&D (or under-reporting of R&D output) can lead to a substantial downward bias in the estimated effect of R&D on output (e.g. Cunéo and Mairesse, 1984; Hall and Mairesse, 1995 and Bartelsman et al., 1996). The literature does not generally consider the extent to which resources devoted to R&D are paid for by other firms (R&D investment by other firms) or result in non-market knowledge output that the firm owns. Most of the literature identifies measure of R&D performance with measures of R&D investment.
- *Depreciation (obsolescence):* the rate at which knowledge becomes obsolete has an immediate impact on the size of the calculated stock of knowledge created by R&D. While in theory rates of depreciation may be higher at firm vs. industry or economy level (Frantzen, 2002 and CBO, 2005), empirical research commonly uses a depreciation rate of 15%. Early experimentation with different depreciation rates shows (Bernstein, 1988; Bernstein and Nadiri, 1989) that estimated R&D impacts are relatively robust to the use of depreciation rates in the range of 8-25%. The impact of obsolescence can greatly vary at the micro or macro level. A company's full stock of R&D may become instantly obsolete if a competitor brings into the market a new radical innovation, experiencing a 100% obsolescence rate. This measurement error theoretically diminishes at the macro level as the diverse experiences of different firms are aggregated. However, studies do not generally account for the fact that obsolescence may be endogenous to the amount of R&D in the economy.
- *Choice of R&D intensity indicator:* by construction, measures of R&D intensity depend on the choice of output variable (value added, gross output and sales). The use of gross vs. net R&D intensities also appears to affect the size of estimated R&D impacts. Mairesse and Sassenou (1991) note a downward bias in R&D returns when using gross instead of net R&D intensities. The role of depreciation is likely related to the complementary or substitutive nature of R&D undertaken.
- *Differences in the composition of labour inputs:* cross-sectional analyses accounting for differences in labour composition (e.g. educational attainment) tend to result in lower estimates of output elasticity (e.g. Mairesse and Cunéo, 1985 and Mairesse and Sassenou, 1989). Hall et al. (2010) attribute this result to the positive correlation (complementarity) between highly qualified labour and R&D.

The stock of external knowledge and knowledge spillovers

22. The literature distinguishes among domestic and international, as well as among intra and inter-industry, knowledge spillovers depending on the direction of knowledge flows between R&D performing and external firms not involved in the knowledge creating activity. R&D has two specific properties which give rise to the existence of knowledge spillovers. The first property – non-rivalry in consumption – reflects the fact that the use of the R&D related knowledge capital by one firm does not prevent or

diminish the use of the same knowledge by other firms.[13] The second property – partial non-excludability – implies that at least some of the newly generated knowledge is partially non-excludable[14].

23. To estimate the economic impact of knowledge spillovers[15], econometric studies ordinarily adopt a measure of the stock of external knowledge which is constructed as a weighted sum of R&D capital stocks of "connected" sources external to the firm, industry or country. Weights are usually proportional to some proximity or flow intensity measure between the recipient i and the assumed source j of the knowledge spillover S_{it}[16] and indicate the likelihood with which knowledge transmits from one party to another. The underlying assumption is that knowledge is more likely to diffuse, the larger the intensity of interaction or the proximity between the spillover recipient and provider.

$$S_{it} \approx K'_{it} = \sum_{j \neq i}^{N} a_{ij} K_{jt} \quad (5)$$

24. The literature has adopted various flow-related weights, reflecting, for instance, the intensity of trade (Coe and Moghadam, 1993; Coe and Helpman, 1995; Coe et al., 1997 and Griffith et al., 2004), foreign direct investment (Hanel, 2000 and van Pottelsberghe and Lichtenberg, 2001), intermediate input transactions (Sveikauskas, 1981; Terleckyj, 1974 and 1980; Goto and Suzuki, 1989 and Keller 2002b), innovation or patent counts (Scherer, 1982 and 1984; Griliches and Lichtenberg, 1984; Jaffe, 1986; Sterlacchini, 1989; Mohnen and Lépine, 1991; Verspagen, 1997 and Los and Verspagen, 2000) or the intensity of collaboration (Di Cagno et al., 2013).[17] Proximity measures in turn may relate to the geographical proximity of spillover sender and receivers or their distance in the technological or product market dimension. Geographical proximity can be computed as distance between spillover sender and recipient (Xu and Wang, 1999; Keller, 2002a and Abdelmoula and Legros, 2009) and the proximity in the technological and product market spaces as un-centred correlation between positions in patent classes (Jaffe, 1986) and lines of business (Bloom et al., 2013) respectively.

25. The measurement of knowledge spillovers is subject of ongoing research. As noted above, there is no unique or "gold standard" approach for measuring knowledge spillovers. The size of external R&D capital stocks is related to data availability and their construction generally entails some subjective judgement about which weighting matrix reflects knowledge flows most accurately. This and the fact that knowledge spillovers can in principle also be negative, can lead to highly variable estimates of knowledge spillover benefits as detailed below.

13. One should note that non-rivalry in consumption does not imply that the economic value of the knowledge to the firm would not depend on whether or not other firms use this knowledge.

14. Some knowledge falls out of the scope of patentable subject matter. In other cases, firms may be able access and benefit from external knowledge through imitation or reverse engineering, for instance.

15. Knowledge spillovers are related to knowledge embodied in research. In contrast, rent spillovers reflect the pecuniary benefits from economic transactions, e.g. intermediate input transactions (Verspagen, 1997).

16. For a survey of the literature on the role of R&D and technology diffusion for economic growth, see Keller (2004) and Jones (2005).

17. The knowledge spillover literature also identifies mobility of technological personnel and scientists (e.g. Almeida and Kogut 1999; Moen 2005; Maliranta et al. 2010) as one conduit for such spillovers. Autant-Bernard et al. (2007) review the empirical evidence on the geography of innovation and role of networks.

- *Weighting scheme and recipients of spillovers:* spillover benefits are sensitive to the choice of the weighting matrix used to aggregate external R&D capital. Ex-ante, it is not perfectly unambiguous which weighting matrix or combination of weighting matrixes would reflect the direction and intensity of R&D related knowledge flows across firms most realistically. Estimated rates of return to external R&D tend to be highly variable and depend, by construction, on the number and identity of spillover recipients accounted for in the econometric analysis.
- *Negative externalities:* the R&D investments of a given firm may impose positive externalities on other firms in form of knowledge spillovers but can also entail negative externalities which in the extreme case may outweigh the former.[18] Negative externalities, for instance, arise as other firms incur adjustment costs (Adams, 1990). To effectively employ a new technology, firms may need to invest in training or reorganise their production process. New technologies can also make competing products obsolete or less valuable leading to a decline in the price and/or demand for certain products. A negative externality may likewise come into bearing if the developed knowledge is not entirely new or unique and simply a substitute to already existing knowledge.

2.1.2 Cost functions (dual approach)

26. The cost function approach typically relies on a wider set of economic variables than the production function approach and it is implemented in the context of an optimisation framework. R&D returns are derived either through the minimisation of a cost function or maximisation of a profit or firm value function which integrates the cost function (CF) alongside a product demand function relating output price (P) to output (Q), the stock of knowledge (K) and other factors that potentially influence demand. The cost function (CF) itself specifies production costs as a function of output (Q), input prices (w, r_C, r_K), labour (L) and physical capital (C) inputs aside the own (K) and possibly external (K') knowledge stock.[19]

$$\text{CF:} = F(Q, w, r_C, r_K, L, C, K, K') \tag{6}$$

27. The dual approach can accommodate for multiple outputs, the adjustment process of quasi-fixed inputs to a long-rung equilibrium as well as financial and pricing decisions the latter of which determine price-mark ups. The set of endogenous variables (variable and quasi-fixed factor inputs) based on which the optimisation problem is solved hinges on the assumption about which factor inputs are likely to be variable (e.g. labour), quasi-fixed (e.g. R&D) or fixed. As identification in the given framework relies largely on the variation in factor prices and such information tends to be more readily available at industry and country level, the dual approach is often implemented based on industry or economy-wide data.

28. Empirical studies using the cost function approach employ a number of different functional forms and specifications outnumbering those found in the production function framework, which makes a comparison of results potentially more difficult. Depending on the functional form chosen, studies either derive a constant rate of return (e.g. translog function) or output elasticity (e.g. quadratic function). The private (net) return to R&D can be computed as estimated shadow price less depreciation and inflation (Hall et al., 2010), the former reflecting the utility of marginally increasing R&D inputs, i.e. relaxing the R&D input constraint. In the case of cost minimisation, the change in marginal utility can be linked to a change in marginal production costs and a price change if R&D also has demand effect.

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18. The empirical evidence generally speaks in favour of the relative dominance of positive R&D externalities (Griliches, 1992a and 2000). See Jones and Williams (2000) for a calibration exercise of private and social returns to R&D, exploring under which parameter constellation positive (negative) externalities dominate.

19. Bernstein (1989), Bernstein and Nadiri (991) and Rouvinen (2002), for instance, include a measure of external R&D capital stocks to account for the effect of knowledge spillovers.

2.2. Empirical implementation

29. Exploiting the cross-sectional variation in the levels of output, standard and R&D input measures and/or their temporal variation within a given unit over time, the empirical literature investigates the link between R&D, productivity and economic growth at firm, industry and country levels. Econometric studies give rise to three parameters indicating the economic impact of R&D: the output elasticity with respect to R&D (γ) and the private (ρ_p) and social (ρ_s) rates of return to R&D.[20] The R&D output elasticity specifies the percentage increase in output resulting from a 1-percent increase in R&D inputs, whereas rates of return to R&D denote the change in output caused by a one unit increase in R&D inputs.

2.2.1 Estimating R&D returns in the production function framework

30. A Cobb-Douglas model is widely used in practice to represent a production function that relates R&D capital (K) to economic output at firm, industry or country level, controlling for physical capital (C) and labour (L) inputs. The parameters A and u reflect technical progress and the error term respectively. The given model assumes a constant elasticity of output with respect to inputs (α, β, γ)[21] and a constant elasticity of substitution across them, assumptions that more general models of production functions relax.

$$Q = A\, L^{\alpha} C^{\beta} K^{\gamma}\, e^{u} \tag{7}$$

31. A log transformation is commonly applied to equation (7) to derive an estimate of the output elasticity with respect to R&D capital (γ_K). In equation (8), subscripts (i) and (t) refer to the unit of analysis and year, and the parameters μ_i and λ_t denote firm (industry or country) and year dummies respectively. The latter set of dummy variables usually replaces the term $\log(A)$, capturing the effect of technological progress. The literature estimates equation (8) using cross-sectional, time-series or pooled data on R&D and standard inputs aside an indicator of economic output or productivity such as TFP. The Cobb-Douglas specification may further be extended to gauge the effect of knowledge spillovers, i.e. to obtain an estimate of the elasticity of output with respect to both own (γ_K) and external ($\gamma_{K'}$) R&D capital.

$$\log(Q_{it}) = \alpha \log(L_{it}) + \beta \log(C_{it}) + \gamma_K \log(K_{it}) + \mu_i + \lambda_t + u_{it} \tag{8}$$

32. Hall et al. (2010) show that estimated elasticity of output with respect to own R&D capital (γ_K) is independent of the choice of depreciation rate and identical to the elasticity for (real) R&D investment (γ_R) under one specific condition: the growth rate (g_i) and depreciation rate (δ_i) of R&D capital are relatively constant over time and thus absorbed by firm, industry or country fixed effects.[22]

$$\gamma_K = \frac{\partial Q}{\partial K}\frac{K}{Q} \cong \gamma_R = \frac{\partial Q}{\partial R}\,\frac{R}{Q} \quad where\ K_{it} \cong \frac{R_{it}}{\delta_i + g_i} \ \rightarrow \log K_{it} = logR_{it} - \log(\delta_i + g_i) \tag{9}$$

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20. Before the capitalization of R&D in National Accounts, R&D expenditures were treated as expense rather than investment leading to a depreciable intangible asset that increases gross value added and gross output at the time of own account production or acquisition of R&D services. If the output measure excludes R&D capital, the estimated return to R&D accounts for both the private and social benefit from R&D. By contrast, if R&D as intangible asset is capitalized, the measured return will refer to the social return to R&D, and an excess return interpretation applies (Haskel and Wallis, 2010).

21. Researchers typically assume constant returns to scale (α =1-β) with respect to conventional inputs, which implies that output changes proportionally with changes in both labour and physical capital inputs.

22. The choice of depreciation rate alters results only little in the cross-sectional dimension (Hall et al., 2010).

33. Gross rates of return to R&D can in turn be obtained by multiplying the given R&D output elasticity estimate with the sample average output-to-R&D capital ratio, as illustrated in equation (10). Information on the depreciation rate (δ) of R&D capital is a pre-requisite for deriving the knowledge stock (K) created by R&D and the gross rate of return to R&D capital (Klette, 1994a and Hall et al., 2010). Also the net rate of return to R&D is inherently related to the depreciation rate of R&D capital as equation (10) highlights. Most econometric studies report gross rather than net rates of return to R&D capital.

$$\rho_P^{gross} \equiv \frac{\partial Q}{\partial K} = \gamma_K \frac{Q}{K} \; and \; \rho_P^{net} \equiv \gamma_K \frac{Q}{K} - \delta \qquad (10)$$

34. While the conversion of the output elasticity into rates of return and vice versa is in principle feasible, converted estimates may differ substantially from directly derived estimates depending on the sample characteristics. As a result of the highly skewed and concentrated distribution of R&D investments across firms, industries and countries (Hall et al., 2010), figures of average output-to-R&D capital ratios may turn out to be very large which immediately impacts converted rates of return to R&D. In some cases, it may thus be preferable to carry out an own estimation of private rates of return to R&D.

35. A further transformation (first differencing) and restatement of equation (8) in terms of growth rates is applied to directly derive an estimate of the private return to R&D. For brevity, subscripts and the error term are omitted. The time effect (λ) now represents a growth rate effect relative to the initial year.

$$\frac{\dot{Q}}{Q} = \alpha\frac{\dot{L}}{L} + \beta\frac{\dot{C}}{C} + \underbrace{\frac{\partial Q}{\partial K}\frac{K}{Q}}_{\gamma_K}\frac{\dot{K}}{K} + \lambda = \alpha\frac{\dot{L}}{L} + \beta\frac{\dot{C}}{C} + \rho\frac{\dot{K}}{Q} + \lambda \qquad (11)$$

36. By subtracting the terms related to the standard inputs from the left hand side of equation (11), an expression of TFP growth as a function of the net R&D investment-output ratio is obtained. If the rate of depreciation of the past period's knowledge stock is assumed to be negligible ($\delta = 0$), private rates of return to R&D can be estimated without employing a measure of the R&D related knowledge stock (K) as TFP growth is a direct function of the R&D intensity indicator. Equation (12) shows that the estimation of private rates of return to R&D involves only two steps in this specific case (b): the computation of TFP or an alternative productivity indicator (e.g. labour productivity) and the estimation of the TFP growth equation. The estimation of the latter requires data on TFP and R&D input for at least two reference years (periods) and can thus in principle be implemented using cross-sectional, time-series or pooled data.

$$(a)\frac{\dot{T}}{T} = \rho\frac{R^{net}}{Q} + \lambda = \rho\frac{R_t - \delta K_{t-1}}{Q} + \lambda; (b)\; \delta = 0\colon \frac{\dot{T}}{T} = \rho\frac{R_t}{Q} + \lambda \qquad (12)$$

37. The choice between estimating the output elasticity with respect to R&D vis-à-vis rate of return to R&D is implicitly linked to the assumption made about which of the two parameters is more likely to be constant across units. Hall et al. (2010) point out that output elasticity estimates tend to be more stable than those of rates of return to R&D. The authors attribute this phenomenon to the inherent uncertainty of R&D outcomes which among other factors such as changes in the intensity of competition, can lead to highly variable ex-post rates of return to R&D deviating strongly from those anticipated by firms ex-ante.

