CPB Netherlands Bureau for Economic Policy Analysis

CPB Discussion Paper | 313

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Abstract

This paper analyses the economic returns to public R&D investments in 22 OECD countries. We exploit a dataset containing time-series from 1963 to 2011 and estimate and compare the outcomes of different types of production function models. Robustness analyses are performed to test the sensitivity of the outcomes for particular model specifications, sample selections, assumptions with respect to the construction of R&D stocks, and variable definitions. Analyses based on Cobb-Douglas and translog production functions mostly yield statistically insignificant or negative returns. In these models we control for private and foreign R&D investments and the primary production factors. Models including additional controls, such as public capital, the stock of inward and outward foreign direct investment, and the shares of high-tech imports and exports, yield more positive returns. Our findings suggest that public R&D investments do not automatically foster GDP and TFP growth. The economic return to scientific research seems to depend on the specific national context.

JEL Codes: I23, O11, O40, O47.

Keywords: science, knowledge, public R&D, economic growth, total factor productivity

* We would like to thank Philip Hans Franses, Noé van Hulst, Luc Soete and Piet Donselaar for valuable comments on earlier drafts. We are also grateful for useful feedback from seminar participants at the IMF, the European Commission, and the Dutch Ministry of Education, and from participants at the *Impact of Science* conference in Amsterdam. Furthermore, we wish to thank Sultan Mehmood and Riley Badenbroek for excellent research assistance. The programs and data used in this paper are available from the authors upon request.

1. Introduction

The main source of modern economic growth lies in productivity growth (Kuznets, 1966; Maddison, 2007), and technological progress is the ultimate source of productivity growth (Abramovitz, 1956; Solow, 1957). That is why the analysis of the role of technological progress, as well as the role of skilled labour in generating it, traditionally plays a large role in analysing economic growth (Schumpeter 1934; Kaldor, 1957; Freeman et al., 1982; Fagerberg, 1988). Formal growth theory, which became dominated by the production function framework from the late 1950s onwards, explicitly modelled technological progress only from the 1990s, long after research and development (R&D, one of the main sources of technological progress) had been integrated in the production function by Griliches (1979). In the "endogenous growth theory" that emerged from formalizing the insights about technology and growth, attention has been focused on the interactions between technology, physical capital and human capital (e.g., Romer, 1986, 1990; Lucas, 1988). Basically endogenous growth theory has added the stock of ideas and human capital to the familiar inputs of physical capital and workers (e.g., Grossman and Helpman, 1991; Aghion and Howitt, 1992; Jones, 2002). The production of ideas and human capital comes with a number of externalities. Human capital formation requires education, but individuals are not always able to borrow against their future human capital. Ideas are capitalized through private investments in R&D, but are to some extent non-rival and non-excludable. R&D investments are also often risky and come with benefits that only materialize in the long run. Internalization of the externalities of this research effort could be a reason for government intervention in terms of public R&D investments. This involves a range of possible investments, such as government funding to foster research in universities or stimulating the absorptive capacity of the economy by adopting appropriate education policies or by designing responsive institutions.

Measurement of the returns to investments in science, technology and innovation (STI) is complex because of the high variability (high risk and a very skewed distribution of returns), because of important complementarities among key endogenous variables (e.g., ideas, human capital and institutions), because of different goals (e.g., radical innovation and imitation) and because the chain of effects is long and often observed indirectly only. These arguments are even stronger for publicly funded or performed R&D, because the returns are even more indirect than in the case of private investments. Despite this difficulty of measuring the returns to public investments, about 30 percent of total R&D expenditures in the OECD area is spent by the government and the higher education sector.[1] In addition, there is evidence in historical cases about specific government-funded projects leading to substantial economic payoffs in the private sector (Mazzucato, 2013). However, the body of econometric studies that rely on production functions to estimate the impact of government-funded R&D shows mixed results (we review these studies below).

This paper contributes to a further understanding of the role of public investments in STI in fostering economic development by documenting econometric estimates of a range of productions functions. Rather than trying to approximate the exact mechanisms for the returns to public investments to materialize in an underlying model, we take an agnostic approach and estimate a macroeconomic relationship between GDP per capita (growth) or TFP (growth) and a number of inputs, for a sample of 22 OECD countries in the period 1963-2011.

[1] In the period 2010-2013 (most recent data available), the joint share of the government and higher education sector in total R&D expenditures in the OECD area fell from 30.9 to 28.9 percent (OECD, 2014).

We estimate three categories of models. We start by estimating Cobb-Douglas production functions that include public, private and foreign R&D, and the primary production factors as inputs.[2] These models assume log-linearity and constant returns to scale. This seems to be a restrictive approach in light of the complexity of the relationship between technology and economic growth. The theory of innovation systems (Lundvall, 1992; Nelson, 1993; Freeman, 1995) stresses that rates of return to (public) R&D can differ across countries because the nature of innovation systems differs, due to availability of actors, their capabilities, and the institutions and culture in the specific country. In addition, rates of return across countries may also differ because of differences in the kind of R&D performed or the specific public sectors that perform the R&D (e.g., universities vs. public labs). That is why we proceed with estimating two types of models that allow for country-specific returns to R&D by including interaction terms between the input factors.

First, we estimate translog models that allow for a more flexible production function and include inputs similar to the Cobb-Douglas models. Second, we estimate augmented production function models that introduce additional inputs (such as public capital, the stock of inward and outward foreign direct investment, and the shares of high-tech imports and exports) that are aimed specifically at capturing the variability in rates of return to R&D.

For our analyses we use data on R&D expenditures from the OECD's Main Science and Technology Indicators (MSTI) and on economic measures from the Penn World Tables (PWT). We perform a large set of robustness analyses to test the sensitivity of the outcomes for particular model specifications, sample selections, assumptions with respect to the construction of R&D stocks, and variable definitions. By comparing various estimation methods, we obtain a balanced view of the relationship between indicators of economic development and public R&D investments and provide guidelines for estimating the macroeconomic returns of STI, in particular the economic effects of public investments.

The main results of the estimated returns from these production functions are the following. The Cobb-Douglas models yield mostly statistically insignificant returns, with estimated elasticities varying from -0.12 to 0.09. The translog models yield mostly statistically significant negative elasticities, with point estimates ranging from -0.29 to 0.01. In the augmented models most of the estimated elasticities are positive and statistically significant. Point estimates are in a range from -0.02 to 0.07.[3] Our findings suggest that public R&D investments do not automatically foster economic growth and that the economic return depends on the specific national context.

Our study is part of a literature that tries to estimate the returns to public investments in STI from a macroeconomic cross-country perspective. This limits the scope of the conclusions that can be drawn from this exercise. First, the estimated coefficients show the economic impact of public investments in STI and do not address the potential broader societal impact. Second, we are unable to assess the returns to specific types of measures to foster economic development. Country-level STI variables are broad indicators that include expenditures on various types of R&D and on R&D performed by different public sectors. In addition, macro-economic analyses directly assess the impact of STI on economic growth and provide only limited insight into the complex underlying mechanisms, although the more flexible production functions go a long way into this direction.

The structure of this paper is as follows. Section 2 reviews the economic literature on the effects of public R&D investments. Section 3 addresses the theoretical insights underlying our three main

[2] The Cobb-Douglas functions are also estimated in an error-correction model framework.
[3] The presented estimates in the translog and augmented models concern average elasticities over all countries.

empirical approaches. Section 4 presents the data and Section 5 provides a detailed description of our methodology. Section 6 presents the estimation results. Section 7 concludes and discusses our findings.

2. Previous studies

There is an extensive literature that addresses the economic value of scientific research. An early summary of this literature that attempts to estimate the returns to publicly funded R&D is in Salter and Martin (2001). They identify three main methodological perspectives: econometrics, surveys and case studies. The (few) case studies that Salter and Martin survey attempt to trace the impact of government-funded research, and usually do not yield quantitative estimates of the return. The econometric studies included in their study are mostly aimed at specific government R&D programs, usually successful ones so that a sample selection bias does exist. These econometric studies are mostly aimed at the United States and show high rates of return (ranging from 20-67%). The survey work summarized by Salter and Martin was initiated by Mansfield (1991), who asked company managers how many of their products (and what proportion of sales) could not have been developed without the aid of government-funded basis research, or which received ‘substantial aid’ from this kind of research. Using the results of the survey, Mansfield calculates a rate or return of 28% to government-funded basic research.

Gheorghiou (2015) extends the overview by Salter and Martin by surveying 27 studies on the economic returns of publicly funded research, including 12 studies that were published after Salter and Martin’s (2001) review. These studies use the same variety of methodologies as observed by Salter and Martin, and also yield a wide variety of indicators on economic returns. 12 of the 27 studies can be characterized as case studies of specific government-funded R&D projects. All these studies report revenues being a multitude of investments, although they do not yield specific rates of return. Another group of 5 studies looks at the use of publicly-funded research by private firms, either by surveys or by looking at citations made in patents to the scientific literature. This yields an estimate of which fraction of private sector innovation projects (or patents) would not have been possible without public science projects feeding knowledge into them. The percentage ranges from 2-75% (the 75% refers to patents). The last category of studies surveyed by Gheorghiou includes 10 studies that yield specific estimates of the rate of return to public R&D, either by using econometric modelling, or by the techniques that Mansfield (1991) pioneered. These rates are always positive, and vary between 12% and 100%.

The econometric literature on the economic returns to R&D investments largely focuses on the impact of private R&D spending on economic growth and productivity (Hall et al., 2010). The number of empirical studies that explicitly takes public R&D into account is limited. Table 1 summarizes the findings of the most important studies in this area. These are all studies that distinguish explicitly between public and private R&D. The studies differ in terms of their sample and in terms of their dependent and independent variables. Some papers investigate GDP (per capita) growth directly, whereas other use productivity (TFP) as the main outcome. The included R&D variables are expressed either in terms of flows of spending as a percentage of GDP or in terms of stocks of spending. Most of the studies use panel data exploiting both differences across countries and over time. Two of the studies only use cross-section (Lichtenberg, 1993) or time-series (Haskel and Wallis, 2013) information.

