

THE IMPACT OF R&D ON REGIONAL PRODUCTIVITY

Dr. Faith Adobamen

Lecturer – International Business

University of Greenwich, London, UK

Abstract:

The impact of regional R&D on productivity, as well as the comparative productivity effects of R&D from the business, government and higher education sectors remains understudied. The objectives of this research are to: (i) compare productivity effects of own R&D and regional knowledge from business, government, and higher education research at the NUTS-2 region levels; (ii) Establish whether business R&D, government R&D and higher education research funding are complements or substitutes.

I estimate a standard Cobb-Douglas production function augmented with own-R&D capital stock from the Business (BERD), Higher education (HERD) and the Government sectors (GOVRD). I estimate both a static and dynamic model of the Cobb-Douglas function. The static model is estimated using OLS with time and regional dummies and the dynamic model is estimated using the system generalised method of moment (System-GMM). The study reports several findings. First, the static results indicate that total R&D has a positive and significant effect on regional productivity. However, with the R&D components (BERD, HERD, and GOVRD), only government R&D was positive and significant. Second, the dynamic results confirm the findings of the static results that only government R&D has a positive and significant effect on productivity. I also find that: (i) regions with higher R&D intensity enjoy higher productivity levels; (ii) the R&D types can be considered as substitutes as opposed to complements.

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Lecturer – International Business

University of Greenwich, London, UK

Introduction:

Research and Development (R&D) consists of creative work undertaken systematically to improve and increase the stock of knowledge; this includes knowledge of man, society, and culture, to develop new applications (Frascati Manual, 2002, p.30). Knowledge is characterized by non-rivalry and non-excludability;¹ these attributes distinguish it from physical capital stock and create the opportunity for significant variations between private and social returns to R&D investment. Hence, the productivity effects of R&D have remained a significant area of research for economists, informed by the ‘endogenous growth models’ (e.g., Romer, 1986; 1990; Grossman and Helpman, 1991). The effect of R&D on productivity can either be direct or indirect. This study examines both the direct and indirect effects of R&D on regional productivity. The *Direct-effect* or private returns to R&D refers to the impact of R&D in a particular region on output in that region. The *Indirect-effect* or social returns to R&D examines the spillover effects of R&D. In other words, it measures the effect of R&D from other regions on output in a particular region.

The impact of R&D on productivity is of interest to both academics and policy makers. The earliest studies of the impact of R&D on productivity were by Minasian (1969) and Griliches (1973). Empirical studies on R&D greatly expanded after the influential study of Griliches (1979) that addressed the conceptual, measurement and econometric issues in examining direct and indirect effects of R&D on productivity. Extensive empirical reviews of R&D have been provided by Hall et al. (2010) and more recently by Ugur et al. (2016), who conducted a meta regression analysis of the effect of R&D on productivity from 1253 estimates across 65 studies. The impact of R&D has therefore remained an important area of academic research.

In analysing the direct or private returns to R&D, a key model in the literature is the knowledge capital model (See e.g., Griliches, 1979), where the standard Cobb-Douglas production function is augmented with the stock of knowledge. This model has remained a cornerstone in productivity studies. The knowledge capital model can also be augmented with external knowledge capital to examine the indirect or spillover effects of R&D on productivity (See e.g., Hall et al., 2010; Griliches, 1992), in an early review of empirical research, acknowledged

¹ It is costly or impossible for one user to exclude others from using goods or services.

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that there is a direct effect of R&D on productivity, and that the productivity impact of external R&D capital was larger than that of own R&D capital. This finding was supported by the review of Hall et. al. (2010) who concluded that social returns to R&D greatly exceeded the private returns to R&D. International R&D has also been found to be important for growth. For instance, Cincera and van Pottelsberghe de la Potterie (2001) showed that foreign R&D is an important contributor to productivity growth, with its output elasticity exceeding that of domestic R&D. However, recent meta-analysis on the productivity effects of R&D found a positive but small effect of R&D capital on productivity with spillover effects from R&D on productivity smaller than own R&D capital (Ugur et al., 2020).