38. Similar to the derivation of the output elasticity to external R&D capital ($\gamma_{K'}$), rates of return to external R&D (ρ_{EXT}^{gross}) can be obtained by including an indicator of the external R&D intensity in the TFP growth equation. To account for the capacity of spillover recipients to absorb external knowledge, some studies also interact external R&D with the FDI, trade or own R&D intensity (Cohen and Levinthal, 1989; Coe and Helpman, 1995 and Griffith et al., 2004) or a measure of the recipient's distance to the technology

frontier. The sum of the private return to R&D and the knowledge spillover returns that other firms generate from external R&D investments reflect the social rate of return to business R&D. As aforementioned, the size of estimated knowledge spillover benefits is closely related to the number and identity of knowledge spillover recipients as well as the selected weighting matrix α_{ij}.

$$\rho_S^{gross} = \underbrace{\frac{\partial Q_{it}}{\partial K_{it}}}_{\rho_P^{gross}} + \underbrace{\sum_{j \neq i} \alpha_{ij} \frac{\partial Q_{jt}}{\partial K'_{jt}}}_{\rho_{EXT}^{gross}} \tag{13}$$

39. In the presence of predominantly positive knowledge spillovers, estimates of private returns to R&D should be expected to increase with the level of data aggregation. Industry-level estimates of private returns to R&D account in principle for domestic intra-industry, while those based economy-wide data account for inter-industry spillovers. In a similar vein, estimates of knowledge spillover and social returns to R&D possibly increase in the level of data aggregation and scope of spillovers measured. These observations highlight the importance of keeping in mind the unit of analysis when assessing the size of R&D return estimates.

2.2.2 Econometric challenges in measuring R&D returns

40. A number of econometric issues afflict the estimation of R&D output elasticity and rates of return to R&D (Griliches, 1987, 1994; Foray et al., 2009 and Hall et al., 2010). These relate to the sensitivity of estimates to outliers (Lichtenberg and Siegel, 1991) and other factors as summarised below.

- *Attenuation bias:* most of the variation in firm, industry or country level R&D data stems from the cross-sectional rather than time dimension. Hence, it may be difficult to identify a significant impact of R&D on economic growth solely based on the within-unit (temporal) variation in the data. Also, measurement error typically induces a larger attenuation bias in the within (time) dimension (Griliches and Mairesse, 1984 and Griliches and Hausman, 1986).
- *Lagged effects*: the impact of R&D on economic performance may materialise only with some time lag and possibly even longer lags persist until knowledge spillover effects bear fruit (Griliches, 1995). Dynamic econometric models can help identify the long-run effects of R&D investments. Given the limited availability of long time-series, studies may be forced to adopt contemporaneous rather than lagged stocks of R&D related knowledge capital, however. This may potentially understate the full effect of R&D on economic growth in the long-run.
- *Selection bias*: If the employed data sample consists, for example, merely of R&D performers or firms in specific scientific sectors, the concern might be raised that the given sample represents a non-random group of firms whose special, unobservable characteristics are possibly correlated with firm performance and growth. This correlation in turn may lead to a bias in estimates unless researchers resort to advanced econometric models that tackle selection bias, e.g. the Heckman selection model (Heckman, 1979) or Roy Model (Roy, 1951).
- *Endogeneity bias*: the omission of other determinants of productivity and economic growth can lead to a bias in estimates if those factors are correlated with R&D. Possible co-founding factors include management skills, sector-specific technical opportunity and macro-economic conditions. The use of firm, industry and country dummies (and combinations thereof) can help account for such factors as long as the latter change only little over time. Autonomous technological change can be captured by time dummies or a time trend. The use of industry (e.g. Odagiri and Iwata, 1986) and time dummies in the TFP equation typically reduces the size and significance of the estimated rate of return to R&D.

- *Simultaneity bias*: output and input choices are co-determined. Studies establish a correlation between R&D and economic growth, yet not its causal impact, unless they tackle the endogeneity of R&D inputs. While the use of lagged input variables can help mitigate simultaneity concerns to some extent, instrumental variable or Generalized Method of Moments (GMM) estimators (Arrelano and Bond, 1991 and Blundell and Bond, 1998) address endogeneity issues directly.
- *Expensing bias*: if R&D is expensed and not capitalised, value added as a measure of output may not include net R&D investment – the value of R&D expenditures less depreciation. This in turn will lead to an expensing bias. Schankerman (1981) shows that the effect of this bias depends on the evolution of the R&D intensity, and can go in either direction.
- *Multi-collinearity*: R&D and physical capital stocks are highly correlated, especially in the time dimension. This can make it difficult to identify a statistically significant effect of R&D. Due to multi-collinearity, estimates may also not be very stable from one specification to another.
- *Cyclical noise and measurement error*: first differencing wipes out permanent differences across units (e.g. firms) but leaves cyclical noise and measurement error in the data. Long differencing over 5 or 10 years or the use of a variable reflecting the rate of capacity utilisation helps remove cyclical noise (Hall et al., 2010). The use of long versus first-differencing may also increase the level of significance with which output elasticities are estimated (Hall and Mairesse, 1995).

3. Review of main findings

41. The body of empirical research on the impact of R&D on economic growth dates back to the early work of Griliches, Minasian and Mansfield in the late 50s, and has steadily been growing ever since. Econometric work has generally confirmed the positive impact of R&D on productivity and economic growth, yet there is a large variation in estimated R&D impacts. Aside from technical aspects related to measurement and estimation – for instance, the inclusion of additional innovation input measures such as human capital and ICT –, econometric studies show that this variation can in parts also be linked to firm and industry and country characteristics and the type of R&D undertaken (e.g. basic vs. applied research).

3.1 R&D output elasticity

42. Firm and industry level studies account for the majority of R&D output elasticity estimates, most of which prove to be statistically significant. According to the survey by CBO (2005), output elasticity estimates based on firm-level data range from about 0.05 to 0.60, whereas those based on industry or sectoral data vary between zero and 0.50. R&D output elasticity estimates drawing on economy-wide data similarly span a wide range from zero to more than 0.60, the central tendency being near to 0.10. **Table 1** contains some additional statements about the size of R&D output elasticity estimates, as found in preceding literature surveys. The fact that R&D output elasticity estimates typically range from 0.10 to 0.20 speaks in favour of a positive relationship between R&D, productivity and output growth.

Table 1. Statements about the size of the R&D output elasticity in previous literature reviews

R&D output elasticity	• The elasticities of R&D at firm level tend to be around **0.1-0.3** (…) and range between **0.08-0.3** at industry level (Nadiri, 1993). • Estimates of the R&D elasticity […] range from about 0.05 to 0.60 for studies that used [firm data] and from zero to 0.50 for studies that used [industry or sector data] (…) The central tendency runs from about **0.10 to about 0.20** (CBO, 2005). • Elasticities of R&D from economy-wide studies are in the same range as or perhaps a bit larger than those from the micro-based estimates. The central tendency is **near 0.10**, but like the elasticities from the micro-based studies, they span a wide range, from roughly **zero to more than 0.60** (CBO, 2005). • [At firm-level], the associated (…) median (mean) elasticity is **0.10 (0.13)** (Wieser, 2005) • Figures for research elasticity ranging from **0.01 to 0.25** but centered on **0.08** or so (Hall et al. 2010)

Source: OECD.

43. The existing econometric evidence further suggests that output elasticities vary across different sets of firms and countries. The seminal study by Patel and Soete (1985), for instance, uncovered a significant variation in the R&D output elasticity across countries over the period 1963-1982. The authors found a very high and significant elasticity for Japan and Germany (0.25-0.30), a lower but significant elasticity for France (0.10-0.15) and an insignificant output elasticity estimate for the United Kingdom. Coe and Helpman (2009) show that institutional differences shape the degree to which countries benefit from their own as well as external R&D investments via international knowledge spillovers. The elasticities of output to own (0.169) and external (0.087) R&D estimated for countries where the quality of tertiary education system is high – among the top third of the 24 countries – exceed those found – 0.068 and 0.04 respectively – for countries that rank lower on this category. A similar case is made for countries where the ease of doing business is on average ranked high (top third) along 10 dimensions, including the start and closure of a business, employing workers and getting credit (World Bank, 2007).

44. The firm-level evidence on the magnitude of the R&D output elasticity by firm size is less clear cut. Employing a sample of large electronics firms listed on the Taiwan stock exchange from 1994-2000, Wang and Tsai (2004) derive an output elasticity of around 0.19, yet find no support for the Schumpeterian hypothesis according to which the economic impact of R&D – as measured by the R&D output elasticity – is an increasing function of firm size. Kafouros (2005) similarly identifies elasticities of rather similar size for large and small firms (0.044 vs. 0.035), using firm data for the UK manufacturing sector (1989-2002). Re-examining the impact of R&D among Taiwanese firms in the manufacturing and electronics industries, Tsai (2005) and Wang and Tsai (2005) identify a "U-type" relationship between the R&D output elasticity and firm size. The study by Kafouros (2005) further uncovers a higher economic impact of R&D among high-tech firms. Only for those firms he identifies a statistically significant R&D output elasticity of 0.11.

3.2 Private rates of return to R&D

45. Private rates of return to R&D (gross of depreciation) obtained from industry, firm and plant level studies have been found to be of similar magnitude[23], ranging from zero to nearly 0.60, depending on the particular specification, time period and data sample chosen (CBO, 2005).[24] **Table 2** highlights some statements made by preceding literature surveys on the magnitude or private rates of return to R&D. Overall, these statements suggest that gross rates of return to R&D tend to be higher than rates of return to ordinary capital investments, the former centring between 0.20 and 0.30.

23. Empirical studies adopting the cost function approach (e.g. Mohnen et al., 1986; Bernstein, 1988, 1989; Bernstein and Nadiri, 1988, 1991 and Mohnen and Lépine, 1991) find similar private rates of return to R&D, ranging from 0.10 to 0.20.

24. In the presence of knowledge spillovers, it is rather counterintuitive to observe similar rates of returns to R&D at firm, industry and country level. Griliches (1992) explains that this result is related to the use of similar depreciation rates in studies independent of their level of aggregation and the fact that gross rates of return contain a depreciation component. He notes that the "relevant private rate of depreciation of R&D stock at the firm level is potentially much higher than what is likely to prevail at the overall industry level".

Table 2. Statements about the size of (gross) private rates of return to R&D in previous literature reviews

Private return to R&D	• (…) rates of return to own R&D **are** about **20-30%** at firm level and range between **20-40%** at industry level (Nadiri, 1993). • The range of estimates of the rate of return to R&D runs from **zero to nearly 0.60**, with a central tendency between **0.20 and 0.30** (CBO, 2005). • Private rates of return average from **20 to 30%** (Fraumeni and Okubo, 2005). • The reported private rates of return [at firm level], if significant, are in a range of **7-69%,** and the elasticities are in a range of 0.03–0.38. The associated median (mean) rate of return **is 27% (28%)** (Wieser, 2005). • R&D rates of return in developed economies during the past half century have been strongly positive and may be as high as **75%** or so, although they are more likely to be in the **20–30%** range. (Hall et al., 2010)

Source: OECD.

46. The econometric evidence put forward further suggests that rates of return to R&D vary notably across different groups of firms, depending on firm characteristics such as industry affiliation, firm size, technology and export orientation. A number of studies find that companies in “scientific” or “research-intensive” industries, such as chemicals, pharmaceuticals and computers produces, enjoy higher rates of return to R&D investments than firms in non-scientific sectors (Odagiri, 1983; Cunéo and Mairesse, 1984; Griliches and Mairesse, 1984; Sassenou, 1988 and Ortega-Argilés et al., 2010). Doraszelski and Jaumandreu (2013) attribute this variation in R&D returns to the degree of uncertainty in the outcome of the R&D process and required risk premium across different industries.[25] Based on an unbalanced panel of more than 1800 Spanish manufacturing firms in nine industries during the 1990s, they observe a significant variation in gross rates of return to R&D across industries, ranging from 0.51 to 1.1.

47. New insights into the magnitude of private rates of return to R&D by firm size, technology and export orientation is brought forward by Kwon and Inui (2003) and Aw et al. (2014). Kwon and Inui (2003), investigating the R&D returns of panel of Japanese manufacturing firms over the period 1995-1998, find that higher rates of return to R&D accrue to large (0.16) vis-à-vis medium-sized and small enterprises (0.02-0.03). Furthermore, Kwon and Inui (2003) observe higher private returns to R&D among high-technology firms. Using data for Taiwanese manufacturing plants in the electronics products industry for the period 2000-2004, Aw et al. (2014) assess the feedback effects between productivity, R&D investments and exporting. The authors find that R&D returns increase with the current and expected future productivity of firms with the latter being positively affected by R&D which in turn reinforces the selection-process into R&D. No such feedback effects are found for R&D and exporting.

48. Econometric studies distinguish among various types of R&D investments when assessing the economic impact of R&D. Commonly used dichotomies include privately vs. publicly-financed R&D, R&D performed by business vs. government and higher education, basic research vs. applied research and development, short-term vs. long-term research and product vs. process R&D. **Box 2** highlights some of the key findings obtained in the literature. While measurement challenges reportedly complicate the more disaggregated analysis of R&D returns by type of R&D investment, the existing evidence suggest that at least some of the variation in private rates of return can be attributed to the type of R&D undertaken.

25. Doraszelski and Jaumandreu (2013) measure the degree of uncertainty by the ratio of the variance of the productivity innovation to the variance of actual productivity. This ratio shows that the unpredictable component accounts for a large part of productivity, between 25% and 75%. Rather than constructing the knowledge stock resulting from R&D investments, Doraszelski and Jaumandreu (2013) estimate a dynamic endogenous model of productivity change in which productivity is assumed to be unobservable.

Box 2. Economic impacts of R&D by type of R&D

Privately and publicly-funded R&D: Terleckyi (1980), Griliches-Lichtenberg (1984) and Lichtenberg and Siegel (1991) find high private returns to company-financed research but no significant effect for federally-funded R&D. In contrast, Bönte (2003) estimates rates of return to federally and industry financed R&D of similar size, using data for the US nonfarm business sector for the period 1956 to 1999. Other studies that assess the size of private rates of return to publicly-funded R&D include Leonard (1971), Goldberg (1979), Seldon (1987), Griliches (1986), Nadiri and Mamuneas (1994), Lichtenberg (1993) and Park (1995). Scotchmer (2004) summarizes the evidence as follows: "the measured impact of public R&D spending on private indicators of value is, as expected, smaller than that of private R&D spending. In fact, many studies find no measurable effect at all." This result does not necessarily imply that public R&D is productivity or growth enhancing. Rather it relates to the lack of appropriate price deflators that help distinguish between real output and price effects in industries with relatively high levels of publicly-financed R&D (Griliches, 1979).[26]

R&D performed by the private, government and higher education sector: Guellec and van Pottelsberghe (2004) find that the impact of public R&D on TFP growth has decreased in a sample of 16 OECD countries from 1980 to 1998 in contrast to the effect of business R&D which has increased over the given time period. The authors conclude that R&D performed in public institutions has nevertheless a large effect on productivity growth, even though its impact is likely to vary greatly across different countries. Haskel et al. (2014) identify statistically significant and positive private returns to R&D performed by the public sector. Estimated rates of return to public R&D vary largely across industries depending on the level of R&D performed by industries (absorptive capacity) and the level of cooperation with universities. Haskel et al. (2014) use data for 6 UK industries covering the period 1995-2007. Early work by Adams (1990) also points to a positive link between academic research and productivity growth in US manufacturing industries. Geographical and technological proximity between firms and academic institutions has been shown to enhance the link between university research, private innovation and economic performance (Adams and Jaffe, 1996).