The estimated effects of public R&D investments on economic growth or productivity vary widely, ranging from significantly positive to significantly negative coefficients. Positive coefficients are found by Guellec and Van Pottelsberghe (2004), Khan and Luintel (2006) and Haskel and Wallis (2013). The first two of these studies distinguish public R&D from private and foreign R&D and estimate the effects on productivity. Guellec and Van Pottelsberghe use an error-correction model to address both short-term and long-term dynamics and conclude that public R&D has a positive long term impact on productivity. The estimated elasticity for public R&D of 0.17 is even larger than that for private R&D (0.13).

Khan and Luintel (2006) set out to reproduce these results, but fail when using the same model with more recent data and a slightly different set of countries. However, when they estimate a model that includes additional explanatory variables such as public infrastructure, foreign direct investments and the share of high-tech imports and exports, they find positive rates of return to public R&D. The model with these additional variables is aimed at capturing the heterogeneity of rates of return across countries, a topic to which we return extensively below. The average estimated elasticity across 16 OECD countries equals 0.21.

A recent study for the United Kingdom by Haskel and Wallis (2013) distinguishes between different kinds of public R&D, including R&D disbursed through the research councils in the country. They find a robust correlation between R&D channelled through research councils and TFP growth, while overall public R&D does not correlate positively with TFP growth.

Coe et al. (2009) employ a larger dataset and similar methodology to the Guellec and Van Pottelsberghe (2004) to reach a different conclusion. They "included measures of publicly financed R&D but did not find that these were significant or robust determinants of total factor productivity" (p. 730). A panel study by Park (1995) also yields negative, but statistically insignificant effects. Two studies even find significant negative effects. Bassanini et al. (2001) use panel data for 15 OECD countries and include both private and public R&D intensities as independent variables. They find a positive estimated effect for private R&D (0.26) and a negative effect for public R&D (-0.37). The authors point to crowding out of private R&D initiatives as a potential explanation for the negative effects of public R&D. In addition they mention that publicly performed research may not be directly targeted at productivity improvements, but rather at generating basic knowledge. The impact of basic knowledge on economic performance is difficult to identify because of the time lags involved and the complex interactions leading to technology spillovers. Lichtenberg (1993), who performs a cross-sectional analysis using average R&D intensities (but not foreign R&D) of 53 countries, also finds negative effects. He argues that a large fraction of public R&D funds is spent on research that does not directly benefit economic growth, such as medical and humanities research.

The picture that emerges from the macroeconomic econometric literature is that the relationship between public R&D spending and economic growth is not very robust. The findings in these studies seem to depend on the model specifications and variable definitions. Our approach aims to contribute to the literature by estimating and comparing the estimates of the most commonly used specifications. This provides a broad overview of estimates of various macroeconomic approaches. In comparison to previous studies, we build a panel database (n=967) with a long time series (1963-2011) for a large number of countries (22 countries). This is important, not only from a statistical point of view, but also because of the long lags involved in the relationship between public R&D and economic outcomes.

Table 1. Summary of macro-econometric literature on the impact of public R&D investments

Authors	Year	Journal/Book	Method	Number of countries	Years	Observations	Dependent variable	Independent variable	Other covariates	Estimated impact of public R&D investments
Lichtenberg	1993	in Siebert H. (ed.), Economic Growth in the World Economy	Cross-section	53	1960-1985	53	Log GDP per capita in 1985/ Log GDP growth per capita 1960-1985	Mean public R&D expenditures % GDP	Total R&D investment, capital formation, human capital	Neutral and negative
Park	1995	Economic Inquiry	Pooled	10	1970-1987	150	Log GDP growth per work hour	Change in log stock of public R&D expenditures per work hour	Physical capital, private R&D per work hour, capacity utilization rate	Negative (non-significant)
Bassanini et al.	2001	OECD Working Paper	Pooled	15	1971-1998	236	Log GDP growth per capita	Log Public R&D expenditures % GDP	Lagged ΔLog GDP, capital formation, human capital, population growth, private R&D	Negative
Guellec and Van Pottelsberghe	2004	Oxford Bulletin of Economics and Statistics	Pooled	16	1980-1998	302	Multifactor productivity growth	Stock and growth of Public R&D expenditures	Stock and growth of private and foreign R&D expenditures, employment rate growth	Positive
Khan and Luintel	2006	OECD Working Paper	Pooled	16 (OECD)	1980-2002	333	Total factor productivity	Stock of public R&D expenditures	Stock and growth of private and foreign R&D expenditures, public infrastructure, foreign direct investment, share of high tech imports and exports	Positive (when adding interactions)
Coe et al.	2009	European Economic Review	Pooled	24	1971-2004	816	Multifactor productivity growth	Stock of public R&D expenditures	Stock of private and foreign R&D expenditures, institutions.	"non-robust and non significant".
Haskel and Wallis	2013	Economics Letters	Time-series	1 (UK)	1980-2009	17	Log market sector total factor productivity growth	Total public R&D expenditures % GDP		Non-significant for overall R&D; Positive for research council R&D

3. Models and theory

Our empirical strategy is based on three broad categories of models: one that is derived directly from a simple production function framework (Cobb-Douglas models), one that attempts to introduce more flexibility in the production function, and does so using an assumption of strong optimality (translog models), and finally one that introduces more flexibility and uses a less strict set of assumptions about optimality (augmented models).

Modern growth theory suggests that new ideas and technological improvements foster economic development. The accumulation of knowledge through investments in human capital and R&D features in these models as a crucial determinant of technological progress and subsequent economic development and productivity growth (e.g., Romer, 1986; 1990; Lucas, 1988; Grossman and Helpman, 1991; Aghion and Howitt, 1992 for the landmark contributions in modern growth theory). The Cobb-Douglas models that we estimate build on these growth models and also follow in the tradition of the work on R&D and productivity in the private sector, as pioneered by Zvi Griliches and his research group (see Griliches, 1998 for an overview). This approach postulates a production function with value added (GDP) as the output variable, a set of "traditional" input variables (employment, capital stock), and R&D-related knowledge stocks. This approach typically looks at cumulated R&D variables (R&D stocks) rather than current R&D outlays (R&D flows). Various types of knowledge capital are likely to affect economic growth through different mechanisms. Human capital investments directly improve the skills of the labour force; private R&D leads to improved products, processes and services; public R&D improves scientific knowledge via basic (or applied) research performed by universities or other public institutions; and foreign R&D affects a country's productivity through cross-border knowledge flows or spillovers. The impact of foreign R&D on a country's economic performance depends on its absorptive capacity (Cohen and Levinthal, 1990), which again can be enhanced by human capital and domestic R&D investments. We explicitly distinguish between different sources of knowledge contribution to economic progress by including human capital and three types of R&D capital (public, private and foreign) in the production functions.[4] In its simplest form, this approach uses a Cobb-Douglas production function, yielding a single equation (in logs) for estimation. A drawback of this model specification is that it assumes that the rates of return to the inputs are constant and hold sample-wide.

There are good theoretical reasons to expect that the assumption of the Cobb-Douglas production function is too restrictive. The literature on innovation systems argues that innovation is a collective process, in which many actors are involved, and that this process can be characterized by very different rates of return under different circumstances (Lundvall, 1992; Nelson, 1993; Soete et al., 2010). The essence of this body of theory is that the complexity of the relationships between the various actors in the innovation "system", as well as the highly uncertain nature of the innovation process, make it impossible for the actors in the system to behave in a fully rational way. Firms and other actors are boundedly rational, and behave in a semi-routinized way. In addition, the systems theory of innovation argues that most of the interactions take place in a limited environment, either locally from a geographical point of view ("regional systems"), within the institutions, culture and routines of national borders ("national systems"), or within the specificities that characterize innovation and production in a specific sector ("sectoral systems").

The outcome of the system, for example in the form of economic returns to investments in STI, depends on specific features and characteristics of the system, such as which actors are available, and

[4] Foreign R&D capital includes both foreign private and foreign public R&D.

what their capabilities are, how much interaction takes place between actors, and how well this interaction is organized, as well as which government policies are in effect. Government policy is motivated by systems failures rather than market failures. Systems failure is a more open and broad notion, leaving more options for government STI policy.

It is not the aim of this paper to apply innovation systems theory in econometric estimates of the rates of return of public R&D. But systems theory is a source of inspiration for our estimations because it stresses the heterogeneity of such rates or return. Across countries these rates of return are likely to vary, which seems to make a universal rate of return unrealistic. Yet, this is what a simple production function perspective explained above asserts.

Next to presenting estimates for Cobb-Douglas production functions we estimate models which allow for heterogeneity across countries. Our second framework is the translog production function (Christensen et al., 1973). This follows in the same tradition of production functions, but, by adding interaction terms between the input variables, builds flexibility into the production function. In effect, the rates or return become dependent on the value of the inputs itself (this will be explained formally below). Thus, the rates of return on public (or private) R&D can become dependent, for example, on the capital-to-labour ratio used in the country's production process, or on the ratio between public and private R&D.

However, the flexibility that the translog production function provides comes at the price of increased demands on rationality of the involved actors. The translog production function itself is a very flexible way of modelling the production process, which implies that to "discipline" its estimated coefficients, additional rigor has to be imposed by estimating it jointly with other equations. In practice, this is done by combining the production function with a number of first-order conditions of the profit-maximizing (or cost-minimizing) problem. This takes the form of additional equations for the factor shares of the inputs used in the production function.