To achieve the research objectives, the following research questions will be addressed:

Research question 1: What effects do Business R&D capital, Government R&D capital and Higher Education R&D capital have on regional productivity in the UK?

Research question 2: Are Business R&D, Government R&D and Higher Education R&D substitutes or complementary?

The paper investigates the direct effects of own R&D capital on regional productivity from 2005 to 2016, distinguishing between the effects of Business R&D (BERD), government R&D (GOVRD) and higher education R&D (HERD) using both a static and dynamic model of the Cobb-Douglas function. The static model is estimated using Pooled OLS with time and regional dummies and the dynamic model is estimated using the system generalised method of moment (System-GMM). The static model results indicate that total R&D has a positive and significant effect on regional productivity. However, with the R&D components (BERD, HERD, and GOVRD), only government R&D was positive and significant. However, in the dynamic model results, Total R&D loses its statistical significance, with only R&D from the government sector having a positive and significant effect on productivity. Hence, results from the dynamic model confirm the findings of the static model results that only government R&D has a positive and significant effect on productivity.

Theoretical and Empirical Review:

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The Development and Application of the Knowledge Capital Model (the primal approach)

In this section, I synthesize the knowledge capital model of Griliches (1979), also referred to as the primal approach.

Studies on the relationship between research and development (R&D) and productivity have played an important role in the theory of economic growth. The main purpose of investing in R&D is to increase the stock of knowledge; this is not limited to the knowledge of man, culture, and society, but is also used to advance new applications of research, and experimental development. Spending on R&D potentially leads to growth through its positive impact on productivity (Romer, 1990; Lucas, 1988). In 2016, £33.1bn (1.6% of GDP) was invested in R&D in the UK, compared to £31.8bn in 2015 (ONS, 2018; Royal Economics Society, 2018).

The idea of the potential impact of knowledge on productivity dates to Alfred Marshall (1890, 1920), who pointed out that the agglomeration of industry in a geographic area can lead to knowledge diffusion, through interactions between employers and employees working in the same region. These studies depart from the neoclassical growth model, which treats technical change as an exogenous process and focuses instead on capital accumulation as the main determinant of output growth. However, recent literature offers more innovative and novel ways of modelling technological progress and its implications for economic growth. Grossman and Helpman (1991) argue that commercially oriented novelty efforts in response to economic incentive are the main driver of productivity growth and technological progress. Hence, it can be argued that innovation relies and feeds on knowledge generated from collective R&D experience, and it alternatively contributes to the stock of knowledge.

Arrow (1962) and Sheshinski (1967) proposed that research and development result from *learning by doing* and can be proxied by the magnitude of the learner's capital stock. Griliches (1979, 1992), contribution on the impact of R&D on productivity brought the emergence of the knowledge capital model, the model is an additional input, proxied by the level of R&D capital stock. Although the Griliches-type model is discussed mainly within an empirical setting based on firm or industry-level data, it is theoretically connected with macro-level endogenous growth models, where innovation is subject to increasing returns that drive economic growth (Romer, 1990).

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Both the Griliches-type and other models of knowledge capital usually draw on a Cobb-Douglas production function, augmented with own R&D capital as separable inputs. The effect on productivity can be estimated either through output elasticities of own R&D capital, or by regressing the total factor productivity from a standard Cobb-Douglas production function on own R&D capital (Griliches 1979, 1992; Coe and Helpman, 1995, 1997). This assumes an augmented knowledge production function with value-added Y as a function of inputs labour L , tangible capital K , and knowledge capital C as depicted in equation (1.1)

$$Y = F(L, K, C) \quad (1.1)$$

where knowledge capital C is the complement to the standard inputs. According to Griliches, the magnitude of knowledge capital is subject to both current and past levels of R&D expenditure. The specific form of the production function can be written as:

$$Y_{it} = Ae^{\lambda t} K_{it}^{\alpha} L_{it}^{\beta} C_{it}^{\gamma} e^{u_{it}} \quad (1.2)$$

Here, Y_{it} is the real output of industry/firm or region i at time t ; C_{it} is the physical capital stock net of depreciation; L_{it} is labour, represented as (number of employees or hours worked); K_{it} is own R&D capital stock (deflated R&D capital); while $Ae^{\lambda t}$ is the rate of disembodied technological change; U_{it} is the idiosyncratic error term; and A is a constant.