Basic research, applied research and development: Employing firm-level data, Mansfield (1980), Link (1981), Griliches (1986) and Lichtenberg and Siegel (1991) provide evidence of a productivity "premium" on basic research, i.e. they find greater private rates of return to basic research than applied research or development. Lichtenberg and Siegel (1991) estimate a rate of return of 1.34 to investment in basic research which is "significantly lower than Mansfield's (1980) estimate of 1.78 and Link's (l981) estimate of 2.31". Recent empirical studies confirm this "premium" on basic research (Khan and Luintel, 2010b and Czarnitzki and Thorwarth, 2012). Using Belgian R&D survey data from 2002 to 2007, Czarnitzki and Thorwarth (2012) identify such a premium only for firms in the high-tech sector, however. A priori, it is not perfectly unambiguous why there would be a stronger relationship between basic research and productivity, in particular as applied research and development tend to be more market-oriented.

Short and long-term research: Mansfield (1980) explains that the distinction between basic research and applied research is not necessarily straightforward, and that basic research may merely be a proxy for long-term R&D, whereby industries that carry out large amounts of long-term R&D typically experience relatively higher rates of productivity increases. Controlling for the magnitude of basic and applied R&D expenditures, Mansfield (1980) finds a positive relationship between long-term research and productivity at firm level, whereby the measured effect of basic research becomes smaller and statistically insignificant in some econometric specifications.

Product and process R&D: R&D can be distinguished as to whether it is directed towards the creation of new and improved goods (product R&D) or the invention of new methods of production (process R&D).[27] Studies that were apt to classify R&D data into process and product expenditures find a higher private rates of return for process vis-à-vis product R&D (e.g. Clark and Griliches, 1984, Griliches and Lichtenberg, 1984a; Link, 1982; Terleckyj, 1980; Scherer, 1982, 1984; Hanel, 1994, 2000 and Medda et al., 2003). Clark and Griliches (1984) attribute this result to adjustment and set up costs of introducing new products. Hall et al. (2010) further note that "the effects of product R&D are difficult to measure because of the poor reflection of quality improvements in price indices". Also, "the two types of R&D are difficult to disentangle and to a certain extent they are complementary."

3.3 Social rates of return to R&D

49. A growing number of studies gauges the economic impact of business R&D within and across industry and national borders (**Annex 1**) in order to obtain an estimate of the implied knowledge spillover benefits and social return to R&D. Eberhardt et al. (2013) show that for a consistent estimation of private returns to R&D it is essential to account for the impact of knowledge spillovers. Econometric studies

26. Hall (1996) discusses the challenges in measuring the private returns to public R&D. Salter and Martin (2001) review the empirical evidence on the economic benefits of publicly funded basic research.

27. Levin and Reiss (1988) develop a theoretical model to show that that process and product R&D can be substitutes or complements depending on the relative size of process and product spillovers and technological opportunity. Their empirical results confirm that differences in technological opportunity affect the resources committed to both process and product R&D.

usually find evidence in support of substantial domestic knowledge spillovers both within and across industries. The evidence base on the relevance of international knowledge spillovers[28] is comparatively thinner and its findings less clear-cut. Not all studies find statistically significant returns to external R&D investments made by other countries (e.g. Lichtenberg, 1993), and those that do, observe a large variation in the size of international spillover benefits. Estimates of social returns to R&D generally exhibit a greater variation than those of private returns, and can range from zero to more than 1. Knowledge spillovers reportedly account for roughly three-fifth of the total return to R&D to society (Sveikauskas, 2007).

50. **Table 3** presents some additional statements on the magnitude of social rates of return to R&D, as found in preceding literature surveys. While these statements are generally supportive of the view that social returns to R&D are substantial, researchers typically urge caution in interpreting these highly variable estimates. Given the large challenges in measuring knowledge spillovers, and international knowledge spillovers in particular, such estimates are likely not to reflect the exact and full return to business R&D investments (Griliches, 1995). Asides from possible differences in the measurement of knowledge spillovers and econometric model, variations in time, industry and country coverage are likely to cause some of the variability in econometric estimates found across studies.[29]

Table 3. Statements about the size of (gross) social rates of return to R&D in previous literature reviews

Social return to R&D	• The spillover effects of R&D are often much larger than the effect of own R&D at the industry level. The indirect and social rates of return often vary from **20 to 100** with average of **50%.** (Nadiri, 1993). • Social rates of return, which include the spillover benefits, are much higher, ranging from an average lower bound of about **30%** to an average upper bound of **80%** (Fraumeni and Okubo, 2005). • The evidence and suggests the private return to R&D is 25 percent, while the social return is **65%**. Spillovers account for roughly **three-fifths** of the social return to R&D (Sveikauskas, 2007) • As to social returns, these are almost always estimated to be substantially greater than the private returns, and often to be quite asymmetric among trading partners and industries. (Hall et al., 2010)

Source: OECD.

3.3.1 Domestic knowledge spillovers

51. Empirical results from firm and industry level studies speak in favour of significant domestic knowledge spillovers exist across firms both within (e.g. Bernstein, 1988 and Rouvinen, 2002) and beyond industry borders. Goto and Suzuki (1989) and Wolf and Nadiri (1993) show that knowledge spillover benefits are greater in industries that are technically related.[30] The existing firm-level evidence further suggests that knowledge spillover benefits depend on business characteristics such as firm size, R&D intensity and use of advanced technologies, but also on the type of innovation induced by R&D. Recent empirical work based on industry and economy-wide data in turn provides first insights into the magnitude of spillovers from R&D and non-R&D related intangible investments and the role of ICT investments.

28. For a survey of work on international R&D spillovers and their relevance for economic growth, see Cincera and van Pottelsberghe (2001) and Mohnen (2001).

29. Social rates of return to R&D reported for the United States, for instance, vary between 51-76% for the period 1966-1977 (Griliches, 1986) and 11-111% for the period 1958-1981 (Bernstein and Nadiri, 1988).

30 . Jaffe et al. (1993) show that knowledge spillovers measured through patent citations are geographically localized, i.e. technology related firms affect other firms' productivity most.

52. Using panel data on US firms over the period 1981-2001, Bloom et al. (2013), for instance, attest the presence of technology spillovers in all sectors but find significantly lower social returns to R&D for small firms as they tend to operate in technological niches in which technological spillovers are limited.[31] Beneito (2001), investigating the R&D-productivity link in a panel of Spanish manufacturing firms over 1990-1996, finds that firms using advanced technologies as well as those whose R&D intensity ranks in the intermediate range experience larger productivity gains from external R&D. Ornagi (2006), modelling the productivity (demand) effect of R&D as a function of the R&D related knowledge capital activated through process (product) innovations[32], finds in turn that the average gap between private and social rates of return is larger for product than for process innovations. Put differently, knowledge spillovers play a more significant role in facilitating quality as opposed to productivity improvements.[33] The results are based on a sample of Spanish manufacturing firms captured over the period 1990-1999.

53. Haskel and Wallis (2010, 2013), using intangible capital investment data for the UK market sector from 1988-2004, yield evidence of significant spillovers returns from public R&D investments (research council funding), however not from private sector intangible capital investment, including R&D. Goodridge et al. (2012), by contrast, find statistically significant spillovers from both R&D and other non-R&D related intangible investment based on industry-level data covering seven UK industries from 1992-2007. Examining the magnitude of knowledge spillovers effects in ten EU member states over 1998-2007, Corrado et al. (2014) similarly find statistically significant returns from R&D and non-R&D intangible capital. The authors further identify a complementarity between ICT and intangible capital, the returns to a country's investments in intangible capital being stronger in ICT intensive industries.

3.3.2 International knowledge spillovers

54. Less developed countries and smaller R&D performers are typically found to benefit more from external R&D capital (Soete and Verspagen, 1993; Park, 1995; Coe et al., 1997; Del Barrio-Castro et al., 2002; Khan and Luintel, 2004; Frantzen, 2002 and Griffith et al., 2006b), whereby trade is found to play a crucial role in facilitating international spillovers (Coe and Helpman, 1995; Coe et al., 1997; Xu and Wang, 1999; Keller, 1998, 2002b; van Pottelsberghe and Lichtenberg, 2001; Falvey et al., 2004; Abdelmoula and Legros, 2009 and Bianco and Niang, 2012).[34] Depending on the knowledge absorption capacity[35] of the receiving country, foreign R&D may even have a larger effect on productivity and growth than own R&D investment (Soete and Verspagen, 1993 and van Pottelsberghe and Lichtenberg, 2001).

31. The authors primarily assess the size of technology spillovers relative to the product market rivalry (crowding out) effect of R&D and find that the former quantitatively dominates the latter such that gross social returns to R&D are at least twice as large as private returns.

32. Ornagi (2006) models product (process) innovation-related knowledge capital as a function of past R&D expenditures which only have an economic effect in years of product (process) innovations. Else, past R&D is not in operation and the value of knowledge capital remains unchanged (no depreciation).

33. The empirical literature measuring the impact of innovation of productivity generally finds substantial returns to product innovation. The empirical evidence on the productivity effect of process innovations is mixed. For a literature survey, see Hall and Mohnen (2013).

34. Both imports and exports are found to be conduits for knowledge spillovers (see Falvey et al., 2004). Ang and Madsen (2013) show that knowledge spillovers from R&D, transmitted through the import channel have had a particularly large impact on the total factor productivity of six Asian economics (China, India, Japan, Korea, Singapore, and Taiwan) over the period 1955-2006.

35. The ease with which firms or countries absorb spillovers depends inter alia on factors such as R&D intensity (Cohen and Levinthal, 1989; Beneito, 2001; Frantzen, 2002 and Griffith et al., 2004) and level of education (Verspagen, 1995 and Coe et al., 2009).

Recent econometric studies also account for the role of human capital and ICT investments[36], when estimating the impact of international knowledge spillovers.

55. Seminal work by Coe and Helpman (1995) estimates a social rate of return of 1.55 to external R&D investments in G7 countries, which is 0.30 percentage points higher than the return to their own R&D investment. The authors later on received some criticism for their approach of weighting and estimating the effect of foreign R&D (Keller, 1998 and Kao et al., 1999). The importance of trade as conduit for international knowledge spillovers was nevertheless confirmed in subsequent econometric work. Xu and Wang (1999), for instance, show that the effects of R&D spillovers from trade in capital goods are robust to the inclusion of unweighted and distance-weighted external R&D capital stocks. Abdelmoula and Legros (2009) similarly find that trade-related R&D spillover effects among 57 EU regions are robust to the introduction of spatial correlation variables in the TFP regression, the latter denoting the geographical distance between the given set of regions.

56. Among the studies covered, the statistical significance of own and foreign R&D effects proves to be relatively robust to the inclusion of measures of human and ICT capital. The magnitude of the estimated R&D impacts tends to decrease, however. Coe et al. (2009), for instance, find that the impact of own and foreign R&D capital on TFP is robust to the inclusion of a measure of the stock of human capital in their econometric model.[37] Frantzen (2000), using cross-sectional data for 21 OECD countries from the early 1960s to early 1990s, similarly identifies a significant productivity impact for domestic and foreign R&D aside the measure of human capital. The author also observes that these two types of investments are highly complementary. Del Barrio-Castro et al. (2002) find that the productivity enhancing effect of human capital reduces the estimated effect of domestic and foreign R&D to a greater extent than previously reported (Engelbrecht, 1997). The authors employ novel data on average years of schooling in 21 OECD countries and attribute this result to improvements in the quality of data on human capital.

4. Exploratory meta-analysis

57. A meta-analysis has been carried out within this study to test to what extent empirical findings are related to the methodological aspects covered in Section 2 aside factors such as unit of analysis, time coverage and the inclusion of a measure of human capital in the econometric model. The meta-analysis comprises a descriptive overview of the scope of the empirical work over time and a regression analysis of the main patterns in estimated R&D returns, exploiting recent, hand-collected estimates of R&D returns.

4.1 Descriptive meta-analysis

58. The descriptive analysis draws upon 216 peer-reviewed articles and selected economic research working papers published from 1958-2014, exploring the economic impact of business R&D investments. **Annex 1** presents a timeline of the empirical publications captured by this survey, providing some basic information on country, industry and time coverage and the type of spillovers explored by studies.

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36. Using industry-level input, output and TFP data from the EU KLEMS database, Inklaar et al. (2007) find that increased investment in ICT capital and growth in human capital contributed substantially to labour productivity growth in market services across all European countries and the US over 1980-2004.

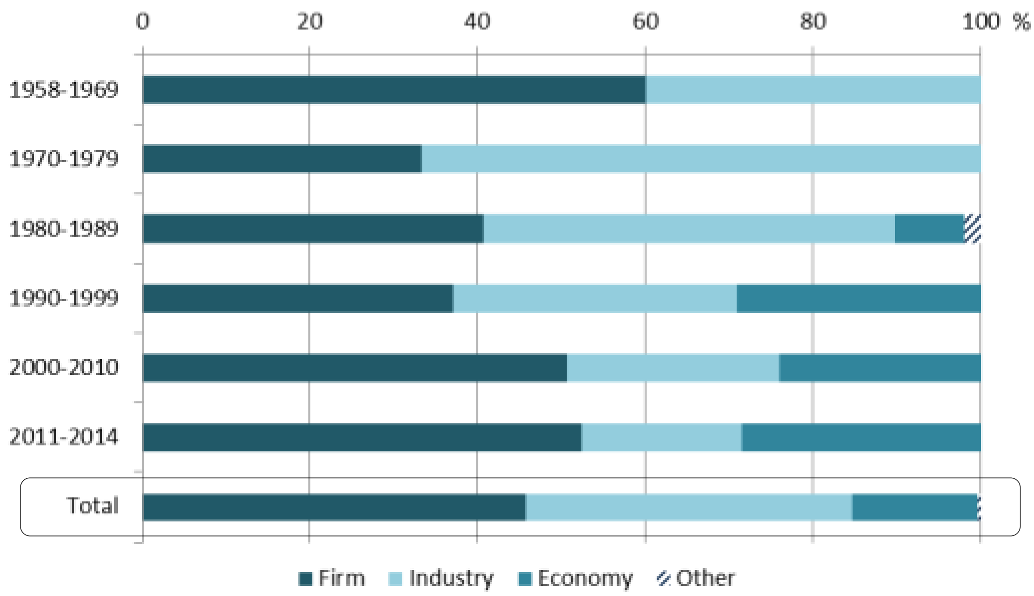
37. Bianco and Niang (2012), using panel data for 24 OECD countries (1971-2004), confirm the results of Coe et al. (2009) and identify substantial cross-country spillovers related to R&D and human capital.

4.1.1 Full set of econometric publications (1958-2014)

59. The first set of descriptive statistics presented in this section exploit information on each study's unit of analysis, country and time coverage. This information was collected for the full set of 216 empirical papers published between 1958 and 2014. A number of findings are worth noting. As **Figure 1** shows, early empirical work relied exclusively on firm and industry level data for the estimation of R&D returns. Based on the results from our search, the first macro analyses using economy-wide data become more common during the 1980s, but most papers continued to be accounted for by industry and firm-level studies. Many of these empirical investigations target the manufacturing sector (see **Annex 1**). More than 20 years ago, Griliches (1992b) attributed this phenomenon to the fact that outputs and prices in manufacturing are more easily measured than those of service industries.