The third theoretical perspective that we apply takes the flexibility (and variability) of rates of return a step further, and relaxes the optimality assumptions of the translog production function. It follows from the approach developed by the OECD (Khan and Luintel, 2006), and introduces additional variables that are solely aimed at capturing the variability in rates of return to R&D. We call this type of models 'augmented production function models'. This approach introduces interactions between the R&D variables and the newly introduced variables, thus in effect making the rates of return dependent on these new variables. By using the newly introduced variables in combination with the estimated parameters, the rates of return to the R&D variables can be calculated for each country, with the variation in the additional variables directly translating into variability of the rates of return to R&D across countries. A drawback of this approach is the large number of parameters to be estimated. Similar to the translog models, this requires restrictions on parameter values, all the more since the available sample of (additional) data is smaller (see Section 4). We discipline the estimates by using a stepwise estimation procedure. Another drawback of this approach is that it lacks a clear theoretical foundation regarding the choice of the additional input factors. Obviously, the quality of the estimates of the rates of return will depend on whether the adequate set of controls has been introduced.

All approaches have advantages and disadvantages. We do not a priori come down at the side of a particular model but estimate and interpret the whole range of estimated coefficients. A detailed presentation of the model specifications follows in Section 5.

4. Data

For our analysis we use a combined dataset containing information on R&D expenditures from OECD's Main Science and Technology Indicators (MSTI) and economic measures from the Penn World Tables (PWT) for a large set of countries over a relatively long time period. We use R&D expenditures as the only indicator for "public science", in full recognition of the fact that this is an incomplete measure. Also, we define "public science" on the basis of who performs the R&D (rather than who funds it), and use a broad categorization of "public". In particular, we consider all R&D that is not performed by private firms as public. In effect, this includes the government sector (public R&D labs), the higher education sector (universities), and the private non-profit sector. The latter is usually a small fraction of total public R&D. Because of limited data availability we make no attempt to break down public R&D by sector, field of science, or by military vs. civil use.

4.1 Data description

Our dataset combines two main sources. First, we use OECD data on R&D expenditures per country: the Main Science and Technology Indicators (MSTI). The OECD has collected such data since 1963 based on the guidelines in the *Frascati Manual*. We dispose of MSTI data on public and private R&D expenditures for 40 countries in the period 1963-2011 (maximum).[5] This is an unbalanced panel: information on R&D expenditures is not available for each country and each year. Information on R&D expenditures becomes available for a larger set of countries in more recent periods: in 1963 this includes 6 countries, in 1972 19 countries, in 1981 22 countries, in 1994 33 countries and in 2007 40 countries.

In our main analyses we restrict the estimation sample to 22 countries for which data are available from 1980. This is a set of highly developed countries including Australia, Austria, Belgium, Canada, Switzerland, Germany, Denmark, Spain, Finland, France, United Kingdom, Greece, Ireland, Iceland, Italy, Japan, the Netherlands, Norway, New Zealand, Portugal, Sweden and the Unites States. In the analyses we use all available data over the whole period 1963-2011 for each of these countries. This concerns on average 44 years per country. The total estimation sample consists of 967 observations.

We use the gross domestic expenditures on R&D (GERD) as an indicator of total R&D expenditures and the gross domestic expenditures on R&D performed by the business enterprise sector (BERD) as an indicator for the private R&D expenditures. Public R&D expenditures are defined as the difference between total and private R&D expenditures (GERD-BERD). This variable contains all resources devoted to research performed by universities and other public research institutions.[6]

Second, we use data on economic variables for each of these countries from Penn World Tables (PWT). As outcome variables we use real gross domestic product (GDP) and total factor productivity (TFP). GDP is in constant national prices (2005 US dollars) and TFP is an index variable that takes

[5] This dataset was constructed by merging the publicly available MSTI data from 1981 to older files stored in the archives of UNU-MERIT.

[6] We choose this definition (based on publicly performed research) because of better data availability. Other definitions of public R&D (based on government financed research, such as GBAORD and GovFinGERD) are used in robustness analyses. Both types of variables are strongly correlated. See the Frascati Manual and MSTI guideline for more information on the data collection and definitions.

value 1 for each country in 2005. In addition, we use physical capital (K), employment (L) and a human capital index (H) as additional production factors.[7]

In the augmented models we add explanatory variables to the traditional production factors. These variables include public capital, the stock of inward and outward foreign direct investments (FDI) and the share of high-tech imports and exports. Data on public capital stocks are shares of public capital in total capital, multiplied by our capital stock variable from PWT. The shares of public capital are taken from UN national accounts database supplemented with various national sources. Data on FDI (inward and outward stocks as percentage of GDP) are taken from the UNCTAD online database. Data on high-tech imports and exports are taken from the UN trade database using definitions of high-tech by OECD. These data are only available for the period from 1981 and missing for Greece, Iceland and New Zealand, so that these countries are missing from the estimations that include these variables.[8]

The R&D data from MSTI come from the currently publicly available records from 1981 and an older version from the UNU-MERIT archives. The amounts in the older dataset were translated into euros for the appropriate countries. To deal with small breaks in the data for the UK, the US and Sweden in 1981, we back casted the old observations using a factor based on the 1981 ratio. For each country and year we determined the ratio of R&D expenditures over GDP in current prices national currencies. This gives the yearly R&D flow variables expressed in fractions of GDP. Missing observations were interpolated linearly.

4.2 Construction of knowledge stocks

Most of the economic theory that deals with the returns to R&D investments uses the concept of knowledge capital stocks. The idea is that R&D investments create a knowledge stock that affects economic performance in the future. Such knowledge stock depends on all previous and current R&D investments, taking into account the depreciation of knowledge capital over time. Consistent with most of the literature we construct knowledge stocks using the perpetual inventory method. This implies that the current stock is constructed using the previous stock and adding the current expenditures minus a deprecation of the knowledge stock:

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

where KC_{it} is the knowledge capital stock of country i in year t, δ is the depreciation rate of knowledge capital and R_{it} denotes the R&D expenditures of country i in year t.

To obtain absolute values of R&D expenditures (R_{it}) we multiplied the flow variable on R&D by our measure for real GDP from PWT. Different assumptions can be made with respect to the depreciation rate. In our main analyses we use a rate of 15% and we test for the robustness of the results to other rates. The determination of the initial knowledge stock furthermore requires assumptions on the pre-sample growth rate. We choose the pre-sample growth rate such that the difference between that growth rate and the growth rate between the first and second period is minimized for each country. Alternatively, we use a single pre-sample growth rate of 5% in our robustness analyses. In order to construct foreign knowledge capital stocks we need additional assumptions on knowledge spillovers between different countries. We construct foreign knowledge capital stocks using weights based on bilateral migration flows. Hence, a country's R&D expenditures per capita spread out to all other

[7] We choose to use PWT because it contains economic data for a larger set of variables and countries compared to MSTI.
[8] The total number of observations in the analyses including those additional variables equals 584.

countries using the number of migrants as weights.[9] The following formula represents this relationship, where *i* is the destination country and *j* is the origin country:

$$R^F_{it} = \sum_j [\ (GERD_{jt} / POP_{jt})*MIGR_{ji}] \qquad (2)$$

The idea is that migration flows reflect the amount of knowledge exchange between countries. Alternatively, we construct foreign knowledge stocks using weights based on distance between countries.[10]

4.3 Descriptive statistics

Table 2 presents the average values by country over time of some important variables. The public and private R&D variables are shown as ratios of GDP.

Table 2. Average values by country (1963-2011)

	Public R&D expenditures as % GDP	Private R&D expenditures as % GDP	Employment (in million persons)	Human capital index	GDP per employed person (US$)	Yearly GDP growth	Initial year in dataset	Number of observations
AUS	0.8%	0.7%	8	3.3	61,480	3.1%	1976	36
AUT	0.6%	0.9%	4	2.5	55,075	2.7%	1967	45
BEL	0.5%	1.1%	4	2.8	60,356	2.4%	1967	45
CAN	0.7%	0.8%	13	3.1	60,430	2.8%	1971	41
CHE	0.5%	1.9%	4	2.8	59,384	1.9%	1963	47*
DEU	0.7%	1.7%	38	2.8	59,904	1.8%	1981	31
DNK	0.7%	1.0%	3	2.8	50,062	2.0%	1967	45
ESP	0.3%	0.4%	15	2.4	50,036	3.0%	1967	45
FIN	0.7%	1.4%	2	2.7	48,165	2.7%	1969	43
FRA	0.8%	1.2%	24	2.4	53,017	2.7%	1963	49
GBR	0.8%	1.3%	26	2.6	48,663	2.2%	1964	48
GRC	0.3%	0.1%	4	2.7	45,439	1.4%	1980	32
IRL	0.4%	0.5%	1	3.0	58,961	4.2%	1963	49
ISL	0.9%	0.6%	0	2.7	43,967	3.1%	1971	41
ITA	0.4%	0.5%	22	2.4	53,602	2.6%	1963	49
JPN	0.8%	1.7%	60	2.9	43,349	4.1%	1963	49
NLD	0.9%	1.0%	7	2.9	57,907	2.8%	1964	48
NOR	0.7%	0.8%	2	3.0	85,258	3.0%	1970	42
NZL	0.7%	0.3%	2	3.4	40,578	2.1%	1972	40
PRT	0.4%	0.2%	4	2.1	31,604	3.2%	1964	48
SWE	0.8%	1.9%	4	2.9	48,485	2.3%	1967	45
USA	0.8%	1.7%	113	3.4	65,986	3.0%	1963	49
Total								967

Notes. * Last observation in 2009.

[9] We obtain data on the number of migrants between countries from the World Bank. This method requires a balanced set of R&D expenditures for all countries over time (otherwise foreign R&D stock would increase over time by construction due to an increasing number of countries for which R&D expenditures are available in the data). Hence, for the purpose of constructing foreign knowledge stock we linearly extrapolated all R&D expenditure data back to 1963.

[10] Other studies have also used weights based on patent matrices or trade flows. We use migration flows because of better data availability.