Taking the natural logarithm and converting other components to lower-case letters, the model (1.2) is then written as:

$$y_{it} = \eta_i + \lambda_t + \alpha l_{it} + \beta c_{it} + \gamma k_{it} + u_{it} \quad (1.3)$$

The log of technological progress produces an industry, firm, or region-specific effect (η_i), accompanied with a time effect (λ_t). There are various assumptions on the empirical work based on the slope coefficient of interest (γ) and the intercept (η_i). Some studies adopt the view that both the slope coefficient and the intercept are constant across firm/industry and use pooled ordinary least square (OLS) for estimating. On the other hand, others assume random intercepts

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but constant slopes, and estimate the model either with the random effect estimator or the between estimator. The former relies on the zero-mean of the random effects to obtain an average intercept coefficient, whereas the latter assumes time-invariant specific effects, which can be purged either by time-differencing the data or de-meaning it. It is worth noting that elasticity estimates from OLS or between estimators are described as *elasticity estimates in the level dimension*; the estimates from differenced or de-meaned data are described as *elasticity estimates in the temporal dimension* (Ugur et al., 2016).

To purge the fixed effect (the unit-specific effects) through time-differencing, model (1.3) can be expressed as follows:

$$\Delta y_{it} = \alpha \Delta l_{it} + \beta \Delta C_{it} + \gamma \Delta k_{it} + \Delta \lambda_t + \Delta u_{it} \quad (1.4)$$

Time differencing can be either between two subsequent years or over longer time periods. The former is referred to as *first differenced*, and the latter as *long differencing*.

The models above assume that the elasticity is constant across firms, industries, and geographical units (countries or regions). As indicated in Hall et al. (2010), however, it may be better to assume rate-of-return equalization instead of elasticity (i.e., factor share) equalization. To estimate rates of return, the difference in R&D stock (Δk_{it}), is converted into R&D intensity with the use of the definition of elasticity coefficient, as shown below:

$$\gamma = \left(\frac{\partial Q_{it}}{\partial K_i} \right) \left(\frac{K_{it}}{Q_{it}} \right) = \rho \left(\frac{K_{it}}{Q_{it}} \right) \quad (1.5)$$

From model (1.5), $\rho = \left(\frac{\partial Q_{it}}{\partial K_i} \right)$ is the marginal product of R&D capital. Hence, if the depreciation rate (δ) is near to zero, the rate of return can be estimated directly using the model below (1.6):

$$\Delta y_{it} = \Delta \lambda_t + \alpha \Delta C_{it} + \beta \Delta l_{it} + \rho \frac{R_{it}}{Q_{it}} + \Delta E_{it} \quad (1.6)$$

where R is R&D investment.

The rate of return in the model is the gross returns, with the assumption that the depreciation rate for R&D capital is zero. Griliches (1979) indicated that if the model is estimated with firm-level data, it will yield estimates of private returns to R&D.

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Empirical Literature on Regional Productivity

Below, I present Table (1.1) with the summary of selected studies that have researched on regional productivity, with details of the period of analysis, measure of regional productivity, country of study and findings. Since it is difficult to fully understand on the most precise measurement of the impact of R&D on productivity, it is important to examine empirical literature to provide further insight on the extent of estimations and different perspective. Many studies are in support that regions are important in investigating on research and development (Attila Varga et al. 2010).

There are 15 reviewed studies in Table (1.1), of the reviewed literature, 9 found studies found strong regional dependence on R&D and productivity, 6 research show a significant positive effect of R&D on regional productivity and whilst, 5 studies indicate strong presence of regional disparity, they found a significant and continuous variation in both productivity in the UK and in the Europe. Except for Hulten et al. (1984) who indicate that regional disparities in output growth is not caused by the variation in productivity growth, but instead in the rate of growth of labour and capital.