Figure 1. Unit of analysis in empirical literature on economic impacts of R&D

Percentage of firm, industry and country level studies by decade of publication



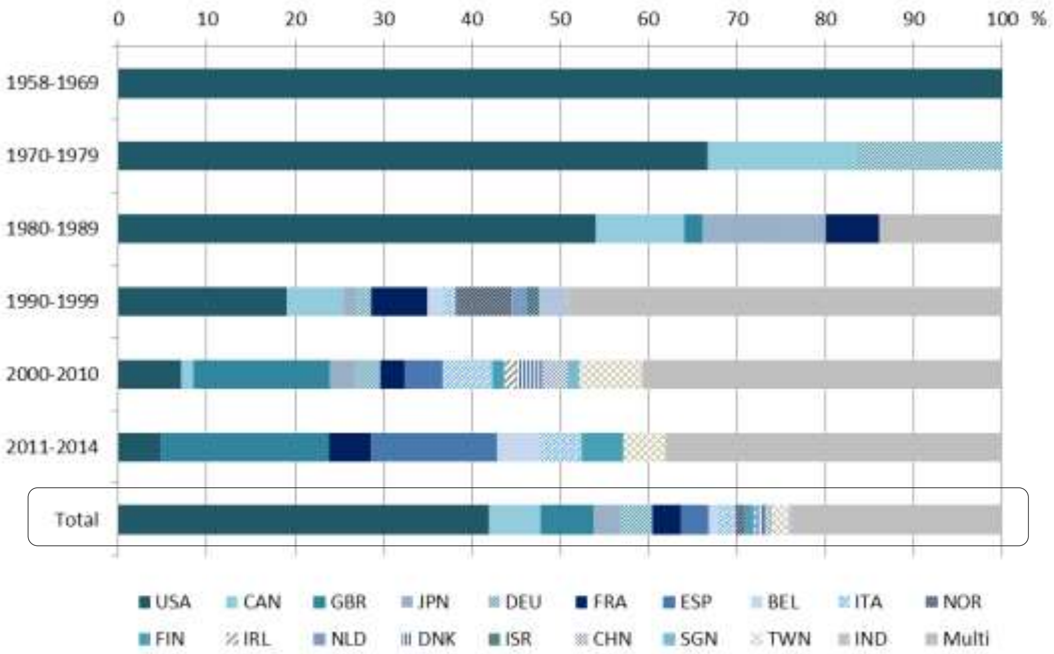
Source: OECD, own calculations based on a survey of peer-reviewed articles and selected economic research working papers on the impact of R&D on productivity and economic growth, as published over 1958-2014.

Notes: Firm as a unit includes plant and business unit, economy comprises region and other refers to state and technological clusters.

60. **Figure 2** further suggests that early empirical work up to the 1980s was predominately focused on the United States and Canada. Multi-country studies began to arise in this period as well and have become an integral part of recent empirical work ever since – approximately 40% of publications published from 2000-2010 cover at least two different countries. Multi-country data allow researchers to explore the extent of international knowledge spillovers. The timeline in **Annex 1** shows that studies have increasingly investigated the role of international spillovers since the 1990s.

Figure 2. Country coverage in empirical literature on economic impacts of R&D

Percentage of single and multi-country studies by decade of publication



Source: OECD, own calculations based on a survey of peer-reviewed articles and selected economic research working papers on the impact of R&D on productivity and economic growth, as published over 1958-2014.

Notes: Selected countries (e.g. USA, CAN, GBR, JPN, DEU and FRA) are covered in both single and multi-country studies.

61. Summary statistics by study vintage for the first and last year of analysis as well as the length of the estimation period are displayed in **Table 4**. As it can be expected, more recent studies use more recent data but the mean (median) estimation period covered by studies has stayed fairly constant over time at around 16 (14) years. This may indicate that previous data may not have existed in a form that could be used according to the study's methodology, for example, if no records existed for all countries in a more recent multi-country study, or if available series have significant breaks or records are not digitised. More sophisticated and recent studies may thus be constrained to use more recent, comprehensive databases.

Table 4. Time coverage in empirical literature on economic impacts of R&D

Data vintage and time coverage by decade of publication

Publication		First year analysis				Last year analysis				Estimation time period (in years)			
Time span	**N**	**Min**	**Mean**	**Med**	**Max**	**Min**	**Mean**	**Med**	**Max**	**Min**	**Mean**	**Med**	**Max**
1958-1969	5	1910	1940	1947	1949	1955	1958	1957	1962	10	19.0	11	46
1970-1979	6	1948	1957	1958	1963	1963	1968	1967	1975	1	12.5	15	19
1980-1989	50	1947	1965	1965	1978	1963	1978	1978	1985	1	14.0	13	31
1990-1999	63	1947	1971	1971	1996	1966	1987	1988	1996	1	16.7	16	32
2000-2010	71	1955	1982	1985	2002	1983	1997	1997	2006	1	16.3	14	46
2011-2014	21	1955	1990	1995	2005	1999	2005	2006	2009	3	16.3	12	52
Total	**216**	**1910**	**1974**	**1972**	**2005**	**1955**	**1989**	**1990**	**2009**	**1**	**15.9**	**14**	**52**

Source: OECD, own calculations based on a survey of peer-reviewed articles and selected economic research working papers on the impact of R&D on productivity and economic growth, as published over 1958-2014.

4.1.2 Selected set of econometric publications (2000-2010)

62. The second set of descriptive statistics draws upon more recent estimates of output elasticity and rates of return to R&D as published in overall 66 econometric studies over the preceding decade (2000-2010). They thus complement the existing evidence on R&D returns provided by preceding surveys (**Annex 1**). All of the covered studies, except for one[38], rely on the estimation of an augmented production function adopting a measure of R&D input.[39] The following descriptive statistics for R&D output elasticity and private and social rates of return to R&D are exclusively based on estimates that are statistically significant at a 10% level. Converted estimates of rates of return to R&D have further been censored at 0.3[40] given the widely-held view in the literature that private rates of return range between 0.2 and 0.3 (**Table 2**) and the notion that conversions of output elasticity estimates are only feasible to the extent that the necessary sample characteristics prevail (Hall et al., 2011).[41] **Annex 2** reports summary statistics for the output elasticity and rate of return figures, highlighting the number of estimates and articles that contribute to each of the presented R&D impact indicators.[42]

63. **Figure 3** shows that output elasticity estimates from firm, industry and country-level studies gravitate around 0.1 and thus fall in the conventional range in terms of their size (**Table 1**). Both mean and median output elasticity figures, indicated by the plus sign and vertical band in the box plot respectively, centre on 0.1. The observation that elasticity estimates from industry-level studies tend to be quite close to those based on firm[43] data has been made earlier in the literature. The same seems to apply for output elasticity estimates based on economy-wide data. Across all levels of analysis, there is a notable variation in output elasticity estimates, as indicated by the width of the box plot reflecting the distance between the first and third quartile of the distribution (interquartile range). The ends of the whiskers represent the lowest and highest data points that are still within the 1.5 interquartile range of the first and third quartile respectively. Points below or above the whiskers are classified as outliers. Negative output elasticity estimates indicate that increases in R&D are associated with a reduction in output. This may be related to adjustment costs or the inability of R&D performers to successfully implement new knowledge in their production processes. Given their low frequency (3%), such estimates do certainly not represent the norm.

38. Anon-Higon and Manjón-Antolín (2007) derive estimates of the private return to R&D using the Levinsohn-Petrin-Doraszelski-Jaumandreu (LP–DJ) procedure which does not rely on a measure of R&D input. For further information on the LP–DJ procedure, see Doraszelski and Jaumandreu (2013).

39. The meta-analysis excludes overall five studies: three studies resorting to the cost function approach (Rouvinen, 2002; Bernstein and Mamuneas, 2006 and Lang, 2009) and two book publications with no free online access (O'Mahony and Vecchi, 2000 and Sveikauskas, 2000).

40. 89 out of the 194 significant rates of return estimates are based on an output elasticity estimate. Hall et al (2010) similarly note that most rate of return estimates reported in their survey rely on a conversion.

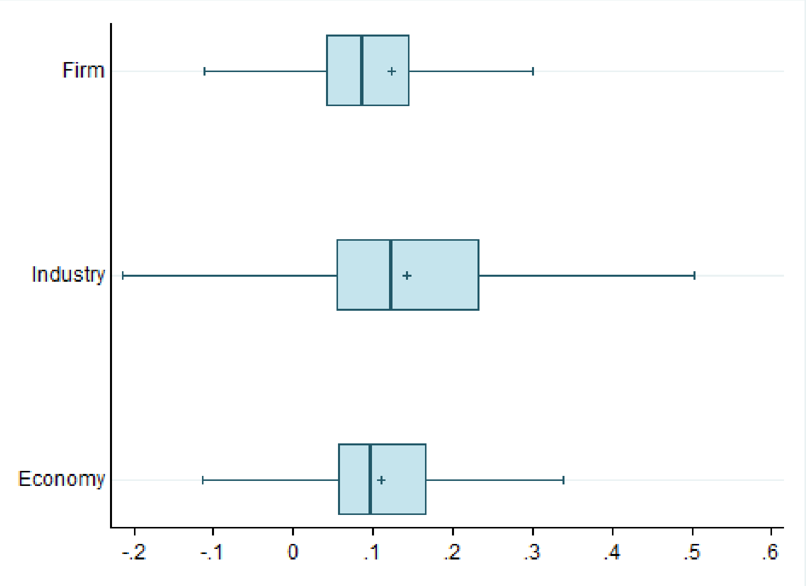
41. Very high average output-to R&D ratios resulting from the often highly skewed distribution of R&D investments in samples, can lead to disproportionally large converted estimates of rates of return to R&D (see equation 10). The descriptive analysis excludes 55 out of 89 converted estimates of private rates of return to R&D. Summary statistics are fairly robust to the use of a higher threshold value of 0.6, leading to the exclusion of 31 converted estimates. The results can be obtained from the author upon request.

42. A comparison of summary statistics for the selected and full set of estimates (Table A3.2 and Table A3.3 Annex 3) reveals that output elasticity statistics are relatively unaffected by the exclusion of insignificant estimates, while private rate of return statistics – not surprisingly – display lower impacts once insignificant and converted estimates above the 0.3 threshold value are excluded from the analysis.

43. Estimates from firm and plant level studies have been pooled. Hall et al. (2010) point out that "plant or establishment data produce results similar to those obtained with firm data, not surprisingly, since they are invariably forced to use firm-level R&D data due lack of disaggregated data on R&D. Given the presence of "within firm" spillovers, it is not even clear that disaggregation would be useful."

Figure 3. R&D output elasticity estimates by unit of analysis

Rate of change in output (in percent)

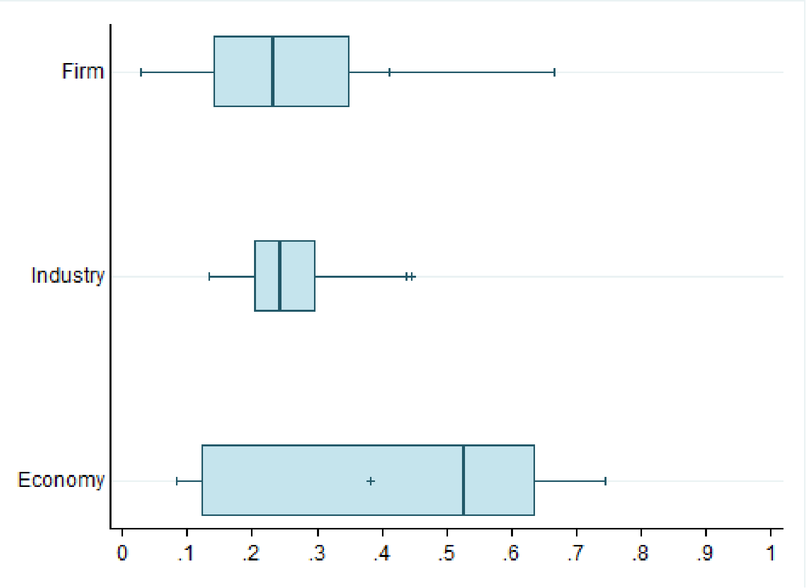


Source: OECD, own calculations based on a survey of peer-reviewed articles and selected economic research working papers on the impact of R&D on productivity and economic growth as published over 2000-2010.

Notes: The chart excludes outside values and insignificant estimates. A 10% significance level is adopted as threshold. The symbol "+" denotes the mean, the symbol "│" denotes the median. Firm as a unit includes plant and business unit, while economy comprises region.

Figure 4. Private return to R&D by unit of analysis

Gross rate of return (in percent)



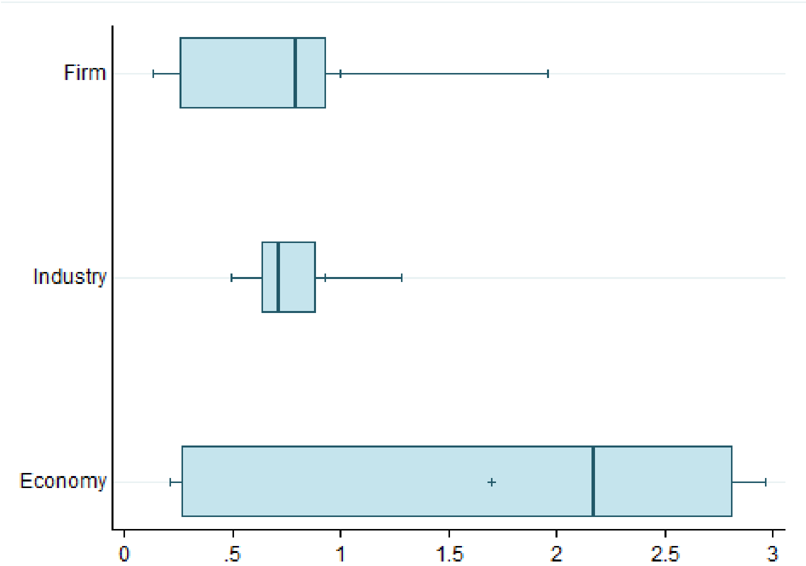
Source: OECD, own calculations based on a survey of peer-reviewed articles and selected economic research working papers on the impact of R&D on productivity and economic growth as published over 2000-2010.

Notes: The chart excludes outside values, insignificant estimates and rates of return to own R&D if indirectly derived from the R&D output elasticity estimate and larger than 0.3. A 10% significance level is adopted as threshold. The symbol "+" denotes the mean, the symbol "│" denotes the median. Firm as a unit includes plant and business unit, while economy comprises region.

64. The median private rate of return from firm and industry level studies (gross of depreciation) amounts to 0.23 and 0.24 respectively (**Figure 4**) and thus falls in the common range of 0.2-0.3. The respective mean rates of return to R&D prove to be larger than their median counterparts due to some extreme values. Generally, there is a significant variation in estimated rates of return to R&D across all units of analysis, as indicated by the box plot interquartile ranges. Estimates based on economy-wide data prove to exhibit the largest variation and span from a lower quartile of 0.12 to an upper quartile of 0.64. The mean and median rate of return to R&D amount to 0.41 and 0.53 at country level, and thus lie well beyond the corresponding firm and industry level estimates. This finding speaks in principle in favour of knowledge spillover effects. However, given the fairly small set of industry and country level estimates at-hand, available statistics should be compared and interpreted with some degree of caution.