The average public R&D expenditures vary from 0.3% in Spain and Greece to 0.9% in the Netherlands and Iceland. The private R&D expenditures differ more strongly among countries and take values between 0.1% in Greece and 1.9% in Switzerland and Sweden. Differences in employment are mainly due to country size. The human capital index is based on completed education levels and takes values between 1 and 5.[11] Average yearly economic growth has been lowest in Greece (1.4%) and largest in Japan (4.1%) over the relevant time period. The last two columns present the initial year in the dataset and the consequent number of observations for each country. The number of observations varies from 31 (for countries whose initial data have become available in 1981) to 49 (for countries whose initial data have become available in 1963).

Figure 1 shows the development of public R&D expenditures for each country over time. The resulting patterns do not show a large volatility over time. Most of the countries have gradually increased their R&D expenditures. In some countries, such as the Netherlands, R&D expenditures have been reasonably stable over time, while few countries, such as the United Kingdom, have decreased the R&D expenditures over the years.

Figure 1. Development of public R&D intensities over time

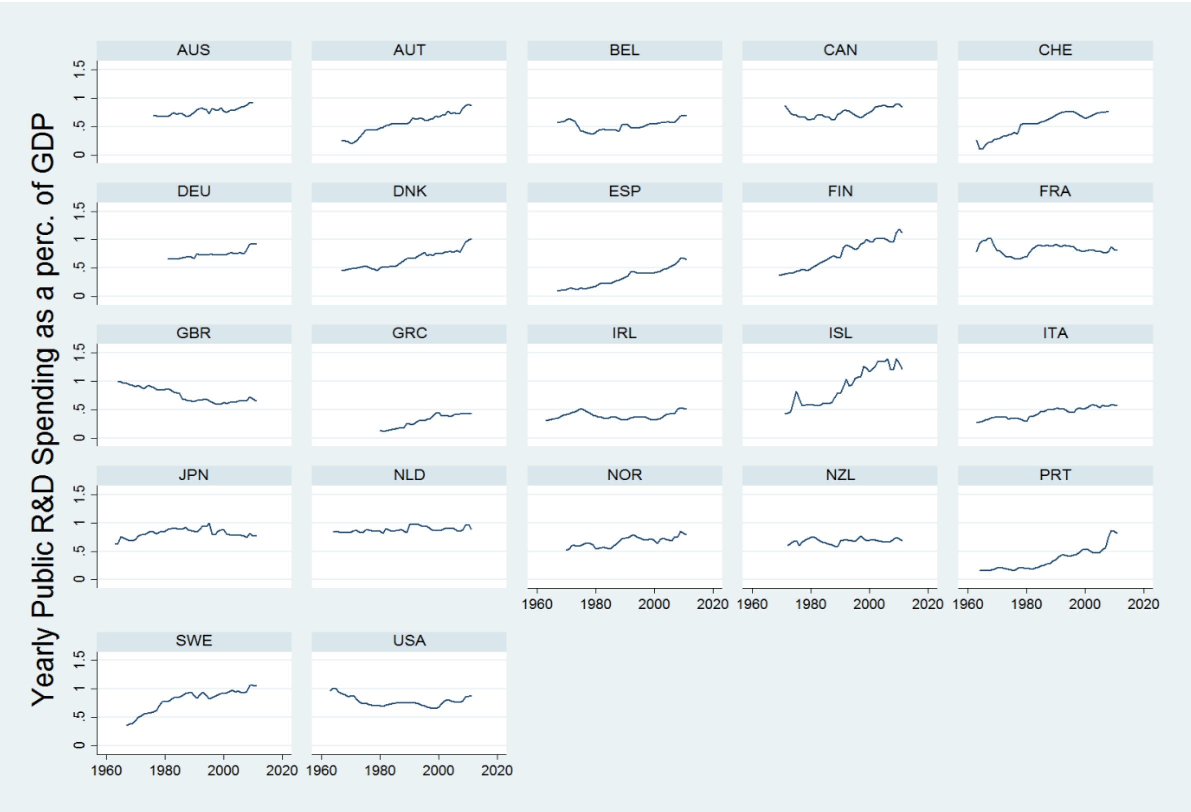


Table 3 presents the correlations between the most important variables in the analyses. In this table the logarithmic transformation of the stock variables are included, since these are used in the empirical analyses (see Section 5). The public R&D stock turns out to be strongly correlated to the private R&D stock as well as to the other primary production factors (physical capital and labour). The private R&D stocks are strongly related to the other production factors as well. Each of these input factors is also strongly correlated to the level of GDP, but less (and negative) to yearly GDP growth.

[11] A twice as high human capital index should be interpreted as a twice as high productivity.

The limited variation in public R&D expenditures over time and the strong correlation with other input factors complicates the empirical analysis of the isolated impact of public R&D on economic growth and productivity.

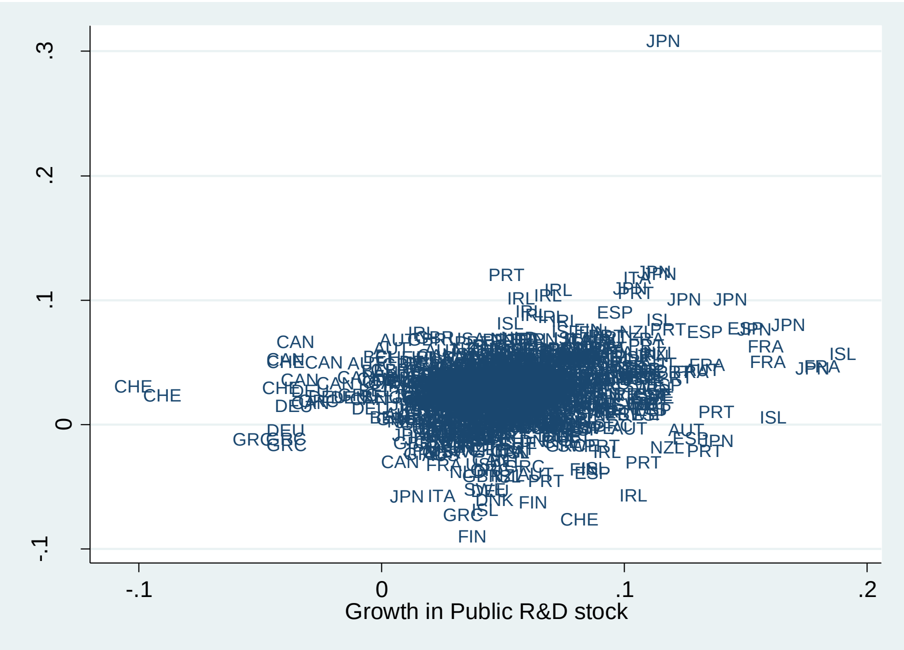
Table 3. Correlation table

	GDP growth	Log GDP t+1	Log public R&D stock	Log private R&D stock	Log foreign R&D stock	Public R&D expenditures % GDP	Log Physical capital	Log Employment
GDP growth	1.00							
Log GDP t+1	-0.08*	1.00						
Log pub. R&D stock	-0.14*	0.96*	1.00					
Log priv. R&D stock	-0.14*	0.92*	0.95*	1.00				
Log for. R&D stock	-0.20*	0.72*	0.75*	0.73*	1.00			
Public R&D exp.	-0.10*	0.18*	0.42*	0.40*	0.20*	1.00		
Log Physical capital	-0.13*	0.99*	0.96*	0.91*	0.69*	0.23*	1.00	
Log Employment	-0.10*	1.00*	0.96*	0.92*	0.73*	0.18*	0.99*	1.00

Notes. * denotes significance at a 1 % significance level.

Figure 2 depicts the relationship between the growth rate of the public R&D stock and next year's GDP growth rate. Each observation presents public R&D growth and related GDP growth in a specific country and year. The growth rate of the public R&D stock depends on the yearly investments, the previous stock and the deprecation rate (here, we assume a 15% depreciation rate). The pattern suggests no clear relationship between the growth of the public R&D stock and R&D growth. Obviously, the figure reflects only a direct association between the variables (not corrected for other covariates) and hence cannot be given a causal interpretation.

Figure 2. Relationship between public R&D (growth) and GDP (growth)



5. Methods

We use three types of production function models to estimate the effects of public R&D: Cobb-Douglas models, translog models and augmented models. In the first two models total production is a function of labour input, capital input and knowledge capital. The functional form of the production function seems to have a large influence on the results of estimations of R&D spillovers (Mohnen, 1992). To assess the effect of the functional form on the estimated coefficients of the return of public R&D, we estimate both the very stringent Cobb-Douglas production function and the very flexible translog production function. We define knowledge capital both in stocks and in flows. The Cobb-Douglas function is estimated for GDP as well as TFP, and also estimated in an error-correction framework. In the augmented models we extend the production functions further by adding other variables that may affect productivity or the effectiveness of knowledge investments.

5.1 Cobb-Douglas production functions

We extend the Cobb-Douglas function by including knowledge capital. In line with Mankiw et al. (1992) we include a variable for human capital (*H*). We split domestic knowledge stocks as in Hall et al. (2010) into a private (KC^P), a public (KC^G), and a foreign (KC^F) knowledge stock. This yields the following production function:

$$Y_{it} = A_{it} K_{it}^{\alpha} L_{it}^{\beta} (KC_{i,t-1}^{P})^{\gamma} (KC_{i,t-1}^{G})^{\tau} (KC_{i,t-1}^{F})^{\theta} H_{i,t-1}^{\eta}, \tag{3}$$

where Y_{it} is total production of country *i* in year *t*, K_{it} is the stock of physical capital, L_{it} is the labour stock, and A_{it} is country- and time-specific technology. In the default specification we assume the effect of the knowledge stocks to be lagged by one year.