Table 1. 1: Empirical Evidence of Regional Productivity

<i>Author(s)</i>	<i>Period of data</i>	<i>Measure of Regional Productivity</i>	<i>Country</i>	<i>Findings</i>
Hulten et al. (1984)	1951–1978	Regional Productivity Growth in U.S. Manufacturing	US	Findings shows that regional differences in output growth is not caused by the variation in productivity growth, but instead in the rate of growth of labour and capital.
Attila Varga et al. (2010)	1998-2002	Agglomeration and interregional network effects on European R&D Productivity	European Regions	The study found evidence of strong regional dependence in the production of Edison type of knowledge and using the same sample, they found the effect of R&D on productivity on temporal variation of R&D expenditure.
Zhang et al. (2012)	2000-2007	Productivity in China's high technology industry: Regional	China	The results find a variation on the impact of R&D on output, and its significance varies a great deal across different regions. Further, the findings suggest that investments on R&D will significantly increase

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		heterogeneity and R&D		output in both eastern and central region. Although, technical progress in the central region will strengthen the R&D output within the region.
Davide Castellani and Fabio Pieri (2013)	2003-2008	R&D offshoring and Productivity growth of Europe regions	Europe Regions	A positive regional productivity was found. R&D offshoring regions have larger productivity growth, but disappears with number of R&D investments developments carried out abroad.
Piras et al. (2012)	1980-2003	Specialisation, R&D and Productivity growth: evidence from EU regions	Europe Regions	The researcher assumes that positive externalities and productivity growth is determined by interregional distances and the size of the economy
D.K Christopolous and E.G. Tsionas (2003)	1971–1995	Convergence and Regional Productivity Differences: Evidence from Greek	Greece	The research found that capital strengthening plays important role in defining productivity variations at regional level.
Ezcurra et al. (2005)	1664-1991	Public Capital, Regional Productivity and Spatial Spillovers	Spain	Results shows that public infrastructure reduces the costs on private production and also increases productivity level.
Garrido-Yserte Ruben and Tomas Mancha (2000)	1980-1993	Regional Productivity Pattern in Europe: An Alternative Approach	OECD Countries	The study adopts a new methodological approach, in exploring greater in depth on labour productivity, they found that significant regional disparity exists.
Raffaello Brozini and Paolo Piselli (2009)	1980-2001	Determinants of Long-run Regional Productivity with Geographical Spillovers: The role of R&D, Human Capital, and Public Infrastructure	Italy	The research found that regional productivity affects R&D activity positivity and public infrastructure of neighbouring regions.
Boddy et al. (2006)	1998-2002	The Determinants of Regional Productivity	UK	The researchers focused on the key determinants of regional disparity in the UK, they found a significant and continuous variation in both productivity in the UK and in the Europe.

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		Differentials: The Model		
Webber et al. (2019)	1980-2012	European Regional Productivity: Does Country Affiliation Matter?	OECD Countries	Findings indicates the importance of national borders for knowing the performance of regional productivity, with the implication on the need for regional policy makers to consider national border effects.
Philips McCann (2020)	2020	Perception of Regional Inequality and the Geography of Discontent: Insights from the UK	UK	The paper examines the extent at which regional inequality exists in the UK. The existence of regional unbalance was noted in the review.
Natalia Aldaz and Joaquin A. Millan (2003)	1978-1988	Regional Productivity in a Spanish Agriculture in a Panel DEA Framework	Spain	The research applied DEA ² to a panel data, a decomposition of productivity indicators in both lower and upper bounds of productivity were utilised and they found that the more efficient production component, the Malmquist technique and the other method Aldaz (1998) indicates technical variation.
K. H. Chen et al. (2009)	1996-2004	Analysis of regional productivity growth in China: A generalised metafrontier MPI Approach	China	Regional inequality was found amongst the two regions that was investigated. Also, productivity variation in coastal region was found to be stronger than the non-coastal region of China.
Tranos et al. (2021)	2015-2019	Digital economy in the UK: Regional Productivity effects on early adoption	UK	A significant positive effect was found on regional productivity level, they illustrate on the sizeable effects of digital economy and its implication on regional productivity.