Figure 5. Social return to R&D by unit of analysis

Gross rate of return (in percent)



OECD, own calculations based on a survey of peer-reviewed articles and selected economic research working papers on the impact of R&D on productivity and economic growth as published over 2000-2010.

Notes: Social rates of return, if not reported separately, are computed as sum of the return to own, external and foreign R&D. External R&D subsumes R&D performed by other firms within national borders. The chart excludes outside values, insignificant estimates (10% significance level) and social rates of return if based on either (i) converted social rates of return to R&D larger than 1 (given a upper bound of 0.8-1, see Table4), (ii) converted rates of return to own (external) R&D larger than 0.3 (1), (iii) firm-level or converted estimates of the return to foreign R&D larger than 3 given a maximum, economy-wide return to foreign R&D of 2.33. The symbol "+" denotes the mean, the symbol "|" denotes the median. Firm as a unit includes plant and business unit, while economy comprises region.

65. **Figure 5** presents evidence on the magnitude of social rates of return to R&D. Mean (median) social rates of return to R&D based on firm and industry data prove to be of similar magnitude, amounting to 1 (0.8) and 0.9 (0.7) respectively. Estimates of social rates of return from economy-wide studies, by contrast, are notably larger. The respective mean (median) social rate of return to R&D amounts to 1.7 (2.2). The variation in estimated social rates of return is also the largest among country-level studies which span from a minimum of 0.2 to a maximum of 3 (**Annex 2**). This finding can possibly be related to the measurement of international knowledge spillovers which, given their geographical scope, are most frequently assessed in the context of economy-wide studies. In relative terms, there is less variability in the size of knowledge spillover benefits across different units of analysis (**Annex 2**). Knowledge spillover benefits account for roughly 61% (median 67%) of the total return to R&D. This finding is in line with the assessment made by Sveikauskas (2007).

4.2 Exploratory meta-regression analysis

66. The second part of the meta-analysis consists of a regression analysis, exploring the link between the size of estimated R&D returns – R&D output elasticity and private rate of return estimates – and the measurement and estimation approach chosen. The meta-regression accounts for the unit of analysis (firm, industry and economy), type of estimate derived (cross-sectional, pooled and temporal), length of time period covered as well as the relative vintage and size of the data sample employed. Moreover, it controls for the type of output and R&D input measure adopted in a given econometric specification, the inclusion of a measure of human capital, the imposition of constant returns to scale (CRS) on labour and physical capital coefficients and the correction for R&D double-counting and expensing. As highlighted in the preceding sections, these factors should help explain some of the variability in estimated R&D returns. **Annex 3** provides definitions and summary statistics for the variables included in the meta-regression.

67. The regression exploits the full set of elasticity and private return estimates collected from empirical studies published over 2000-2010, irrespective of their level of significance. As one robustness test, meta-regressions are rerun using the selected sample of significant output elasticity and private return estimates (**Annex 4: Table A4.1 and Table A4.2**) presented in the first, descriptive part of the meta-analysis. A second robustness test explores the sensitivity of output elasticity meta-regression results to the introduction of regional dummy variables (Asia, Europe and North America) reflecting the geographical scope of studies (**Annex 4: Table A4.3**). Such information is available for single country studies and multi-country studies reporting country-specific estimates. Standard errors are robust to heteroskedasticity in all meta-regressions.[44] An extended analysis covering a larger set of publications would better allow for an additional clustering of standard errors by publication which may seem advisable given the likely dependence of estimates within one article. This exploratory analysis relies on a relatively small number of publications from which elasticity (55 articles) and private return (19 articles) estimates were collected.

68. **Table 5** displays the results from an ordinary least squares (OLS) regression employing the full sample of statistically significant and insignificant R&D output elasticity estimates. The size of the sample varies depending on the given specification. The first set of regression results suggest that elasticity estimates based on industry and economy-wide data exceed those based on firm-level data – by roughly 0.06 percentage points looking at the last and most comprehensive specification. The results further indicate that temporal estimates, which solely rely on the within unit variation over time, are generally smaller than cross-sectional estimates. The size gap amounts to 0.06-0.09 percentage points, depending on the specification. This finding is in line with the observation that R&D data typically vary less over time than across units and that multicollinearity between R&D and physical capital stocks and measurement error related attenuation bias tend to be larger in the time dimension. While the effect of time coverage and relative data vintage is less clear-cut, there seems to a positive, even though small correlation between sample size and the magnitude of the estimated R&D output elasticity.

69. Among the concerned set of output elasticity estimates, those based on a specification including a productivity rather than sales measure as outcome variable appear to be smaller, holding all else equal. No such pattern can be observed for studies that adopt value-added as measure of output. The results further suggest that studies employing alternative measures of R&D input (e.g. R&D dummy variable, see Annex 3: Table A3.1) tend to find a higher R&D output elasticity relative those including a measure of the knowledge capital stock created by R&D. One finding worth nothing is the attenuating effect of introducing a measure of human capital which reduces the size of the estimated R&D output elasticity by roughly 0.06 percentage points, holding all else equal. While some of the aforementioned effects prove to

44. Hetereoskedastictity of standard errors can be a problem in meta-regressions (Stanley and Jarrell, 2005). A weighted-least squares regression using the standard error of the estimates as analytical weight (Wieser, 2005) represents an alternative approach to deal with hetereoskedastictity.

be data sample dependent, this specific effect of introducing a measure of human capital is robust to changes in the sample of output elasticity estimates employed (Table A4.1) and to extensions of the econometric specification by regional dummy variables (Table A4.3)[45].

Table 5. Meta-analysis of R&D output elasticity estimates

Ordinary Least Squares (OLS) Regression

R&D output elasticity	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Unit Industry (0/1)	0.044	0.004	0.029	0.057	0.064	0.061
	(0.019)**	(0.019)	(0.018)	(0.022)**	(0.023)***	(0.024)**
Unit Economy (0/1)	0.021	-0.021	0.010	0.039	0.062	0.061
	(0.010)**	(0.015)	(0.019)	(0.022)*	(0.028)**	(0.028)**
Cross and within unit variation (0/1)		-0.038	-0.051	-0.036	-0.034	-0.029
		(0.024)	(0.025)**	(0.024)	(0.024)	(0.024)
Within unit variation (0/1)		-0.060	-0.086	-0.077	-0.073	-0.071
		(0.025)**	(0.026)***	(0.025)***	(0.025)***	(0.026)***
Time period (in years)		-0.001	-0.002	-0.002	0.001	0.002
		(0.001)	(0.001)*	(0.001)*	(0.002)	(0.002)
Relative data vintage (first year)		-0.003	-0.003	-0.003	-0.001	-0.001
		(0.001)***	(0.001)**	(0.001)**	(0.002)	(0.002)
Sample size (observations in 100)			0.001	0.001	0.001	0.001
			(0.000)**	(0.000)***	(0.000)***	(0.000)***
Productivity index (0/1)				-0.047	-0.054	-0.049
				(0.021)**	(0.021)**	(0.025)**
Value added (0/1)				-0.018	-0.023	-0.020
				(0.018)	(0.019)	(0.020)
R&D intensity (0/1)				0.007	0.018	0.016
				(0.021)	(0.022)	(0.023)
Alternative R&D input (0/1)				0.077	0.090	0.088
				(0.037)**	(0.038)**	(0.039)**
Human capital (0/1)					-0.056	-0.060
					(0.020)***	(0.022)***
CRS imposed (0/1)						-0.014
						(0.009)
Correction double counting (0/1)						0.009
						(0.015)
Correction expensing bias (0/1)						0.044
						(0.056)
Constant	0.096	0.244	0.249	0.252	0.149	0.124
	(0.007)***	(0.052)***	(0.061)***	(0.066)***	(0.087)*	(0.091)
R-squared	0.01	0.04	0.07	0.10	0.11	0.11
Number of estimates (N)	624	624	479	479	479	479

* $p<0.1$; ** $p<0.05$; *** $p<0.01$

Source: OECD, own analysis based on a survey of peer-reviewed articles and selected economic research working papers on the impact of R&D on productivity and economic growth as published over 2000-2010.

Notes: The meta-analysis covers 55 publications and includes both statistically significant and insignificant estimates, applying a 10% significance level as threshold. The reference group comprises firm-level studies that employ estimators which exclusively rely on the cross-sectional variation in the data, adopt sales as a measure of output and R&D capital as a measure of R&D input. Standard errors are robust to heteroskedasticity.

70. **Table 6** presents the results from the meta-regression based on the combined set of statistically significant and insignificant estimates of private rates of return to R&D. Except for a dummy variable indicating whether or not an estimate relies on a conversion of an R&D output elasticity estimate, econometric specifications remain unchanged. The effect of sample size is not necessarily clear-cut and tends to change in terms of direction and/or statistical significance across different specifications: This includes the effect of data aggregation (unit of analysis), time coverage, data vintage and the measure of output. Converted estimates in turn seem to be larger than estimates of private returns to R&D derived from a TFP growth equation, at least looking at the three last, more extensive specifications. The meta-regression results also suggest that temporal estimates, relying exclusively on the within-unit (temporal)

45. The extended model is estimated on a reduced set of R&D output elasticity estimates from 36 publications.

variation in the data, are lower than cross-sectional estimates. Pooled estimates of private returns to R&D, relying on both the cross-sectional and within-unit variation in the data, prove to be larger than the latter, by contrast. These effects are qualitatively plausible and consistent with the effects alluded to in Section 2.2. However, the point estimates should be interpreted with some degree of caution as the size of meta-regression coefficients is only very imprecisely measured and thus varying notably across specifications.

Table 6. Meta-analysis of private return to R&D estimates

Ordinary Least Squares (OLS) Regression

Private return to R&D	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Unit Industry (0/1)	0.155	0.059	0.056	0.405	0.386	0.940
	(0.104)	(0.233)	(0.250)	(0.338)	(0.343)	(0.504)*
Unit Economy (0/1)	-0.010	-0.003	0.382	0.421	0.434	2.250
	(0.078)	(0.384)	(0.386)	(0.599)	(0.591)	(0.716)***
Converted estimate (0/1)	0.120	-0.029	-0.082	0.211	0.215	0.784
	(0.090)	(0.100)	(0.099)	(0.112)*	(0.113)*	(0.207)***
Cross and within unit variation (0/1)		0.351	0.465	0.131	0.126	1.074
		(0.086)***	(0.098)***	(0.143)	(0.143)	(0.260)***
Within unit variation (0/1)		-0.065	-0.091	-0.502	-0.524	-0.383
		(0.043)	(0.076)	(0.124)***	(0.120)***	(0.158)**
Time period (in years)		0.014	0.007	0.021	0.025	-0.059
		(0.015)	(0.018)	(0.025)	(0.025)	(0.028)**
Relative data vintage (first year)		0.009	0.025	0.022	0.023	-0.012
		(0.015)	(0.016)	(0.015)	(0.015)	(0.011)
Sample size (observations in 100)			-0.011	-0.006	-0.006	-0.019
			(0.004)***	(0.004)	(0.004)	(0.005)***
Productivity index (0/1)				0.121	0.136	-0.989
				(0.117)	(0.117)	(0.301)***
Value added (0/1)				0.593	0.605	-0.256
				(0.100)***	(0.100)***	(0.219)
R&D intensity (0/1)				0.353	0.367	1.625
				(0.157)**	(0.159)**	(0.296)***
Human capital (0/1)					-0.139	-0.155
					(0.109)	(0.080)*
CRS imposed (0/1)						0.331
						(0.229)
Correction double counting (0/1)						0.742
						(0.233)***
Correction expensing bias (0/1)						-1.807
						(0.445)***
Constant	0.423	-0.169	-0.468	-1.091	-1.166	-0.156
	(0.046)***	(0.649)	(0.706)	(0.677)	(0.667)*	(0.517)
R-squared	0.04	0.13	0.19	0.27	0.27	0.35
Number of estimates (N)	206	206	187	187	187	187

* $p<0.1$; ** $p<0.05$; *** $p<0.01$

Source: OECD, own analysis based on a survey of peer-reviewed articles and selected economic research working papers on the impact of R&D on productivity and economic growth as published over 2000-2010.

Notes: The meta-analysis covers 19 publications and includes both statistically significant and insignificant estimates, applying a 10% significance level as threshold. Estimates of private returns to R&D indicate rates of return gross of depreciation. The dummy variable "Alternative R&D input" – equal to 1 in the case of 5 observations – was omitted from the regression due to multicollinearity. The reference group comprises firm-level studies that employ estimators which exclusively rely on the cross-sectional variation in the data, adopt sales as a measure of output and R&D capital as a measure of R&D input. Standard errors are robust to heteroskedasticity.

71. The introduction of a measure of human capital has again the expected attenuating effect on R&D return estimates, even though this effect gains statistical significance only in the second of the two concerned specifications. A 0.15 percentage point reduction in gross rates of return to R&D can be reported based on the given sample. As expected and discussed in the literature, the correction for R&D double counting leads to an increase in estimated R&D returns. Correcting for expensing bias proves to have the opposite effect. As Schankerman (1981) highlighted, the effect of R&D expensing bias can in principle go in either direction depending on how the R&D intensity in the sample evolves. The results from the meta-regression of private rates of return to R&D are relatively robust to the restriction of the data sample to selected, significant estimates of private returns to R&D (**Annex 4: Table A4.2**). While the

effects of correcting for R&D double counting and expensing bias and introducing a measure of human capital remain unchanged in terms of direction and statistical significance, higher rates of return to R&D are found for industry and country level vis-à-vis firm-level studies and the effect of converting elasticity estimates is less unambiguous in this case. Moreover, a positive and statistically significant effect is now found for imposing constant returns to scale on the coefficients of standard inputs. Mairesse and Sassenou (1991) and Hall and Mairesse (1995) point out that the latter typically helps recover time-series estimates.

5. Concluding remarks

72. This report's review of the econometric literature has shown that despite the various measurement and estimation approaches, researchers generally find a positive and statistically significant impact of R&D on productivity and economic growth. The results of a meta-analysis based on recent econometric estimates published over 2000-2010 suggest that the R&D output elasticity runs in the order of 0.10. Gross rates of return to own R&D based on firm and industry data prove to lie in the range of 0.20-0.30, while estimates based on economy-wide data tend to exceed the former, both in terms of size and the variability. Estimated gross rates of return to R&D thus generally surpass those of ordinary capital. Across all unit of analysis, social rates of return to R&D are in turn found to be significantly larger than private rates of return to R&D, the average (median) social return to R&D amounting to roughly 1.2 (0.8). On average, knowledge spillover benefits make up for approximately three-fifths of the social return to R&D.

73. This finding supports in principle the view that markets fail to generate sufficiently large incentives for firms to undertake R&D and that firms consequently underinvest in R&D from the social perspective. While the given econometric evidence on the relative magnitude of social vis-à-vis private rates of return to R&D provides a rationale for government funding of business R&D, it is not sufficient as evidence for the net benefit of public support for R&D. The net benefit of specific policies ultimately depends on the relative magnitude of social returns to R&D vis-à-vis administrative and compliance costs associated with the provision of government funding. Both administrative and compliance costs and social returns to R&D possibly depend on the type and design of the employed funding instrument.