To estimate the model, we make a number of adjustments. First, we take labour and human capital together in a quality-adjusted labour variable *LH*. Second, we normalize *Y* and *K* by *LH*. Third, we split A_{it} into a country-specific technology (M_i) and a time-specific technology (Ω_t) component. Finally, we take logs on both sides and estimate the model in first differences, giving estimation equation

$$\Delta(y_{it} - lh_{it}) = \Delta\omega_t + \alpha\Delta(k_{it} - lh_{it}) + \gamma\Delta kc_{i,t-1}^{P} + \tau\Delta kc_{i,t-1}^{G} + \theta\Delta kc_{i,t-1}^{F} + \phi\Delta lh_{it} + \varepsilon_{it}, \tag{4}$$

where $\phi = \alpha + \beta - 1$.

When knowledge capital is defined in stocks, as in Equation (4), the effect of public R&D is estimated as a constant elasticity: $\tau = \frac{\partial Y}{\partial KC^G}\frac{KC^G}{Y}$. To estimate the model based on flows in R&D, let's first define $\rho = \frac{\partial Y}{\partial KC^G}$ as the marginal productivity of public R&D capital. Similarly, we define χ and ζ as the marginal productivities of private and foreign R&D. Second, the yearly change in knowledge capital is $\Delta KC_{it} = -\delta KC_{i,t-1} + R_{it}$, where δ is the depreciation rate of knowledge capital and $R_{i,t}$ are R&D expenditures in year *t*. Finally, if we assume that δ is sufficiently small, we can use $\Delta KC_{it} \approx R_{it}$ and rewrite Equation (4) as

$$\Delta(y_{it} - lh_{it}) = \Delta\omega_t + \alpha\Delta(k_{it} - lh_{it}) + \chi\frac{R^P_{i,t-1}}{Y_{i,t-1}} + \rho\frac{R^G_{i,t-1}}{Y_{i,t-1}} + \zeta\frac{R^F_{i,t-1}}{Y_{i,t-1}} + \phi\Delta lh_{it} + \varepsilon_{it}. \tag{5}$$ [12]

Instead of assuming a constant elasticity τ , Equation (5) assumes a constant marginal product ρ .When we further assume a constant discount rate *r*, ρ can be given the interpretation of the gross internal rate of return (not corrected for depreciation).

The elasticity τ and the rate of return ρ are related through $\frac{KC^G}{Y}$ so that estimates obtained for one can be easily translated into estimates of the other. In practice, however, the ratio of knowledge capital to GDP can vary substantially over time and across countries, so that estimating the model in flows instead of stocks can make a large difference for the estimated effects (Hall et al., 2010). Given this sensitivity, we will present estimates based on stocks as well as flows.

Another approach we can take to estimate the return to public knowledge capital is by estimating a model for total factor productivity (*TFP*). When we assume constant returns to scale, perfect competition and profit maximizing firms, we can replace α and β in Equation (3) by the income shares of capital ($\hat{\alpha}$) respectively (quality adjusted) labour ($\hat{\beta}$). Then, we can construct

$$TFP_{it} = \frac{Y_{it}}{K^{\alpha}_{it} LH^{\beta}_{it}}$$

and rewrite Equation (3) as

$$TFP_{it} = A_{it}(KC^P_{i,t-1})^{\gamma}(KC^G_{i,t-1})^{\tau}(KC^F_{i,t-1})^{\theta}. \tag{3'}$$

When we take logs and first differences we get estimation equation

$$\Delta tfp_{it} = \Delta\omega_t + \gamma\Delta kc^P_{i,t-1} + \tau\Delta kc^G_{i,t-1} + \theta\Delta kc^F_{i,t-1} + \varepsilon_{it} \tag{6}$$

for a TFP model in stocks, and

$$\Delta tfp_{it} = \Delta\omega_t + \chi\frac{R^P_{i,t-1}}{Y_{i,t-1}} + \rho\frac{R^G_{i,t-1}}{Y_{i,t-1}} + \zeta\frac{R^F_{i,t-1}}{Y_{i,t-1}} + \varepsilon_{it} \tag{7}$$

for the model in flows.

---

[12] We use here that $\tau\Delta kc^G_t = \frac{\partial Y_t}{\partial KC^G_t}\frac{KC^G_t}{Y_t}\Delta kc_t{}^G = \rho\frac{KC^G_t}{Y_t}\Delta kc^G_t \approx \rho\frac{KC^G_t}{Y_t}\frac{\Delta KC^G_t}{KC^G_{t-1}}$. When ΔKC^G_t is relatively stable over time, the last term reduces to $\rho\frac{\Delta KC^G_t}{Y_t}$. Instead of assuming that δ is small, we can also replace ΔKC^G_t by R_{it} when $\frac{KC^G_{i,t-2}}{Y_{i,t-2}}$ is stable. In that case, $\rho\frac{\Delta KC^G_{i,t-1}}{Y_{i,t-1}} = \rho\frac{R^G_{i,t-1}}{Y_{i,t-1}} - \rho\frac{\delta KC^G_{i,t-2}}{Y_{i,t-2}}$, where the last term is a constant. This constant disappears into the error term.

Error Correction Model

To assess the effect of model specification on the estimations, we also estimate error correction models (ECMs) for the Cobb-Douglas production function. ECMs are also used by Guellec and Van Pottelsberghe (2004). Since we are primarily interested in a single cointegration relationship, namely between output (*Y* or *TFP*) and its input variables, we do not estimate a multivariate ECM but only a conditional ECM for output. For *y* this model is specified as

$$\begin{aligned} \Delta y_{i,t} &= \alpha_i + \beta_1 \Delta lh_{i,t} + \beta_2 \Delta k_{i,t} + \beta_3 \Delta kc^P_{i,t} + \beta_4 \Delta kc^G_{i,t} + \beta_5 \Delta kc^F_{i,t} + \ldots \\ &\ldots \theta y_{i,t-1} + \gamma_1 lh_{i,t-1} + \gamma_2 k_{i,t-1} + \gamma_3 kc^P_{i,t-1} + \gamma_4 kc^G_{i,t-1} + \gamma_5 kc^F_{i,t-1} + \varepsilon_{i,t}. \end{aligned} \tag{8}$$

The change in *y* is now a function of short run effects of shocks in the input variables and an adjustment towards the long-term relationship between the level *y* and the level of its input variables. To stay close to the model in Equation (4) we constrain all parameters to be equal across countries. The long-term elasticity of KC^G is given by $-\gamma/\theta$. A similar model is also specified for *TFP*.

5.2 Translog production functions

The Cobb-Douglas production function assumes a (log)linear functional form, constant factor shares and a constant elasticity. Particularly, assuming a single linear functional form and constant elasticity for a diverse set of countries could be too restrictive. A translog production function allows us to deviate from these restrictive assumptions (Christensen et al., 1973). In the translog production function second order effects and interaction terms are included. The specification of the model is

$$\begin{aligned} y_{it} = \; & \alpha_0 + \alpha_K k_{it} + \alpha_L lh_{it} + \alpha_{KC^P} kc^P_{i,t-1} + \alpha_{KC^G} kc^G_{i,t-1} + \alpha_{KC^F} kc^F_{i,t-1} + \alpha_T T_t + \\ & \frac{1}{2}\alpha_{K,K} k^2_{it} + \alpha_{K,L} k_{it} lh_{it} + \alpha_{K,KC^P} k_{it} kc^P_{i,t-1} + \alpha_{K,KC^G} k_{it} kc^G_{i,t-1} + \alpha_{K,KC^F} k_{it} kc^F_{i,t-1} + \alpha_{K,T} k_{it} T_t + \\ & \frac{1}{2}\alpha_{L,L} lh^2_{it} + \alpha_{L,KC^P} lh_{it} kc^P_{i,t-1} + \alpha_{L,KC^G} lh_{it} kc^G_{i,t-1} + \alpha_{L,KC^F} lh_{it} kc^F_{i,t-1} + \alpha_{L,T} lh_{it} T_t + \\ & \frac{1}{2}\alpha_{KC^P,KC^P} \left(kc^P_{i,t-1}\right)^2 + \alpha_{KC^P,KC^G} kc^P_{i,t-1} kc^G_{i,t-1} + \alpha_{KC^P,KC^F} kc^P_{i,t-1} kc^F_{i,t-1} + \alpha_{KC^P,T} kc^P_{i,t-1} T_t + \\ & \frac{1}{2}\alpha_{KC^G,KC^G} \left(kc^G_{i,t-1}\right)^2 + \alpha_{KC^G,KC^F} kc^G_{i,t-1} kc^F_{i,t-1} + \alpha_{KC^G,T} kc^G_{i,t-1} T_t + \\ & \frac{1}{2}\alpha_{KC^F,KC^F} \left(kc^F_{i,t-1}\right)^2 + \alpha_{KC^G,T} kc^F_{i,t-1} T_t + \alpha_{T,T} T^2_t + \mu_i + \varepsilon_{1,it}. \end{aligned} \tag{9}$$

Calendar years are included using a (log) linearized time variable *T*, which allows the inclusion of interaction effects between calendar year and the other variables in a relatively parsimonious way. Country dummies are included (μ_i), but these do not interact with the other variables. The larger functional flexibility comes at the expense of a large number of parameters. To accommodate the inclusion of this large number of parameters without over-fitting, a number of first order conditions based on profit maximizing behaviour by firms are estimated simultaneously. More specifically, we assume that the relative prices of physical capital, labour, and private knowledge capital are equal to their marginal return. This implies that their income shares are equal to their elasticities, or:

$$\frac{P_{K_{it}}K_{it}}{P_{Y_{it}}Y_{it}} = \alpha_K + \alpha_{K,K}k_{it} + \alpha_{K,L}lh_{it} + \alpha_{K,KC^P}kc^P_{i,t-1} + \alpha_{K,KC^G}kc^G_{i,t-1} + \alpha_{K,KC^F}kc^F_{i,t-1} + \alpha_{K,T}T_t + \varepsilon_{2,it}$$

$$\frac{P_{L_{it}}L_{it}}{P_{Y_{it}}Y_{it}} = \alpha_L + \alpha_{K,L}k_{it} + \alpha_{L,L}lh_{it} + \alpha_{L,KC^P}kc^P_{i,t-1} + \alpha_{L,KC^G}kc^G_{i,t-1} + \alpha_{L,KC^F}kc^F_{i,t-1} + \alpha_{L,T}T_t + \varepsilon_{3,it}$$

$$\frac{P_{KC^P_{it}}KC^P_{it}}{P_{Y_{it}}Y_{it}} = \alpha_{KC^P} + \alpha_{K,KC^P}k_{it} + \alpha_{L,KC^P}lh_{it} + \alpha_{KC^P,KC^P}kc^P_{i,t-1} + \alpha_{KC^P,KC^G}kc^G_{i,t-1} +$$
$$\alpha_{KC^P,KC^F}kc^F_{i,t-1} + \alpha_{KC^P,T}T_t + \varepsilon_{4,it},$$

where P_j is the rental price of input factor *j.* [13]

These three restrictions are estimated simultaneously with Equation (9) using seemingly unrelated regression (SUR).