Specifically, there is evidence to justify the effect of R&D on regional productivity. For example, Ruben and Mancha (2000) in search for regional productivity pattern in Europe, observed that significant regional disparity exists. Castellani and Pieri (2013) supports this idea, a positive regional productivity was found in their study, with offshoring regions having larger productivity growth, but disappears with number of investments developments carried

² Data envelopment analysis (DEA), this is a non-parametric approach, used in operations research and economics for estimation production frontiers.

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out abroad. This is similar with Zhang et al., (2012) indicating a variation on the impact of R&D on output, and its significance appears to vary a great deal across different regions.

Further, the findings suggest that investments on R&D will significantly increase output in both eastern and central region. Although, technical progress in the central region will strengthen the R&D output within the region. McCann (2020) however, focuses on the awareness of regional disparity in the UK, the existence of regional unbalance was indicated in the review.

In an earlier study, Coe and Helpman (1995) argued that a country's productivity depends on its domestic and foreign R&D capital stock. Alternatively, Hulten et al. (1984) in examining the regional productivity growth in the US, shows that regional differences in output growth is not caused by the variation in productivity growth, but instead in the rate of growth of labour and capital.

In Boddy et al. (2006), however, a drift in determining the differentials in regional productivity is observed, they argue that the key determinants of regional disparity in the UK, is the continuous variation in both productivity in the UK and in the Europe. This is in line with Webber et al. (2019) with emphasis on the importance of national borders for knowing the performance of regional productivity, with the implication on the need for regional policy makers to consider national border effects. K. H. Chen et al. (2009) verifies of this claim, regional inequality was found amongst the two regions that was investigated in China. Also, productivity variation in coastal region was found to be stronger than the non-coastal region of China. Although, Brozini and Piselli (2009) found that regional productivity affects R&D activity positively and public infrastructure of neighbouring regions matters.

To summarise, the empirical studies on regional productivity reviewed above shows that there is strong evidence of regional disparities on productivity and that regional productivity is affected by capital stock, infrastructure and R&D. Very few studies apart from Brozini and Piselli (2009) have studied the impact of R&D in a particular region on productivity in that region. This paper contributes to the literature by examining the impact of R&D capital on productivity in the UK. The next table provides insights on the methods of estimations used in the R&D literature.

Table (1.2) provides the estimates of empirical research on elasticity and rate of return with firm and industry-level data. The table includes study attributes such as the period of the data,

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the country of origin for the sectors in the study, the dependent variable used; and the method of estimation reported in each of the research. Overall, of the 30 studies presented in Table (1.2), 21 studies reported used the Pooled OLS estimation, 6 used the Total OLS, 11 reported studies used the First Difference method of estimation, with 8 studies using the Long Difference estimation. The studies that reported with System-GMM method of estimation were 9.

With respect to measuring the dependent variable, of the reported 30 literature, 16 studies used value Added as the dependent variable. 12 used Sales as the dependent variable, and 2 studies used both sales and Value Added (VA) as the dependent variable.

A large proportion of the literature utilize OECD data, followed by US, France, UK and Germany. Whilst 70% of the studies use firm-level data, 20% are based on industry-level data.