74. The exploratory meta-regression undertaken as part of this survey examined the link between the size of estimated R&D returns and the chosen measurement and empirical strategy. The analysis shows that output elasticity and private return estimates relying solely on the within-unit (temporal) variation in the data are generally smaller than their cross-sectional or pooled counterparts the latter of which rely on both the cross and within unit variation in the data. This result can be attributed to the fact that R&D investments show relatively more variation in the cross-sectional than time dimension. Correcting for R&D double counting turns out to have, as expected, a positive effect on the size of estimated private rates of return to R&D. The same holds true for imposing constant returns to scale on the coefficients of conventional inputs, at least among the selected sample of significant estimates of private returns to R&D. In contrast, controlling for human capital proves to have an attenuating effect of on the size of estimated R&D impacts. Both R&D output elasticity and private return estimates turn out to be smaller once a measure of the stock of human capital is included in the econometric specification.

75. The latter finding highlights the importance of accounting for other innovation inputs such as human capital, ICT and non-R&D related intangibles in empirical work in order to comprehensively assess the economic impact of business R&D investments and polices that seek to stimulate such investments. The survey's findings speak also in favour of a micro-data based approach in assessing the efficacy of public support for business R&D by type of firm given the notable variation in estimated economic returns to R&D across different groups of firms. The meta-analysis approach undertaken as part of this survey is also relevant for the new OECD-NESTI distributed micro-data project on the incidence and impact of public support for business R&D as a means for pooling and investigating country-level estimates.

ANNEX 1: EMPRICIAL RESEARCH ON THE ECONOMIC IMPACT OF R&D – TIMELINE

#	Author(s)	Year	Country Coverage	Time Period	Unit of Analysis	Industry Sector Focus	Knowledge Spillover	Reference
1	Griliches	1958	USA	1910-1955	Industry	Agriculture		
2	Minasian	1962	USA	1947-1957	Firm	Chemical, Pharmaceutical		W
3	Griliches	1964	USA	1949, 1954, 1959	Industry	Agriculture		
4	Mansfield	1965	USA	1946-1962	Firm	Manufacturing, Petroleum, Chemical		
5	Minasian	1969	USA	1948-1957	Firm	Chemical		N, C
6	Leonard	1971	USA	1957-1968	Firm	Manufacturing		
7	Globerman	1972	CAN	**	Industry	**	**	N
8	Bardy	1974	DEU	**	Firm	**	**	N
9	Terleckyj	1974	USA	1948-1966	Industry	Manufacturing, Non-manufacturing	Interindustry	N, S, F, M, C
10	Link	1978	USA	1963	Industry	Manufacturing		N
11	Goldberg	1979	USA	1958-1975	Industry	Manufacturing		
12	Griliches	1980a	USA	1959-1977	Industry	Manufacturing		H, N, W, M, C
13	Griliches	1980b	USA	1957-1965	Firm	Manufacturing		H, N, M, C
14	Mansfield	1980	USA	1960-1976	Firm	Manufacturing , Petroleum, Chemical		N, W, M, C
15	Nadiri	1980a	USA	1949-1978	Economy, Industry	Manufacturing		N, M
16	Nadiri	1980b	USA	1958-1975	Industry	Manufacturing		N
17	Nadiri and Bitros	1980	USA	1965-1972	Firm	5 industries		N
18	Terleckyj	1980	USA	1948-1966	Industry		Interindustry	N, C
19	Link	1981	USA	1971-1976	Firm	Manufacturing		W, C
20	Schankerman	1981	USA	1963	Firm	5 industries		H, N, W, M, C
21	Sveikauskas	1981	USA	1959-1969	Industry	Manufacturing		N, S, F, M
22	Link	1982	USA	**	**	**	**	
23	Scherer	1982	USA	1964-1978	Industry	Manufacturing	Interindustry	N, S, F, M, C
24	Sveikauskas and Sveikauskas	1982	USA	1959-1969	**	Manufacturing	**	C
25	Griliches and Mairesse	1983	FRA, USA	1973-1978	Firm, Industry	Manufacturing		N, W, M, C
26	Link	1983	USA	1975-1979	Firm	**	Interfirm	N, W

#	Author(s)	Year	Country Coverage	Time Period	Unit of Analysis	Industry Sector Focus	Knowledge Spillover	Reference
27	Odagiri	1983	JPN	1969-1981	Firm	Scientific, Non-scientific	**	N, W, C
28	Postner-Wesa	1983	CAN	**	Industry	**	**	N
29	Cardani and Mohnen	1984	FRA, ITA	1965-1977	Industry	Manufacturing		
30	Clark and Griliches	1984	USA	1971-1980	Business units**	Manufacturing		H, N, M, C
31	Cunéo	1984	FRA	1972-1977	Firm	Scientific, Non-scientific		
32	Cunéo and Mairesse	1984	FRA	1972-1977	Firm	Scientific, Non-scientific		H, N, W, M, C
33	Griliches and Lichtenberg	1984a	USA	1959-1978	Industry	Manufacturing	Interindustry	H, N, C
34	Griliches and Lichtenberg	1984b	USA	1959-1976	Industry	Manufacturing		N, C
35	Griliches and Mairesse	1984	USA	1966-1977	Firm	Scientific, Non-scientific		H, W, M, C
36	Longo	1984	CAN	**	Firm	**	**	N
37	Scherer	1984	USA	1973-1978	Industry	Manufacturing, Non-manufacturing	Interindustry	N, S, F, M
38	Mairesse and Cunéo	1985	FRA	1974-1979	Firm	4 industries		H, N, W
39	Odagiri	1985	JPN	1960-1977	Industry	Manufacturing	Interindustry	H, N
40	Patel and Soete	1985	DEU, FRA, GBR, JPN, USA	1963-1982	Economy	Manufacturing		
41	Suzuki	1985	JPN	1965-1982	Industry	Manufacturing		
42	Griliches	1986	USA	1966-1977	Firm	Manufacturing		H, N, W, C
43	Jaffe	1986	USA	1973-1979	Firm	Manufacturing	Interfirm**	N, C
44	Mohnen, Nadiri and Prucha	1986	DEU, JPN, USA	1965-1978	Economy	Manufacturing		H, N
45	Odagiri and Iwata	1986	JPN	1966-1982	Firm	Manufacturing		H, N, W, M, C
46	Schankerman and Nadiri	1986	USA	1947-1976	Industry **	Telecommunications**		N
47	Seldon	1987	USA	1950-1980	Industry	Forest product	Interinstitutional**	
48	Bernstein	1988	CAN	1978-1981	Firm	7 industries	Intra-Interindustry	H, N, C
49	Bernstein and Nadiri	1988	USA	1958-1981	Industry	5 industries	Interindustry	N, S, F, M
50	Englander, Evenson, and Hanazaki	1988	G7	1970-1983	Industry			C
51	Hanel	1988	CAN (Québec)	1971-1982	Industry	Manufacturing	Interindustry	N
52	Jaffe	1988	USA	1972-1977	Firm	19 industries	Within and out-of technology cluster	H
53	Mansfield	1988	JPN	1960-1979	Industry	Manufacturing		N, M, C
54	Patel and Soete	1988	CAN, FRA, GBR, JPN, USA	1967-1985	Economy	**	**	N, M
55	Sassenou	1988	JPN	1973-1981	Firm	**	**	N, W

#	Author(s)	Year	Country Coverage	Time Period	Unit of Analysis	Industry Sector Focus	Knowledge Spillover	Reference
56	Bernstein	1989	CAN	1963-1983	Industry	10 industries	Interindustry	H, N
57	Bernstein and Nadiri	1989	USA	1965-1978	Industry	4 industries	Intraindustry	H
58	Fecher and Perelman	1989	selected OECD countries**	**	**	**	**	
59	Goto and Suzuki	1989	JPN	1976-1984	Industry	Manufacturing	Interindustry	H, N, W, S, F, M, C
60	Jaffe	1989	USA	1972-1981	State, Technology		Interinstitutional**	
61	Sterlacchini	1989	GBR	1954-1984	Industry	Manufacturing	Interindustry	H, N, C
62	Bartelsman	1990a	USA	1958-1986	Industry	**	**	H
63	Bartelsman	1990b	USA	**	**	**	**	H
64	Bernstein and Nadiri	1990	USA	1959-1966	Firm	4 industries		H, N
65	Fecher	1990	BEL	1981-1983	Firm	Manufacturing	Intra-International	N, W
66	Griliches and Mairesse	1990	JPN, USA	1973-1980	Firm	Manufacturing		H, N, W, C
67	Mohnen	1990	CAN	1965-1982	Economy	Manufacturing	Interindustry	H
68	Nadiri and Prucha	1990	JPN, USA	1960-1980	Industry	Electrical machinery		N
69	Bernstein and Nadiri	1991	USA	1957-1986	Industry	6 industries	Interindustry	N, S, F, M
70	Klette	1991	NOR	1977-1985	Plant	3 industries		H
71	Lichtenberg and Siegel	1991	USA	1972-1985	Firm	Manufacturing		H, N, W, C
72	Mohnen and Lepine	1991	CAN	1975-1983	Industry	Manufacturing	Interindustry	H, N
73	Vuori	1991	FIN, NOR, SWE	1964-1983	Industry	Manufacturing		
74	Fecher	1992	11 OECD countries**	1970-1986	Industry	Manufacturing, Services		
75	Fecher and Perelman	1992	6 OECD countries	1971-1986	industry		**	
76	Mohnen	1992a	CAN, other OECD countries**	**	**	**	International	
77	Mohnen	1992b	5 OECD countries	1964-1985	Economy	**	**	H
78	Nguyen and Kokkelenberg	1992	USA	1973-1981	Plant	Manufacturing		
79	Coe and Moghadam	1993	FRA	1971-1991	Economy	Private nonfarm sector		M
80	Hall	1993	USA	1964-1990	Firm	Manufacturing		H
81	Lichtenberg	1993	53 countries	1960-1985	Economy		International	H, M
82	Suzuki	1993	JPN	1981-1989	Firm	Electrical machinery	Intraindustry	
83	Wolff and Nadiri	1993	USA	1947-1977	Industry	Manufacturing	Interindustry	H
84	Antonelli	1994	ITA	1980-1989 **	Firm	**	Interfirm**	

#	Author(s)	Year	Country Coverage	Time Period	Unit of Analysis	Industry Sector Focus	Knowledge Spillover	Reference
85	Griliches	1994	USA	1958-1989	Industry	Manufacturing		M, C
86	Hanel	1994	CAN	1974-1989	Industry	Manufacturing	Interindustry, International	
87	Klette	1994	NOR	1975-1986	Plant	High-tech manufacturing	Intraindustry	
88	Nadiri and Mamuneas	1994	USA	1956-1986	Industry	Manufacturing		
89	Coe and Helpman	1995	22 OECD countries (G7)**	1971-1990	Economy		International	H, M
90	Griliches and Regev	1995	ISR	1979-1988	Firm	Manufacturing, Mining		
91	Hall and Mairesse	1995	FRA	1980-1987	Firm	Manufacturing		H, W, M, C
92	Park	1995	10 OECD countries	1970-1987	Economy		International, Interinstitutional**	H,
93	Perelman	1995	11 OECD countries	1970-1987	Economy			
94	Raut	1995	IND	1975-1986	Firm	Manufacturing	Intraindustry	
95	Verspagen	1995	9 OECD countries	1973-1988	Industry	Manufacturing		H, M, C
96	Adams and Jaffe	1996	USA	1974-1988	Plant	Chemical	Intra-Interfirm	H
97	Bartelsman et al.	1996	NLD	1985-1993	Firm	Manufacturing		H, W
98	Basant and Fikkert	1996	IND (8 OECD countries)**	1974-1982	Firm	Manufacturing	Intraindustry, International	
99	Bernstein	1996	CAN, USA	1964-1986	Industry		Intra-International**	
100	Bernstein and Yan	1996	CAN, JPN	1964-1982	Industry	Manufacturing	Intra-International	
101	Klette	1996	NOR	1989-1990	Plant	Manufacturing	Intrafirm	
102	Klette and Johansen	1996	NOR	1980-1992	Plant	4 industries		
103	Mairesse and Hall	1996	FRA, USA	1981-1989	Firm	Manufacturing		H, W
104	Mohnen, Jacques and Gallant	1996	CAN	1963-1988	Industry	Pulp and paper, Wood	**	
105	Nadiri and Kim	1996a	JPN, KOR, USA	1974-1990	Economy	Manufacturing		H
106	Nadiri and Kim	1996b	G7 countries	1964-1991	Economy		International	H
107	Sakurai et al.	1996	10 OECD countries	1970-1990 **	Economy, Industry	Manufacturing, Services	Interindustry, International	
108	Bernstein and Yan	1997	CAN, JPN	1964-1982	Industry	Manufacturing	International	H
109	Coe, Helpman and Hoffmaister	1997	98 countries	1971-1990	Economy		International	H
110	Engelbrecht	1997	21 OECD countries	1971-1985	Economy		International	
111	Meijl	1997	FRA	1978-1992	Industry		Interindustry	
112	Nadiri and Prucha	1997	6 OECD countries	1964-1991	Economy			
113	Verspagen	1997	EU**, USA	1980-1994	Economy**	Manufacturing	Interindustry	H
114	Bernstein	1998	CAN, USA	1962-1989	Industry	Manufacturing	Interindustry, International	H

#	Author(s)	Year	Country Coverage	Time Period	Unit of Analysis	Industry Sector Focus	Knowledge Spillover	Reference
115	Bernstein and Mohnen	1998	JPN, USA	1962-1986	Industry	Manufacturing**	International	H, W
116	Capron and Cincera	1998	EU, AUS, CAN, JPN, USA	1987-1994	Firm	Manufacturing**	Interfirm**	H
117	Cincera	1998	World	1987-1994	Firm	**	**	W
118	Crépon, Duguet and Mairesse	1998	FRA	1986-1990	Firm	Manufacturing		H
119	Harhoff	1998	GER	1979-1989	Firm	Manufacturing		H, W
120	Jones and Williams	1998	USA	1961-1989	Industry	Manufacturing		M, C
121	Keller	1998	22 OECD countries	1971-1990	Economy		International	H
122	Bayoumi, Coe and Helpman	1999	G7, 5 country regions**	1996 (2075) **	Economy	Manufacturing	International	
123	Kao, Chiang, Chen	1999	22 OECD countries	1971-1990	Economy		International	H
124	Xu and Wang	1999	21 OECD countries	1983-1990	Economy		International	
125	Frantzen	2000	21 OECD countries	1961-1991	Economy		International	
126	Hanel	2000	CAN (G7)**	1974-1989	Industry	Manufacturing	Interindustry, International	
127	Harhoff	2000	DEU	1979-1989	Firm	Manufacturing	Interfirm**	
128	Los and Verspagen	2000	USA	1974-1993	Firm	Manufacturing	Interfirm**	H
129	O'Mahony and Vecchi	2000	Europe, JPN, USA	1993-1997	Firm	Machinery, Chemical	**	W
130	Sveikauskas	2000	USA	1958-1983	Industry	**	**	H
131	Atella and Quintieri	2001	ITA	1969-1990	Economy, Industry	Manufacturing	Intra-International	
132	Beneito	2001	ESP	1991-1996	Firm	Manufacturing	Interfirm**	
133	Brantstetter	2001	JPN, USA	1983-1989	Firm	5 industries	Intra-International	
134	Funk	2001	22 OECD countries (G7)**	1971-1990	Economy	Market sector**	International	
135	Hu	2001	CHN	1995	Firm		Interinstitutional**	
136	Lichtenberg and van Pottelsberghe	2001	13 OECD countries (G7)**	1971-1990	Economy		International	H
137	Madden, Savage and Bloxham	2001	16 OECD, 5 Asian countries**	1980-1995	Economy		International	
138	Wakelin	2001	GBR	1988-1996	Firm	Manufacturing	Intra-Interindustry**	H, W
139	Wieser	2001	12 EU countries **, USA	1989-1998	Firm	Manufacturing	Intra-Interindustry, International	
140	Ballot et al.	2002	FRA, SWE	1987-1993	Firm	Manufacturing		
141	Del Barrio-Castro et al.	2002	21 OECD countries	1966-1995	Economy		International	
142	Frantzen	2002	14 OECD countries	1972 – 1994	Industry	Manufacturing	Intra-Interindustry, International	