The marginal effect of public knowledge capital now depends on the levels of all factors. The elasticity is:

$$\frac{\partial y_{it}}{\partial kc^G_{i,t-1}} = \alpha_{KC^G} + \alpha_{KC^G,KC^G}kc^G_{i,t-1} + \alpha_{K,KC^G}k_{it} + \alpha_{L,KC^G}lh_{it} + \alpha_{KC^P,KC^G}kc^P_{i,t-1} +$$
$$\alpha_{KC^G,KC^F}kc^F_{i,t-1} + \alpha_{KC^G,T}T_t.$$

We report the marginal effects at the population sample average of each variable.

5.3 Augmented production functions

In addition to the Cobb-Douglas and translog production functions we estimate models that include additional variables and their interactions. We follow as the approach developed by the OECD (Khan and Luintel, 2006) and add publically financed physical capital (K^G), the share of high tech imports in all imports (HT^{imp}), the share of high tech exports in all exports (HT^{exp}), and inward and outward foreign direct investment (FDI^{in} and FDI^{out}). Given the additional set of parameters needed to estimate this model, we only focus on the model for *TFP* here. Further, to stay close to the approach of Khan and Luintel (2006), we estimate the models in levels instead of first differences and add lagged *TFP* as an explanatory variable. For the same reason, we include human capital as a separate indicator instead of using a measure of quality adjusted labour.

First, we include only level effects of the additional variables. This gives

$$\begin{aligned} tfp_{it} = \quad & \mu_i + \omega_t + \tau tfp_{i,t-1} + \lambda_1 H_{i,t-1} + \lambda_2 k^G_{i,t-1} + \lambda_3 kc^P_{i,t-1} + \lambda_4 kc^G_{i,t-1} + \\ & \rho_1 kc^F_{i,t-1} + \rho_2 HT^{imp}_{i,t-1} + \rho_3 HT^{\exp}_{i,t-1} + \rho_4 FDI^{in}_{i,t-1} + \rho_5 FDI^{out}_{i,t-1} + \varepsilon_{it} \end{aligned}. \qquad (10)$$

Second, we also add interactions between the different variables. To keep the model somewhat parsimonious we differentiate between a set of core variables (H, k^G, kc^P, kc^G) and non-core

[13] Rental prices for private R&D capital and fixed capital are assumed to be equal to the a price index (respectively the price level of the capital stock and the GDP price deflator) multiplied by a depreciation rate (respectively 0.15 for knowledge capital and 0.1 for physical capital) plus an interest rate equal to 0.05. The labour share of income is taken directly taken from PWT (share of labour compensation in GDP at current national prices).

variables ($kc^F, HT^{imp}, HT^{\exp}, FDI^{in}, FDI^{out}$). The core variables interact with each other and with the non-core variables. This gives

$$
\begin{aligned}
tfp_{it} = \quad & \mu_i + \omega_t + \tau tfp_{i,t-1} + \lambda_1 H_{i,t-1} + \lambda_2 k^G_{i,t-1} + \lambda_3 kc^P_{i,t-1} + \lambda_4 kc^G_{i,t-1} + \\
& \rho_1 kc^F_{i,t-1} + \rho_2 HT^{imp}_{i,t-1} + \rho_3 HT^{\exp}_{i,t-1} + \rho_4 FDI^{in}_{i,t-1} + \rho_5 FDI^{out}_{i,t-1} + \\
& \phi_1 H_{i,t-1} k^G_{i,t-1} + \phi_2 H_{i,t-1} kc^P_{i,t-1} + \phi_3 H_{i,t-1} kc^G_{i,t-1} + \\
& \phi_4 k^G_{i,t-1} kc^P_{i,t-1} + \phi_5 k^G_{i,t-1} kc^G_{i,t-1} + \phi_6 kc^P_{i,t-1} kc^G_{i,t-1} + \\
& \xi_{1,1} H_{i,t-1} kc^F_{i,t-1} + \xi_{1,2} H_{i,t-1} HT^{imp}_{i,t-1} + \xi_{1,3} H_{i,t-1} HT^{\exp}_{i,t-1} + \\
& \xi_{1,4} H_{i,t-1} FDI^{in}_{i,t-1} + \xi_{1,5} H_{i,t-1} FDI^{out}_{i,t-1} + \\
& \xi_{2,1} k^G_{i,t-1} kc^F_{i,t-1} + \xi_{2,2} k^G_{i,t-1} HT^{imp}_{i,t-1} + \xi_{2,3} k^G_{i,t-1} HT^{\exp}_{i,t-1} + \\
& \xi_{2,4} k^G_{i,t-1} FDI^{in}_{i,t-1} + \xi_{2,5} k^G_{i,t-1} FDI^{out}_{i,t-1} + \\
& \xi_{3,1} kc^P_{i,t-1} kc^F_{i,t-1} + \xi_{3,2} kc^P_{i,t-1} HT^{imp}_{i,t-1} + \xi_{3,3} kc^P_{i,t-1} HT^{\exp}_{i,t-1} + \\
& \xi_{3,4} kc^P_{i,t-1} FDI^{in}_{i,t-1} + \xi_{3,5} kc^P_{i,t-1} FDI^{out}_{i,t-1} + \\
& \xi_{4,1} kc^G_{i,t-1} kc^F_{i,t-1} + \xi_{4,2} kc^G_{i,t-1} HT^{imp}_{i,t-1} + \xi_{4,3} kc^G_{i,t-1} HT^{\exp}_{i,t-1} + \\
& \xi_{4,4} kc^G_{i,t-1} FDI^{in}_{i,t-1} + \xi_{4,5} kc^G_{i,t-1} FDI^{out}_{i,t-1} + \varepsilon_{it}.
\end{aligned}
\tag{11}
$$

Similar to the translog function, we need to implement some restriction on parameter values to prevent over fitting, the more since the number of observations is smaller. We restrict the number of parameters by using a two-step method. In the first step, we estimate the full model. In the second step, we remove some statistically insignificant variables according to a cut-off *p*-value, and re-estimate the model. In the main estimations we only remove interaction variables between core- and non-core variables using a *p*-value of 0.2.

6. Estimation results

This section presents and discusses the estimation results of the models presented in Section 5. Section 6.1 presents the results of the baseline models, while section 6.2 shows the sensitivity analyses. Section 6.3 discusses country heterogeneity.

Before we turn to the estimation models we first analyse the order of integration of our time series. We also analyse whether the long term relationship between the time series is stable by performing cointegration tests. The results can be found in appendix A. We perform various panel unit root tests on the log-transformed series of all the variables in the standard production functions. This yields mixed findings. The Levin-Lin-Chu (LLC) test, using a common autoregressive parameter for all countries, rejects the null hypothesis of integration except for *tfp*, and $\frac{R^P}{Y}$, $\frac{R^G}{Y}$, $\frac{R^F}{Y}$. The Im-Pesaran-Shin (IPS) test, using a different autoregressive parameter for each country, confirms the null-hypothesis of all variables having a unit root, except for foreign knowledge capital. The results for the de-trended versions of these tests are more mixed. We proceed by assessing whether there is a cointegration relationship between the time series. We follow Boswijk (1994) and perform a Wald test on the joint significance of the adjustment parameter and all long-term parameters. This test is performed using a fixed-effect conditional error correction model (ECM) for *y* and *tfp*, using country-specific parameters for the short-term effects and the adjustment towards the long-run relationship.

We perform the Wald test for each country separately. This test points to a cointegration relationship between GDP and the input variables. For each country the chi-squared value is above the critical value, which implies that the null hypothesis of no cointegration is rejected. The results for cointegration between TFP and the input variables are more mixed across countries. This suggests that we should be cautious in the interpretation of the TFP models, especially for those specified in levels rather than first-differences.

6.1 Baseline results

Table 4 presents the estimation results of the Cobb-Douglas, translog, and augmented production functions. The first four columns concern Cobb-Douglas production functions, using either GDP (columns 1 and 2) or TFP (columns 3 and 4) as dependent variables.[14] In both models the included R&D variables are either in stocks or in flows. The fifth and sixth columns concern the error-correction model using either GDP or TFP and R&D stock variables. The seventh column presents the results of the translog production function, using GDP as outcome variable and R&D stock variables. The last column shows the augmented production function model, using TFP as the outcome variable and R&D stock variables as covariates. The table only shows the estimated coefficients for public R&D, private R&D, and physical capital. [15] Robust standard errors are in parentheses.