Table 1. 2: Overview of primary-study properties on R&D elasticity estimates: Industry and Firm-level

<i>Research Author</i>	<i>Country</i>	<i>Dependent Variable</i>	<i>Period of Data</i>	<i>Method of Estimation</i>
Aldieri et al. (2008)	US	Sales	1988-1997	First Diff, GMM, within
Ballot et al. (2006)	OECD-other, France	Value Added (VA)	1987-1993	Pooled OLS, GMM
Bartelsman (1990)	US	Output	1956-1988	Pooled OLS, within
Bartelsman et al. (1996)	OECD-other, France	Value Added (VA)	1995-1993	Total OLS, Long Diff
Blanchard et al. (2005)	France	Value Added (VA)	1994-1998	Pooled OLS, GMM, within
Boler et al. (2012)	OECD-other, France	Sales	1997-2005	Pooled OLS, GMM
Bond et al. (2002)	UK, Germany	Sales	1987-1996	Pooled OLS, GMM
Bonte (2003)	Germany	Value Added (VA)	1980-1993	Long Diff, First Diff, within, between
Cincera (1998)	OECD-other, France	Sales	1978-1994	Pooled OLS, Long Diff, First Diff, within, GMM, between
Cuneo and Mairesse (1984)	France	Value Added (VA)	1972-1977	Within, Pooled OLS
Eberhardt et al. (2013)	OECD-other, France	Value Added (VA)	1980-2005	Pooled OLS, First Diff, GMM, CF Frame
Frantzen (2002)	OECD-mixed	Output	1972-1994	Pooled OLS
Griffith et al. (2006)	UK	Value Added (VA)	1990-2000	Pooled OLS, IV, GMM

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Griliches (1980b)	US	Sales	1957-1965	Total OLS, between
Griliches (1998)	US	Value Added (VA), Sales	1966-1977	Total OLS, Diff
Griliches and Mairesse (1981)	US	Sales	1966-1977	Pooled OLS, within, between
Hall (1993)	US	Sales	1964-1990	Pooled OLS, Long Diff, First Diff
Hall and Mairesse (1995)	US	Value Added (VA)	1980-1987	Pooled OLS, Long Diff, First Diff, within
Harhoff (1994)	Germany	Sales	1977-1989	Pooled OLS, Long Diff, First Diff, within
Hsing and Lin (1998)	US	Sales	1994	Total OLS
Kafourous (2005)	UK	Sales	1989-2002	Pooled OLS
Kwon and Inui (2003)	OECD-mixed	Value Added (VA)	1995-1998	Pooled OLS, Long Diff, First Diff, within
Lehto (2007)	OECD-mixed	Value Added (VA)	1987-1998	Pooled OLS, IV, within, between
Mairesse and Hall (1996)	France, US	Sales, Value Added (VA)	1981-1989	Pooled OLS, Long Diff, First Diff, GMM, within
Ortega-Argiles et al. (2010)	OECD-other	Value Added (VA)	2000-2005	Pooled OLS, between
O'Mahoney and Vecchi (2000)	OECD-other	Sales	1993-1997	Pooled OLS, First Diff
Rogers (2010)	UK	Value Added (VA)	1989-2000	Pooled OLS
Schankerman (1981)	US	Value Added (VA)	1963	Total OLS
Smith et al. (2004)	OECD-other	Value Added (VA)	1995-1997	Total OLS, First Diff
O'Mahoney and Vecchi (2009)	France, Germany, UK, OECD-other	Sales	1988-1997	GMM, First Diff

Source: Ugur et al. (2016; 2020)

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METHODOLOGY AND DATA:

Estimation Strategy

Static Model

My framework for examining the impact of R&D on productivity follows the estimation of the standard Cobb-Douglas production function augmented with own-R&D capital and the external R&D capital (Griliches 1979; Ugur et al. 2020). Assuming perfect competition in the factor markets and separability of the conventional input (labour and capital), the production function can be written as:

$$Y_{it} = Ae^{\lambda t} C_{it}^{\beta_1} L_{it}^{\beta_2} K_{it}^{\beta_3} e^{u_{it}} \quad (1.3.26.)$$

where i is a subscript for the NUTS-2 subdivisions, and t denotes time in years from 2005 to 2016. Y_{it} is the real output, C_{it} is the physical capital stock; L_{it} is labour, K_{it} is own R&D capital stock; while $Ae^{\lambda t}$ is technological progress, with the rate of disembodied technological change denoted by λ_t ; and u_{it} is the idiosyncratic error term.