#	Author(s)	Year	Country Coverage	Time Period	Unit of Analysis	Industry Sector Focus	Knowledge Spillover	Reference
143	Greenhalgh and Longland	2002	GBR	1987-1994	Firm	Manufacturing, Services		
144	Hanel and St-Pierre	2002	CAN, JPN, USA, other OECD countries	1988 **	Firm	Manufacturing	Interfirm**	
145	Keller	2002a	8 OECD countries	1970-1991	Industry	Manufacturing	National Interindustry, International Intra-Interindustry	
146	Keller	2002b	14 OECD countries	1970-1995	Industry	Manufacturing	International (G5)**	
147	McVicar	2002	GBR (14 other OECD countries)**	1973-1992	Industry	Manufacturing	Interindustry, International	
148	Rouvinen	2002	FIN	1985-1997	Firm	Manufacturing	Intra-Interindustry	
149	Bassanini and Scarpetta	2003	16 OECD countries	1971-1998	Economy		Interinstitutional**	
150	Bond, Harhoff, van Reenen	2003	DEU, GBR	1988-1996	Firm	12 industries		H
151	Bönte	2003	USA	1956-1999	Industry	Private nonfarm sector	Interinstitutional**	
152	Cameron	2003	GBR	1960-1995	Industry	Manufacturing		
153	Frantzen	2003	14 OECD countries	1972-1994	Industry	Manufacturing	International	
154	Kwon and Inui	2003	JPN	1995-1998	Firm	Manufacturing		H
155	Medda, Pigga and Siegel	2003	ITA	1992-1997	Firm	Manufacturing	Interinstitutional**	H
156	Wang and Tsai	2003	TWN	1994-2000	Firm, Industry	Manufacturing**		H, M, C
157	Griffith, Redding, van Reenen	2004	12 OECD countries	1974-1990	Industry	Manufacturing	International**	H
158	Guellec and van Pottelsberghe	2004	16 OECD countries	1980-1998	Economy		International, Interinstitutional**	
159	Hu and Jefferson	2004	CHN (Beijing)	1991-1997	Firm	5 industries		
160	Khan and Luintel	2004	10 OECD countries	1965-1999	Economy		International	
161	Medda, Pigga and Siegel	2004	ITA	1995-1997	Firm	Manufacturing	Interinstitutional**	
162	Park	2004a	14 OECD countries, KOR, SGN, TWN	1980-1995	Industry	Manufacturing, Non-manufacturing	Interindustry, International	
163	Park	2004b	22 OECD countries	1971-1990	Economy		International	
164	Peri	2004	CAN, USA,18 European countries	1975-1996	Region		Interregional**	
165	Smith et al.	2004	DNK	1995-1997	Firm	Manufacturing		
166	Wang and Tsai	2004	TWN	1994-2000	Firm	Electrical machinery		
167	Cameron, Proudman and Redding	2005	GBR (USA)**	1970-1992	Industry	Manufacturing	Technology transfer (USA)**	
168	Cassidy, Görg and Strobl	2005	IRL	2000-2001	Plant	Manufacturing		
169	Chen and Yang	2005	TWN	1990-1997	Firm	Manufacturing	Intraindustry**	
170	Kafouros	2005	GBR	1989-2002	Firm	Manufacturing		H
171	Mairesse et al.	2005	FRA	1998-2000	Firm	Manufacturing		H

#	Author(s)	Year	Country Coverage	Time Period	Unit of Analysis	Industry Sector Focus	Knowledge Spillover	Reference
172	Tsai	2005	TWN	1995-2000	Firm	Manufacturing		
173	Wang and Tsai	2005	TWN	1994-2000	Firm	Manufacturing**		C
174	Bernstein and Mamuneas	2006	USA	1955-1999	Industry	Manufacturing**		
175	Griffith, Harrison, van Reenen	2006	GBR (USA)**	1990-2000	Firm	Manufacturing	Intraindustry, International (USA)	H
176	Khan and Luintel	2006	16 OECD countries	1980-2002	Economy		Interinstitutional**, International**	
177	Ornaghi	2006	ESP	1990-1999	Plant	Manufacturing	Intraindustry**	H
178	Anon Higon	2007	GBR (G7, ESP, IRL)**	1970-1997	Industry	Manufacturing	Interindustry, International	
179	Anon Higon and Manjón Antolín	2007	GBR	2002-2006	Firm	Manufacturing, Services		
180	Falk	2007	19 OECD countries	1970-2004	Economy	Manufacturing**		
181	Aiello and Cardamone	2008	ITA	1980-2003	Firm	Manufacturing	Interfirm**	
182	Lokshin, Belderboss and Carree	2008	DNK	1996-2001	Firm	Manufacturing	Interfirm**	
183	Mairesse and Mulkay	2008	FRA	1999	Economy, Industry	Manufacturing	Interregional**	
184	Maté-García,Rodríguez-Fernández	2008	ESP	1993-1999	Firm	Manufacturing		
185	Todo and Shimizutani	2008	JPN	1996-2002	Firm	Manufacturing	International	
186	Tsang, Yip, Toh	2008	SGN	1993-1999	Firm	Manufacturing		
187	Coe, Helpman and Hoffmaister	2009	24 OECD countries	1971-2004	Economy		International**	
188	Hall, Foray and Mairesse	2009	USA	1994-2005	Firm	5 Industries**		H
189	Lang	2009	DEU	1960-2005	Industry	Manufacturing		
190	O'Mahony and Vecchi	2009	DEU, FRA, GBR, JPN, USA	1988-1997	Firm	7 industries	Interfirm**	
191	Haskel and Wallis	2010	GBR	1986-2004	Economy		Interinstitutional**	
192	Khan and Luintel	2010a	10 OECD countries	1970-2006	Economy		International	
193	Khan, Luintel and Theodoridis	2010b	16 OECD countries	1982-2004	Economy		Interinstitutional, International**	
194	Ortega-Argilés et al.	2010	9 EU countries	1987 – 2005	Firm, Industry	Manufacturing, Services**		
195	Rogers	2010	GBR	1989-2000 **	Firm	Manufacturing, Non-manufacturing	Intraindustry**	H
196	Anon Higon et al.	2011	GBR	2002-2006	Firm	Manufacturing		
197	Autant-Bernard et al.	2011	FRA	2000-2002	Plant	Manufacturing, Extractions, Other**	Intra-Interfirm	
198	Aw, Roberts and Xu	2011	TWN	2000-2004	Plant	Electrical machinery		
199	Bravo-Ortega, Garcia Marin	2011	65 countries	1965-2005	Economy		International	

#	Author(s)	Year	Country Coverage	Time Period	Unit of Analysis	Industry Sector Focus	Knowledge Spillover	Reference
200	Ortega-Argilés et al.	2011	9 European countries**	2000-2005	Firm	Manufacturing, Services**	Intraindustry**	
201	Bianco and Niang	2012	24 OECD countries	1971-2004	Economy		International	
202	Czarnitzki and Thorwarth	2012	BEL (Flanders region)	2002-2007	Firm	Manufacturing		
203	Eid	2012	17 OECD countries	1981-2006	Economy		Interinstitutional**	
204	Goodridge	2012	GBR	1992-2007	Industry	7 Industries**	Interindustry**	
205	Hall et al.	2012	ITA	1995-2006	Firm	Manufacturing		
206	Ang and Madsen	2013	CHN, IND, JPN, KOR, SGN, TWN	1955-2006	Economy		International**	
207	Barge-Gil and Lopez	2013	ESP	2005-2009	Firm	Manufacturing, Services		
208	Bloom, Schankerman, van Reenen	2013	USA	1981-2001	Firm	Manufacturing, Services	Interfirm**	
209	Di Cagno et al.	2013	31 European countries**	1994-2005	Economy		International**	
210	Doraszelski and Jaumandreu	2013	ESP	1991-1999	Firm	Manufacturing		H
211	Eberhardt, Helmers and Strauss	2013	10 OECD countries	1980-2005	Industry	Manufacturing	Cross-sectional dependence**	
212	Haskel and Wallis	2013	GBR	1988-2006**	Economy	Market sector**	Interinstitutional**	
213	Revilla and Fernandez	2013	ESP	1998-2008	Firm	Manufacturing		
214	Corrado, Haskel and Lasino	2014	10 EU countries	1998-2007	Industry		Interindustry, International	
215	Haskel et al.	2014	GBR	1995-2007	Industry	8 Industries**	Interindustry, Interinstitutional**	
216	Ilmakunnas and Piekkola	2014	FIN	1998-2008	Firm	Manufacturing, Services		

Sources: OECD, based on a survey of peer-reviewed articles and selected economic research working papers on the impact of R&D on productivity and economic growth, as published over 1958-2014.

Notes: (i) This survey is based on a literature search involving Elsevier's Scopus scientific publication database and google scholar searches as carried out by December 2014. Key word search items include "return, R&D, productivity". The scope of the review is confined to peer-reviewed articles and selected economic research working papers investigating the impact of business R&D on productivity and economic growth. Some country-level studies resort to data on gross domestic expenditures on R&D (GERD) rather than business expenditures on R&D (BERD) in which case estimates reflect the aggregate effect of private and public R&D investment on the economic performance of the market sector (or total economy). (ii) Year denotes the year of publication of the article or working paper. Time period indicates the overall time period (first and last year) covered by the empirical study. R&D spillovers refers to the type(s) of knowledge spillover(s) investigated by the study (intra/interfirm, intra/interindustry, intra/international and interinstitutional from government or higher education to business). (iii) The last column provides references to previous literature surveys (N=Nadiri, 1993; C=CBO, 2005; F=Fraumeni and Okubo, 2005; W=Wieser, 2005; S=Sveikauskas, 2007; M=Mc Morrow and Röger, 2009 and H=Hall et al., 2010) which report for selected studies R&D output elasticity and/or private and social return to R&D estimates aside technical information on the type of data and estimation approach used. (iv) ** See article for further details.

ANNEX 2: META-ANALYSIS OF R&D RETURNS: DESCRIPTIVES

Table A2. R&D output elasticity and private and social rates of return to R&D by unit of analysis

1. R&D output elasticity (in percent)

Unit	# Articles	N	Min	Mean	Median	Max	SD
Firm	30	218	-0.30	0.11	0.09	0.64	0.11
Industry	9	75	-0.40	0.14	0.12	0.73	0.16
Economy	18	245	-0.15	0.12	0.10	0.61	0.11
Total	55	538	-0.40	0.12	0.10	0.73	0.12

2. Private return to R&D (in percent)

Unit	# Articles	N	Min	Mean	Median	Max	SD
Firm	15	107	0.03	0.38	0.23	1.83	0.41
Industry	2	16	0.13	0.45	0.24	2.03	0.57
Economy	2	16	0.08	0.41	0.53	0.74	0.27
Total	19	139	0.03	0.39	0.24	2.03	0.42

3. Social return to R&D (in percent)

Unit	# Articles	N	Min	Mean	Median	Max	SD
Firm	5	14	0.13	1.00	0.79	3.78	1.09
Industry	3	24	0.50	0.93	0.71	3.65	0.68
Economy	1	15	0.21	1.70	2.17	2.96	1.24
Total	9	53	0.13	1.17	0.77	3.78	1.02

4. R&D spillover benefits as percentage of social return to R&D (in percent)

Unit	# Articles	N	Min	Mean	Median	Max	SD
Firm	5	14	0.02	0.49	0.64	0.81	0.31
Industry	1	3	0.52	0.77	0.88	0.92	0.22
Economy	1	15	0.42	0.68	0.72	0.79	0.12
Total	7	32	0.02	0.61	0.67	0.92	0.25

Source: OECD, own calculations based on a survey of peer-reviewed articles and selected economic research working papers on the impact of R&D on productivity and economic growth as published over 2000-2010.

Notes: The meta-analysis covers overall 66 publications. Summary statistics are exclusively based on significant estimates. A 10% significance level is adopted as threshold. Firm as a unit includes plant and business unit, while economy comprises region. Table 1: The total number of publications amounts 55 given that two publications derive estimates at two different levels of aggregation. Table 2: summary statistics exclude estimates of private returns to R&D if indirectly derived from the R&D output elasticity estimate and larger than 0.3. Table 3: summary statistics exclude estimates of social returns to R&D if based on either (i) indirectly derived (industry level) estimates of the social return to R&D larger than 1, (ii) indirectly computed rates of return to own (external) R&D larger than 0.3 (1), (iii) firm-level or indirectly derived estimates of the return to foreign R&D larger than 3 (the maximum, economy-wide return to foreign R&D is 2.33). One industry-level study reports social returns to R&D without deriving an estimate of the at industry level private return to R&D, leading to a one unit increase in the number of industry-level studies reporting social rates of return to R&D relative to the number of industry-level studies deriving private rates of return to R&D. Table 4: summary statistics are based on observations for which both private and social rates of return to R&D are given.

ANNEX 3: META-ANALYSIS: DEFINITION OF VARIABLES & SUMMARY STATISTICS

Table A3.1 Definition of Variables

Variables	Definition
R&D output elasticity	Percentage increase in output measure as result of a one percent increase in R&D inputs.
Private return to R&D	Rate of change in output caused by a one unit increase in the R&D input (gross of depreciation).
Unit Firm (0/1)	Dummy variable=1 if unit of analysis is firm, plant or business unit.
Unit Industry (0/1)	Dummy variable=1 if unit of analysis is industry.
Unit Economy (0/1)	Dummy variable=1 if unit of analysis is economy or region.
Cross unit variation (0/1)	Dummy variable=1 if the estimation relies only on cross-sectional variation in the data.
Cross and within unit variation (0/1)	Dummy variable=1 if the estimation relies on cross-sectional and temporal variation in the data.
Within unit variation (0/1)	Dummy variable=1 if the estimation relies only on temporal variation within the unit of analysis.
Converted estimate (0/1)	Dummy variable=1 if the private return to R&D is derived from an R&D output elasticity estimate.
Time period (in years)	Overall time period (in years) covered by the empirical analysis.
Relative data vintage (first year)	First year analysis minus first year earliest study covered by meta-analysis (1955) plus one.
Sample size (observations in 100)	Number of firm, industry or country level observations included in the estimation (in 100).
Productivity index (0/1)	Dummy variable=1 if the output measure reflects a productivity index (e.g. labour productivity).
Value added (0/1)	Dummy variable=1 if output is measured as value-added.
R&D capital stock (0/1)	Dummy variable=1 if the specification includes R&D capital stock as a measure of R&D input.
R&D intensity (0/1)	Dummy variable=1 if the specification includes R&D intensity as a measure of R&D input.
Alternative R&D input (0/1)	Dummy variable=1 if the specification includes one of the following R&D input measures: R&D expenditure, R&D dummy variable, difference firm and sectoral R&D intensity and R&D labour stock; or estimates R&D impacts using the LP-DJ procedure which adopts no R&D input measure.
Human capital (0/1)	Dummy variable=1 if the specification includes a measure of the stock of human capital.
CRS imposed (0/1)	Dummy variable=1 if the article states to impose constant rates of scale (CRS) on labour and physical capital coefficients in a given specification ($\alpha + \beta = 1$).
Correction double counting (0/1)	Dummy variable=1 if the article states to remove R&D expenditure components in labour and/or physical capital inputs in a given specification in order to avoid a double counting bias.
Correction expensing bias (0/1)	Dummy variable=1 the article states to tackle the expensing bias resulting from the expensing rather than capitalisation of R&D in a given econometric specification.