Table 4. Estimated impact of public R&D in baseline models

	Cobb-Douglas				ECM		Translog	Augmented Model
	GDP		TFP		GDP	TFP	GDP	TFP
	stocks	flows	stocks	flows	stocks	stocks	stocks	stocks
Public R&D	.006	-.489	.032	-.521	-.126***	-.287***	-.159***	.039***
	(.022)	(.545)	(.024)	(.569)	(.046)	(.068)	(.015)	(.011)
Private R&D	-.004	.165	.002	-.022	.088***	.061*	.011***	.016***
	(.017)	(.236)	(.018)	(.272)	(.026)	(.035)	(.001)	(.006)
Physical capital	.580***	.603***			.178		.329***	
	(.111)	(.107)			(.110)		(.004)	
R^2 value	.612	.620	.386	.398	.674	.396	.997	.997
Observations	945	945	945	945	945	945	967	584

Notes. * / *** denotes significance at a 10 / 1 % significance level.

The Cobb-Douglas model yields statistically insignificant effects of public R&D on GDP and TFP. Point estimates are (slightly) positive in the stock specifications and negative in the flow specifications. The estimates in the stock specification should be interpreted as elasticities. Hence, a 1 percent increase in public R&D expenditures increases GDP with 0.006 percent. The estimates in the flow specification should be interpreted as rates of return. The error-correction model and translog model show statistically significant negative effects of public R&D. The augmented model, which includes additional production factors, such as public capital, the stock of inward and outward foreign direct investments and the shares of high-tech imports and exports, yields a statistically significant positive effect of public R&D. The estimated elasticity equals 0.04.[16] The number of observations in this analysis is smaller, since the additional variables are not available in the years before 1981 and

[14] These variables are normalized by quality-adjusted labour (see Section 5.1).
[15] In the translog and augmented models, the presented average marginal effects are based on the variable means over all included countries and years. The full table of estimation results is available upon request.
[16] This is the result of the model that includes interaction terms. Inclusion of the additional production factors without adding interaction terms yields a statistically insignificant effect of public R&D (-.009).

not for Greece, Iceland and New Zealand. The estimated impact of private R&D is insignificant in the Cobb-Douglas models and statistically significant and positive in the translog, ECM, and augmented models. For physical capital positive elasticities are found in all models, ranging from 0.18 to 0.60.

6.2 Sensitivity analyses

We proceed by performing a large set of sensitivity tests to probe the robustness of these results. Table 5 presents the estimated effects of public R&D in various types of sensitivity analyses. Each cell represents a separate regression. The columns correspond to the models described in Table 4. Each row corresponds to a separate sensitivity test.

The top panel shows sensitivity tests related to the model specification, such as the exclusion of covariates and the use of different lag structures for the R&D variables. The latter may be important, since it can take years before public R&D investment eventually results in productivity gains. The exclusion of covariates does not importantly affect the results, except for the augmented production function model. Removing private R&D as explanatory variable yields a statistically insignificant effect, while removing public capital yields a statistically significant negative effect of -0.02. As expected, the inclusion of a single R&D variable that takes into account both public and private R&D yields somewhat more positive results. The estimated elasticities for total R&D stock variables are statistically significant (at a 5 and 10% level) and positive in the Cobb-Douglas models. Changes in the lag structure of the R&D variables do not alter the main findings.

The second panel addresses heterogeneity in effects across time periods and countries. The impact of public R&D might have been larger during certain periods or in specific countries. The Cobb-Douglas models yield positive elasticities if we restrict the sample to the 1981-2011 period, one of which is statistically significant at a 5% level. A further restriction to the more recent 1990-2011 period gives all statistically insignificant elasticities. In both periods the translog models and the ECM models for TFP still yield - even more strongly - negative significant effects. The estimated coefficient in the augmented model turns insignificant in the 1990-2011 period. Performing the analyses on a sample of EU27 countries does not alter the main findings, while the inclusion of all available 40 countries yields positive elasticities in the Cobb-Douglas models. Expanding the number of countries is not feasible in the augmented model due to limited data availability (see Section 4). The augmented model shows a statistically insignificant effect when only the EU-27 countries are included. The impact of public R&D may also differ across countries with relatively high and low level of knowledge investments. Splitting the sample based on the country's public R&D intensities yields no clear conclusion on the observed differences. The point estimates for highly R&D intensive countries are lower in most of the Cobb-Douglas models (one of which is significant at the 10% level) and the augmented model, but larger in the translog and ECM models.

The third panel investigates the robustness of the results to different assumptions with respect to the construction of R&D stocks. This concerns both the use of other depreciation and pre-sample growth rates, and the use of different weights for the construction of the foreign R&D stock. Changing the depreciation rate from 15% to either 10 or 20% yields similar results. Also, the use of a single pre-sample growth rate of 5% hardly affects the results. The construction of foreign R&D using weights based on distance measures gives more positive elasticities in the Cobb Douglas models, one of which is statistically significant. The results of the other models are not importantly affected.

Table 5. Sensitivity analyses: estimated impact of public R&D

	Cobb-Douglas				ECM		Translog	Augmented Model
	GDP		TFP		GDP	TFP	GDP	TFP
	stocks	flows	stocks	flows	stocks	stocks	stocks	stocks
Baseline model	.006	-.489	.032	-.521	-.126***	-.286***	-.159***	.039***
Model specifications								
Excluding private R&D	.006	-.312	.032	-.545	-.047	-.242***	-.152***	.011
Excluding foreign R&D	.008	.102	.031	.117	-.123**	-.284***	-.103***	.027***
Excluding public capital								-.021***
Total R&D (private + public)	.051*	.010	.079**	-.138	.077*	-.205***	.006	.040**
2-year lags for all R&D variables	.004	-.467	.029	-.554	-.125***	-.286***	-.190***	.038***
10-year lags for all R&D variables	-.003	.255	-.013	.447	-.038	-.067	-.257***	.042***
Samples								
1981-2011	.088**	1.167	.035	1.211	-.059	-.346***	-.291***	.039***
1990-2011	.003	1.321	-.082	.644	.067	-.413***	-.221***	-.002
EU 27	.065	-.036	.001	-.074	-.396**	-.439***	-.265***	.014
All 40 countries	.084*	.007	.051*	-.003	-.324***	-.355***	-.102***	
Countries with low R&D intensity	.019	1.212	.013	1.168	-.162**	-.258***	-.160***	.074***
Countries with high R&D intensity	-.092*	-1.132	.020	-.407	.037	-.176	-.084***	.008
Construction of R&D stocks								
Depreciation rate 10%	.000	-.489	.021	-.521	-.093*	-.242***	-.150***	.055***
Depreciation rate 20%	.011	-.467	.031	-.554	-.104**	-.258***	-.198***	.023**
Pre-sample growth rate 5%	-.034	-.489	.002	-.521	-.118***	-.260***	-.202***	.024**
Foreign R&D based on distance weights	.091**	1.008	.041	1.038	-.096	-.368**	-.237***	.031***
Definitions of public R&D								
GovFinGERD (from 1981)	-.120***	-.000**	-.143***	-.000**	-.171	-.550***	-.111***	.013*
GBAORD (from1981)	-.021	-.341	-.049*	-.059	-.086	-.275***	-.186***	.043***

Notes. Each cell represents a separate regression. * / ** / *** denotes significance at a 10 / 5 / 1 % significance level.

The bottom panel shows the results for two other definitions of public R&D. In these analyses the sample is restricted to the period 1981-2002, since the two alternative definitions are not available for earlier periods. Changing the definition to all R&D expenditures financed by the government (based on either public budgets or survey information) yields negative elasticities in most models. Only the augmented production function model still shows positive and statistically significant effects.

In both the translog and augmented models the advantage of a flexible form comes at the expense of a large number of parameters. To be able to estimate these complex models additional assumptions are needed. In the translog model we assume profit- maximizing behaviour in the private sector; in the augmented model we remove non-significant variables using a two-step estimation method (see Section 5). Appendix B shows the results in case of some alternative assumptions regarding the estimation procedures. Table B.1 presents the results for the translog model using either two restrictions (by removing the first-order condition with respect to private R&D) or four restrictions (by adding a first-order condition for public R&D). The model using two restrictions still yields a (even larger) negative effect (-.272), but the model using four restrictions yields a positive effect (.007). The latter model assumes profit-maximizing behaviour with respect to public investments in R&D too. Though assuming profit-maximizing behaviour only for private actors seems most plausible, it is of interest to note that the results of the translog model are sensitive to other assumptions. Table B.2 presents the results for the augmented model using different criteria for the selection of variables and different threshold *p*-values in the two-step estimation procedure. If we use a stricter threshold value for significance and apply the selection procedure to all variables, the estimated effect becomes close to zero (-.003) and statistically insignificant.

To summarize, we find that the results from estimating Cobb-Douglas production functions are in some cases sensitive to specific assumptions, especially with respect to the sample taken into account, the construction methods for the foreign R&D stock and the use of different definitions of public R&D. Nevertheless, in most analyses we find statistically insignificant effects of public R&D on output. The estimates of the error-correction models range from negative (significant) to statistically insignificant estimated coefficients. Especially the models for TFP yield robust negative and significant coefficients. The results of the translog production functions are negative and robust to several sensitivity tests. The augmented production function models show mostly positive and statistically significant effects. These results seem to be sensitive to the inclusion of specific covariates, and the sample taken into account. Both the results of the translog and augmented models are somewhat sensitive to the specific assumptions with respect to the estimation procedure. The overall picture that emerges from the set of analyses is that estimates of Cobb-Douglas and translog production functions do not provide evidence for positive returns to investments in public R&D. At the same time, the augmented models more often yield positive results. These findings suggest that it is hard to draw universal conclusions about the effects of public R&D investments on output (growth), but that differences across countries may be important for an efficient use of R&D resources.