Taking natural logarithms (1.3.26) can be written as:

$$\log Y_{it} = \eta_i + \lambda_t + \beta_1 \log C_{it} + \beta_2 \log L_{it} + \beta_3 \log K_{it} + u_{it} \quad (1.3.27.)$$

Where the log of technological progress ($Ae^{\lambda t}$) yields a region-specific effect (η_i) and a time effect (λ_t). The slope coefficients yield elasticity estimates with respect to each input. I modify the basic model in equation (1.3.27.), by augmenting it with all the R&D components (RDCs) that I will analyse. Real output is proxied by gross value added in constant 2017 prices (y), physical capital stock (C) and own R&D capital stock (K) were both constructed using the perpetual inventory method as detailed in sections, and Labour is in thousands of hours worked (L). To control for the technical ability of the regions, an RD intensity dummy variable is also included that is 1 for regions with R&D intensity that are beyond the median region and 0 if

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otherwise. Finally, two control variables are added. The size of the region is proxied by population and skill intensity, which serves as a measure of absorptive capacity, is proxied by hrste. The full specification are presented in equations 1.3.28a and 1.3.28b below. In 1.3.28a, own R&D capital stock is proxied by total R&D capital stock (TERD). In 1.3.28b, TERD is disaggregated into its 3 components: namely R&D capital from the Business sector (BERD), government sector (GOVRD) and higher education sector (HERD). In both models, X represents the control variables.

$$\log Y_{it} = \eta_i + \lambda_t + \beta_1 \log C_{it} + \beta_2 \log L_{it} + \beta_3 \log TERD_{it} + \gamma_1 RD_intensity_{it} + \gamma_2 X_{it} + u_{it} \quad (1.3.28a.)$$

$$\log Y_{it} = \eta_i + \lambda_t + \beta_1 \log C_{it} + \beta_2 \log L_{it} + \beta_3 \log BERD_{it} + \beta_4 \log HERD_{it} + \beta_5 \log GOVRD_{it} + \gamma_1 RD_intensity_{it} + \gamma_2 X_{it} + u_{it} \quad (1.3.28b.)$$

Dynamic model

To control for productivity dynamics, equations 1.2.8a and 1.2.8b can be re-written to include the lagged dependent variable as follows:

$$\log Y_{it} = \eta_i + \lambda_t + \alpha \log Y_{it-1} + \beta_1 \log C_{it} + \beta_2 \log L_{it} + \beta_3 \log TERD_{it} + \gamma_1 RD_intensity_{it} + \gamma_2 X_{it} + u_{it} \quad (1.3.29a.)$$

$$\log Y_{it} = \eta_i + \lambda_t + \alpha \log Y_{it-1} + \beta_1 \log C_{it} + \beta_2 \log L_{it} + \beta_3 \log BERD_{it} + \beta_4 \log HERD_{it} + \beta_5 \log GOVRD_{it} + \gamma_1 RD_intensity_{it} + \gamma_2 X_{it} + u_{it} \quad (1.3.29b.)$$

Empirical strategy

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In view of obtaining consistent and unbiased estimated results of the Cobb-Douglas production function, a number of estimation issues needs to be addressed.

The first concern is heterogeneity bias which arises from the correlation of the region specific effects (η_i) and the explanatory variables. The second concern is the endogeneity of the production inputs and R&D capital. Nickell (1996) and Griliches and Mairesse (1998) indicate that inputs should be considered as endogenous variables, due to the fact that producers makes their selections based on the costs of the inputs and also other factors related to productivity. These factors are more visible to the producers than the econometrician. The dynamic model leads to another source of endogeneity arising from the correlation of the lagged dependent variable and the error term. A third concern is that of heteroskedasticity and autocorrelation.