Table A3.2 Summary statistics – Meta-analysis of R&D output elasticity estimates

Variable	N	Mean	Median	Min	Max	SD
R&D output elasticity	624	0.1108	0.089	-1.008	0.73	0.1276
Unit Industry (0/1)	624	0.1282	0	0	1	-
Unit Economy (0/1)	624	0.4167	0	0	1	-
Cross and within unit variation (0/1)	624	0.7099	1	0	1	-
Within unit variation (0/1)	624	0.2067	0	0	1	-
Time period (in years)	624	18.8590	20	1	44	11.4916
Relative data vintage (first year)	624	25.0128	25	1	47	10.9242
Sample size (observations in 100)	479	13.7385	3.54	0.24	110.04	21.8551
Productivity index (0/1)	624	0.6699	1	0	1	-
Value added (0/1)	624	0.1522	0	0	1	-
R&D intensity (0/1)	624	0.2067	0	0	1	-
Alternative R&D input (0/1)	624	0.0385	0	0	1	-
Human capital (0/1)	624	0.2212	0	0	1	-
CRS imposed (0/1)	624	0.2500	0	0	1	-
Correction double counting (0/1)	624	0.1699	0	0	1	-
Correction expensing bias (0/1)	624	0.0096	0	0	1	-

Table A3.3 Summary statistics – Meta-analysis of private return to R&D estimates

Variable	N	Mean	Median	Min	Max	SD
Private return to R&D	206	0.5086	0.30	-0.01	3.48	0.5246
Unit Industry (0/1)	206	0.2233	0	0	1	-
Unit Economy (0/1)	206	0.0825	0	0	1	-
Cross and within unit variation (0/1)	206	0.6068	1	0	1	-
Within unit variation (0/1)	206	0.1165	0	0	1	-
R&D Converted estimate (0/1)	206	0.4320	1	0	1	-
Time period (in years)	206	12.6866	10	3	31	6.7328
Relative data vintage (first year)	206	32.0728	34	6	47	10.1573
Sample size (observations in 100)	187	12.6866	8.95	0.21	83.36	10.1573
Productivity index (0/1)	206	0.4709	0	0	1	-
Value added (0/1)	206	0.3641	0	0	1	-
R&D intensity (0/1)	206	0.6068	1	0	1	-
Human capital (0/1)	206	0.0437	0	0	1	-
CRS imposed (0/1)	206	0.3204	0	0	1	-
Correction double counting (0/1)	206	0.3350	0	0	1	-
Correction expensing bias (0/1)	206	0.0583	0	0	1	-

Source: OECD, own calculations based on a survey of peer-reviewed articles and selected economic research working papers on the impact of R&D on productivity and economic growth as published over 2000-2010.

Notes: The meta-analysis covers both statistically significant and insignificant estimates, adopting a 10% significance level as threshold, as reported in overall 66 empirical publications. Summary statistics are provided for the variables included in the specifications.

ANNEX 4: META-ANALYSIS: ROBUSTNESS TESTS

Table A4.1 Meta-analysis of R&D output elasticity estimates [significant estimates ONLY]

Summary statistics

Variable	N	Mean	Median	Min	Max	SD
R&D output elasticity	538	0.1213	0.1173	-0.4	0.73	0.1173
Unit Industry (0/1)	538	0.1394	0	0	1	-
Unit Economy (0/1)	538	0.4554	0	0	1	-
Cross and within unit variation (0/1)	538	0.7658	1	0	1	-
Within unit variation (0/1)	538	0.1729	0	0	1	-
Time period (in years)	538	19.8625	20	1	44	11.4854
Relative data vintage (first year)	538	24.1784	24	1	47	10.8569
Sample size (observations in 100)	415	14.0582	3.52	0.24	110.04	22.7413
Productivity index (0/1)	538	0.6952	1	0	1	-
Value added (0/1)	538	0.1561	0	0	1	-
R&D intensity (0/1)	538	0.1617	0	0	1	-
Alternative R&D input (0/1)	538	0.0297	0	0	1	-
Human capital (0/1)	538	0.2454	0	0	1	-
CRS imposed (0/1)	538	0.2584	0	0	1	-
Correction double counting (0/1)	538	0.1617	0	0	1	-
Correction expensing bias (0/1)	538	0.0093	0	0	1	-

Ordinary Least Squares (OLS) Regression

R&D output elasticity	(1)	(2)	(3)	(4)	(5)	(6)
Unit Industry (0/1)	0.032	-0.023	0.008	0.032	0.046	0.045
	(0.020)	(0.020)	(0.020)	(0.024)	(0.026)*	(0.028)
Unit Economy (0/1)	0.013	-0.048	-0.013	0.012	0.041	0.043
	(0.010)	(0.016)***	(0.021)	(0.023)	(0.031)	(0.031)
Cross and within unit variation (0/1)		-0.038	-0.044	-0.023	-0.020	-0.016
		(0.028)	(0.030)	(0.028)	(0.029)	(0.030)
Within unit variation (0/1)		-0.043	-0.065	-0.051	-0.047	-0.045
		(0.030)	(0.032)**	(0.032)	(0.032)	(0.034)
Time period (in years)		-0.001	-0.002	-0.002	0.002	0.002
		(0.001)	(0.001)*	(0.001)*	(0.002)	(0.002)
Relative data vintage (first year)		-0.004	-0.004	-0.004	-0.001	-0.001
		(0.001)***	(0.001)**	(0.002)**	(0.002)	(0.002)
Sample size (observations in 100)			0.001	0.001	0.001	0.001
			(0.000)**	(0.000)***	(0.000)**	(0.000)**
Productivity index (0/1)				-0.036	-0.046	-0.044
				(0.025)	(0.026)*	(0.033)
Value added (0/1)				-0.027	-0.036	-0.034
				(0.020)	(0.021)*	(0.024)
R&D intensity (0/1)				0.021	0.036	0.035
				(0.023)	(0.026)	(0.026)
Alternative R&D input (0/1)				0.113	0.134	0.135
				(0.045)**	(0.048)***	(0.049)***
Human capital (0/1)					-0.063	-0.066
					(0.022)***	(0.024)***
CRS imposed (0/1)						-0.009
						(0.010)
Correction double counting (0/1)						0.007
						(0.017)
Correction expensing bias (0/1)						0.022
						(0.067)
Constant	0.111	0.287	0.281	0.261	0.138	0.117
	(0.007)***	(0.060)***	(0.074)***	(0.078)***	(0.101)	(0.108)
R-squared	0.01	0.04	0.06	0.09	0.10	0.10
Number of estimates (N)	538	538	415	415	415	415

* *p*<0.1; ** *p*<0.05; *** *p*<0.01

Source: OECD, own analysis based on a survey of peer-reviewed articles and selected economic research working papers on the impact of R&D on productivity and economic growth as published over 2000-2010.

Notes: The meta-analysis covers 54 publications and is exclusively based on estimates that are statistically significant at a 10% level. The reference group comprises firm-level studies that employ estimators which exclusively rely on the cross-sectional variation in the data, adopt sales as a measure of output and R&D capital as a measure of R&D input. Standard errors are robust to heteroskedasticity. Summary statistics are provided for variables included in at least one specification.

Table A4.2 Meta-analysis of private return to R&D estimates [selected, significant estimates ONLY]

Summary Statistics

Variable	N	Mean	Median	Min	Max	SD
Private return to R&D	139	0.3935	0.239	0.0291	2.029	0.4169
Unit Industry (0/1)	139	0.1151	0	0	1	-
Unit Economy (0/1)	139	0.1151	0	0	1	-
Cross and within unit variation (0/1)	139	0.5108	1	0	1	-
Within unit variation (0/1)	139	0.1295	0	0	1	-
R&D Converted estimate (0/1)	139	0.2446	0	0	1	-
Time period (in years)	139	11.5684	10	3	31	7.6367
Relative data vintage (first year)	139	32.6115	35	6	47	11.2059
Sample size (observations in 100)	139	15.5274	14.54	0.21	83.36	13.6325
Productivity index (0/1)	139	0.4173	0	0	1	-
Value added (0/1)	139	0.3669	0	0	1	-
R&D intensity (0/1)	139	0.7698	1	0	1	-
Human capital (0/1)	139	0.0647	0	0	1	-
CRS imposed (0/1)	139	0.2518	0	0	1	-
Correction double counting (0/1)	139	0.2950	0	0	1	-
Correction expensing bias (0/1)	139	0.0576	0	0	1	-

Ordinary Least Squares (OLS) Regression

Private return to R&D	(1)	(2)	(3)	(4)	(5)	(6)
Unit Industry (0/1)	0.144 (0.145)	0.499 (0.120)***	0.465 (0.127)***	0.380 (0.242)	0.373 (0.242)	0.171 (0.300)
Unit Economy (0/1)	-0.025 (0.078)	1.003 (0.212)***	1.243 (0.231)***	0.888 (0.417)**	0.890 (0.414)**	1.381 (0.486)***
Converted estimate (0/1)	-0.307 (0.060)***	-0.509 (0.080)***	-0.603 (0.102)***	-0.071 (0.111)	-0.069 (0.112)	0.311 (0.103)***
Cross and within unit variation (0/1)		0.337 (0.083)***	0.406 (0.088)***	0.321 (0.175)*	0.319 (0.175)*	0.907 (0.180)***
Within unit variation (0/1)		-0.019 (0.049)	0.000 (0.051)	-0.280 (0.126)**	-0.288 (0.125)**	-0.075 (0.130)
Time period (in years)		-0.012 (0.014)	-0.021 (0.015)	-0.007 (0.019)	-0.006 (0.018)	-0.036 (0.018)**
Relative data vintage (first year)		0.024 (0.013)*	0.033 (0.015)**	0.019 (0.015)	0.019 (0.015)	-0.007 (0.005)
Sample size (observations in 100)			-0.011 (0.003)***	-0.008 (0.003)***	-0.008 (0.003)***	-0.018 (0.004)***
Productivity index (0/1)				0.072 (0.087)	0.077 (0.086)	-0.609 (0.193)***
Value added (0/1)				0.376 (0.128)***	0.380 (0.129)***	-0.083 (0.149)
R&D intensity (0/1)				0.620 (0.170)***	0.624 (0.171)***	1.343 (0.187)***
Human capital (0/1)					-0.043 (0.062)	-0.071 (0.040)*
CRS imposed (0/1)						0.493 (0.160)***
Correction double counting (0/1)						0.202 (0.107)*
Correction expensing bias (0/1)						-0.881 (0.348)**
Constant	0.455 (0.049)***	-0.474 (0.585)	-0.487 (0.641)	-0.883 (0.601)	-0.902 (0.601)	-0.245 (0.253)
R-squared	0.10	0.33	0.41	0.55	0.55	0.59
Number of estimates (N)	139	139	125	125	125	125

* $p<0.1$; ** $p<0.05$; *** $p<0.01$

Source: OECD, own analysis based on a survey of peer-reviewed articles and selected economic research working papers on the impact of R&D on productivity and economic growth as published over 2000-2010.

Notes: The meta-analysis covers 19 publications and is exclusively based on estimates that are statistically significant at a 10% level. Converted estimates above a 0.3 threshold are likewise excluded from the analysis (see Section 5.1.2, Figure 3). Estimates of private returns to R&D indicate rates of return gross of depreciation. The dummy variable "Alternative R&D input" – equal to 1 in the case of 3 observations – was omitted from the regression due to multicollinearity. The reference group comprises firm–level studies that employ estimators which exclusively rely on the cross-sectional variation in the data, adopt sales as a measure of output and R&D capital as a measure of R&D input. Standard errors are robust to heteroskedasticity. Summary statistics are provided for variables included in at least one specification.

Table A4.3 Meta-analysis of R&D output elasticity estimates [including region fixed effects]

Ordinary Least Squares (OLS) Regression

R&D output elasticity	(1)	(2)	(3)	(4)	(5)	(6)
Unit Industry (0/1)	0.025 (0.042)	-0.043 (0.045)	-0.027 (0.059)	0.043 (0.064)	0.049 (0.061)	-0.047 (0.076)
Unit Economy (0/1)	0.070 (0.027)***	-0.027 (0.028)	-0.029 (0.033)	0.034 (0.030)	0.110 (0.062)*	0.060 (0.058)
Europe (0/1)	-0.031 (0.015)**	-0.064 (0.015)***	-0.058 (0.023)**	-0.051 (0.022)**	-0.061 (0.023)***	-0.080 (0.027)***
North America (0/1)	-0.056 (0.033)*	-0.138 (0.046)***	-0.134 (0.056)**	-0.091 (0.066)	-0.122 (0.077)	-0.174 (0.080)**
Cross and within unit variation (0/1)		-0.085 (0.029)***	-0.083 (0.033)**	-0.033 (0.031)	-0.016 (0.034)	-0.005 (0.034)
Within unit variation (0/1)		-0.087 (0.028)***	-0.101 (0.031)***	-0.072 (0.028)**	-0.060 (0.029)**	-0.072 (0.028)**
Time period (in years)		0.004 (0.003)	0.001 (0.004)	0.001 (0.004)	0.003 (0.004)	0.004 (0.005)
Relative data vintage (first year)		-0.002 (0.002)	-0.003 (0.004)	-0.002 (0.004)	-0.000 (0.004)	0.000 (0.005)
Sample size (observations in 100)			0.000 (0.000)	0.001 (0.000)	0.001 (0.000)	0.001 (0.000)*
Productivity index (0/1)				-0.072 (0.029)**	-0.063 (0.030)**	-0.029 (0.039)
Value added (0/1)				-0.023 (0.019)	-0.032 (0.020)	-0.026 (0.021)
R&D intensity (0/1)				0.053 (0.039)	0.070 (0.043)	0.042 (0.043)
Alternative R&D input (0/1)				0.091 (0.041)**	0.101 (0.043)**	0.065 (0.044)
Human capital (0/1)					-0.134 (0.062)**	-0.162 (0.059)***
CRS imposed (0/1)						-0.071 (0.026)***
Correction double counting (0/1)						0.005 (0.016)
Correction expensing bias (0/1)						0.247 (0.069)***
Constant	0.117 (0.012)***	0.234 (0.098)**	0.315 (0.162)*	0.224 (0.184)	0.140 (0.160)	0.150 (0.203)
R-squared	0.03	0.09	0.09	0.12	0.14	0.19
Number of estimates (N)	362	362	241	241	241	241

* *p*<0.1; ** *p*<0.05; *** *p*<0.01

Source: OECD, own analysis based on a survey of peer-reviewed articles and selected economic research working papers on the impact of R&D on productivity and economic growth as published over 2000-2010.

Notes: The meta-analysis covers 36 publications and includes both statistically significant and insignificant estimates, applying a 10% significance level as threshold. The country coverage is confined to single country studies that allow for a categorization of estimates by region (Europe, Asia and North America). Estimates form multi-country studies are considered whenever they are country specific. The reference group comprises firm-level studies covering Asian economies (CHN, JPN, TWN and SGN) that employ estimators which exclusively rely on the cross-sectional variation in the data, adopt sales as a measure of output and R&D capital as a measure of R&D input. Standard errors are robust to heteroskedasticity. Summary statistics are provided for variables included in at least one specification.

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