6.3 Country heterogeneity

Table 6 shows the estimated country-specific effects of public R&D in the translog (column 1) and augmented production function model (column 2). Both models allow for country heterogeneity by including interaction terms. The first row presents the average estimated effect across all countries; the next rows present the country-specific coefficients. In line with the general results presented in Tables 4 and 5, all country-specific effects in the translog model are negative and statistically significant. In the augmented model, that includes additional production factors, the estimated effects are positive for most countries. In these models the return to public R&D is more closely related to the national context. In some countries the point estimates are negative. The differences in the estimated impact of public R&D on TFP across countries are driven by the interaction terms. We find country-specific coefficients in a range from -0.02 in the US to 0.14 in Ireland. There are no clear differences between large and small countries. The estimated elasticities do not indicate that the returns to public R&D investments are typically higher in large countries (where knowledge spillovers to other countries are less likely). In the Netherlands the return to public R&D investments is slightly above average.[17]

Table 6. Country specific effects: Estimated impact of public R&D in translog and augmented production functions

	Translog	Augmented model
	GDP	TFP
All countries	-.159***	.039***
AUS	-.204***	-.017
AUT	-.144***	.044***
BEL	-.156***	.064***
CAN	-.220***	.001
CHE	-.142***	.024**
DEU	-.251***	-.005
DNK	-.143***	.056***
ESP	-.118***	.030***
FIN	-.139***	.073***
FRA	-.181***	.002
GBR	-.200***	.003
GRC	-.129***	
IRL	-.114***	.141***
ISL	-.096***	
ITA	-.135***	.025**
JPN	-.169***	.068**
NLD	-.174***	.067***
NOR	-.175***	.108***
NZL	-.162***	
PRT	-.078***	.040***
SWE	-.181***	.031**
USA	-.209***	-.024
Observations	967	584

Notes. *** / ** denotes significance at a 1 / 5 % significance level.

[17] Appendix B shows the country-specific effects of the translog (Table B.1) and augmented (Table B.2) models in case of some alternative assumptions regarding the estimation procedures.

7. Conclusions and discussion

This paper investigates the returns to public R&D investments by means of a cross-country macro-economic analysis. We exploit long time series data and use a broad variety of models to assess the impact of public R&D spending on economic growth and productivity. The overall picture that emerges from our estimations is that the estimated returns to public R&D investments are not unambiguously positive. Our analysis points out that the relationship between public R&D and economic performance is highly country-specific, and that only models that allow for heterogeneity across countries provide positive and statistically significant estimates of the rates of return. This confirms the findings of Khan and Luintel (2006), and is generally consistent with the theory of innovation systems.

Most of the estimates based on Cobb-Douglas production functions – including error-correction models - yield statistically insignificant effects. These models take into account public, private and foreign R&D, and the primary production factors. In translog production function models most of the estimated elasticities are negative and statistically significant, something that is at odds with our theoretical hypotheses. These models are based on similar production factors and allow for country heterogeneity by including interaction terms, but make much stronger assumptions on fully rational behaviour of the (private) actors involved in STI. Models that include additional variables (public capital, the stock of inward and outward foreign direct investments and the share of high-tech imports and exports) and allow for country heterogeneity show mostly positive effects. In these models the return to public R&D investments is more strongly related to the national context.

A number of remarks is in place with respect to the interpretation of the results. Firstly, the results concern marginal effects that apply to (small) adjustments compared to the observed investment levels. Hence, non-positive and non-significant coefficients do not imply that previous investments had not improved economic performance. Secondly, the empirical analysis is limited to economic outcomes. The societal value of scientific research is broader than its economic value in terms of growth or productivity. A large fraction of public R&D spending is not specifically targeted at direct productivity improvement. Medical research, for example, can enhance health outcomes without directly affecting economic growth. In addition, much of the basic research performed at universities and public institutions is at best only indirectly related to long run economic growth.

It is difficult to identify the economic return to public R&D only by macro-economic approaches. Scientific research is not a homogeneous good as public R&D investments can apply to different research fields and different types of research (varying from more basic to more applied work). Its relationship with economic growth is indirect and long term, and the underlying mechanism involves many complex interactions with other relevant actors in the innovation system. Analyses at the macro level focus directly on the impact of science on economic growth and hence provide only limited insights into the relevant underlying processes. In addition, the limited variation in R&D spending over time and the strong correlation with other production factors compromise the empirical analyses.

Our findings suggest that spending on public R&D does not yield an automatic return. The return seems to be dependent on the national context, in which institutions and government policies play an important role. Hence, rather than evaluating what the absolute monetary value of public investments in R&D is, it would be helpful to know more about optimal ways of spending public funds. Micro-economic evaluations can provide insights into the effectiveness of specific institutions or science policy measures and learn how the value of science can be improved. But such micro studies are also, by their very nature, often focused on a narrow context that makes it difficult to capture the full effects of public R&D. Therefore, studying knowledge networks is of interest too because of the importance of spillovers for the economic impact of public efforts to foster economic development. Future research along these lines is likely to contribute to unravelling the 'black box' of the economic value of public investments in science, technology and innovation.

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Appendix A: Results for integration and cointegration tests

Table A.1. P-values of unit root tests

	LLC	IPS	LLC detrend	IPS detrend
lY	0.00	0.79	0.00	0.11
lTFP	0.06	0.99	0.11	0.25
lL	0.01	1.00	0.01	0.96
lK	0.00	0.00	0.00	1.00
lKCp	0.00	0.01	0.00	1.00
lKCg	0.00	1.00	0.00	0.99
lKCf	0.00	0.00	0.00	1.00
Rp/y	0.33	1.00	0.08	0.79
Rg/y	0.06	0.99	0.00	0.00
Rf/y	0.26	1.00	0.03	0.29

Notes. Levin-Lin-Chu (LLC) and Im-Pesaran-Shin (IPS) tests. Null hypothesis is no integration.

Table A.2. Cointegration test: Wald test of joint significance of adjustment parameter and long-term parameters

	Y		TFP	
	Adjustment coefficient	Chi2	Adjustment coefficient	Chi2
AUS	-0.51	68***	-0.31	18**
AUT	-0.92	42***	-0.37	11
BEL	-0.75	38***	-0.42	12
CAN	-0.59	78***	-0.14	12
CHE	-0.49	28***	-0.33	5
DEU	-0.87	42***	-0.56	9
DNK	-0.58	110***	-0.41	22***
ESP	-0.72	87***	-0.38	46***
FIN	-0.50	29***	-0.32	12
FRA	-0.71	43***	-0.28	26**
GBR	-0.87	60***	-0.40	10
GRC	-0.75	72***	-0.04	8
IRL	-0.71	60***	-0.31	13
ISL	-0.61	36***	-0.44	14*
ITA	-1.04	107***	-0.57	43***
JPN	-0.83	38***	-0.21	9
NLD	-0.71	29***	-0.66	19***
NOR	-0.42	41***	-0.19	17**
NZL	-0.71	133***	-0.56	30**
PRT	-0.45	83***	-0.40	9
SWE	-0.40	24**	-0.52	17**
USA	-0.85	204***	-0.39	19***

Notes. * null-hypothesis of no cointegration is rejected at the 10% significance level, ** rejected at the 5% significance level and *** rejected at the 1% significance level.

Appendix B: Translog and augmented models using alternative estimation procedures

Table B.1. Estimated impact of public R&D in translog production functions using different estimation procedure (three different sets of restrictions)

	2 Restrictions: **Wrt physical capital, labour**	**3 restrictions:** **Wrt physical capital, labour, private R&D**	**4 restrictions:** **Wrt physical capital, labour, private R&D, public R&D**
	GDP		
All countries	-.272***	-.159***	.007***
AUS	-.281***	-.204***	.008***
AUT	-.366***	-.144***	.005***
BEL	-.420***	-.156***	.004***
CAN	-.300***	-.220***	.010***
CHE	-.519***	-.142***	.005***
DEU	-.386***	-.251***	.002
DNK	-.282***	-.143***	.005***
ESP	-.302***	-.118***	.008***
FIN	-.270***	-.139***	.002
FRA	-.250***	-.181***	.008***
GBR	-.289***	-.200***	.009***
GRC	-.098***	-.129***	.009***
IRL	-.315***	-.114***	.012***
ISL	-.008	-.096***	.006***
ITA	-.238***	-.135***	.008***
JPN	-.094*	-.169***	.007**
NLD	-.209***	-.174***	.007***
NOR	-.273***	-.175***	.003***
NZL	-.217***	-.162***	.013***
PRT	-.073***	-.078***	.013***
SWE	-.441***	-.181***	.005***
USA	-.323***	-.209***	.009***
Observations	967	967	967

Notes. ** / *** denotes significance at a 5 / 1 % significance level.

Table B.2. Estimated impact of public R&D in augmented production functions using different estimation procedures

Selection	Core-non core interactions			All variables	
P-value	1	0.2	0.05	0.2	0.05
All countries	.046***	.039***	.036***	.019**	-.005
AUS	-.030	-.017	-.018	-.020*	-.019*
AUT	.054***	.044***	.039***	.022**	.001
BEL	.058***	.064***	.034***	.039***	-.003
CAN	-.003	.001	.004	-.004	-.014
CHE	.043**	.024**	.020*	.007	-.006
DEU	-.005	-.005	.012	-.014	-.016*
DNK	.064***	.056***	.050***	.028***	.002
ESP	.034***	.030***	.023**	.015	-.009
FIN	.084***	.073***	.071***	.037***	.007
FRA	.007	.002	.007	-.007	-.016*
GBR	.014	.003	.006	-.007	-.014
IRL	.179***	.141***	.077***	.102***	.019***
ITA	.029**	.025**	.032***	.010	-.009
JPN	.080**	.068**	.102***	.034***	.003
NLD	.075***	.067***	.057***	.040***	.001
NOR	.118***	.108***	.107***	.073***	.023***
PRT	.052**	.040***	.014	.019*	-.008
SWE	.036**	.031**	.032***	.012	-.004
USA	-.024	-.024	.011	-.022	-.024**

Notes. * / ** / *** denotes significance at a 10 / 5 / 1 % significance level.

Publisher:

CPB Netherlands Bureau for Economic Policy Analysis
P.O. Box 80510 | 2508 GM The Hague
T (070) 3383 380

October 2015 | ISBN 978-90-5833-705-4