The first concern is addressed through the use of fixed effects estimator. Specifically, for the static models, I apply the pooled OLS estimator to equations 1.3.28a and 1.3.28b controlling for regional and time effects using regional and time dummies. The second concern is addressed through the use of the System GMM estimator which is able to control for heterogeneity bias as well as endogeneity arising from both the lagged dependent variables and the independent variables. I opt for the system GMM rather than the first-differenced GMM because of well-known biases of the first-differenced GMM estimator in short persistent panels (See e.g., Blundell and Bond (1998)). The third concern is addressed by using cluster robust standard errors in all regressions that are robust to heteroskedasticity and within-group autocorrelation. Region specific influences might exist that may have impacted on the effects of R&D on regional productivity and external presence, these factors are known to the region, but not known by the econometrician. For example, high quality management and other infrastructure development in a region are part of those factors. Haskel et al. (2007) suggests that the remedy to the problem is by taking the difference of the data in order to rid any possible correlation between the explanatory variable and region-specific effects.

Arellano and Bond (1990) pointed out that GMM estimator will be consistent and efficient, if the error term is found to be non-persistent. According to Blundell and Bond (1998) lagged levels and lagged differences are both used as instruments in estimating production function parameters. Also, it is worth noting that standard errors are robust and corrected for finite sample bias (as shown by Windmeijer, 2000).

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University of Greenwich, London, UK

Another estimation issue is the cluster errors. According to Bertrand, Duflo and Mullainathan (2004) maintain that regressions performed by micro units and inclusion of aggregate markets, or region variables, the standard errors of the OLS will be underestimated. This can lead to a more complicated error if not accounted for, thereby leading to a spurious finding of statistical significance on the variable of interest. Javorick (2004) controls this error by imputing the simple-cluster robust option. As argued by Xu and Sheng (2012) using the simple cluster is inadequate to account for the problem, they proposed the use of Wooldridge (2006) this approach adopts the two-stage estimation, where it has both inter and intra group components in the error term, which helps to better control the cluster effects. It also further accounts for the problem of multicollinearity and identification problem between region dummies and firm dummies

Finally, another estimation problem, is the reverse causality. Reverse causality relates to the direction of the cause and effect of a variable on another variable, this relationship is the reverse of a cause-and-effect connection between those variables. For example, if variable X causes a change in Y as expected, reverse causality occurs in the opposite directions, which mean that Y will cause a change or changes in X. Econometric and statistical studies have developed various ways of dealing with the problem of reverse causality. This includes: first difference (FD) models with lagged dependent variables (Allison, 2009). Another method is through the use of the first difference GMM or/and system GMM estimators. These GMM estimators tackle reverse causality in a dynamic panel data setting through the use of instrumental variables (Leszczensky and Wolbring, 2019).

This study relies on the System GMM estimator, as proposed by Arellano and Bond (1991) and Blundell and Bond (1998) which helps to account for simultaneity or endogeneity bias and reverse causality, it combines equations from levels and first difference and eliminates the region-specific effects, using the lagged levels of variables as valid instruments. Thus, as noted by Blundell and Bond (1998) system GMM estimator is efficient and consistent in a standard Cobb Douglas production function, while taking account for endogeneity issue. With the rationale explained above, my thesis relies on System GMM as more efficient method for estimating the effect of R&D on regional productivity.

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Model, Estimation Problems and Data

Model Baseline Model

In examining the impact of R&D on productivity, I adopt the approach that has been used extensively in previous literature (Griliches, 1979; Coe et al., 1997; van Pottelsberghe de la Potterie and Lichtenberg, 2001; Clarke and Griliches, 1984). The method follows estimation of the standard Cobb-Douglas production function augmented with own-R&D capital and the external R&D capital (Griliches 1979; Ugur et al., 2020). Thus, the traditional production function is extended by introducing the R&D components as a generator of knowledge.

My empirical model is built as follows:

$$y_{it} = \eta_i + \lambda_t + \alpha c_{it} + \beta l_{it} + \gamma k_{it} + BERD_{it}^\gamma + GOVRD_{it}^\gamma + HERD_{it}^\gamma + u_{it} \quad (1.4.1.)$$

where the log of technological progress ($Ae^{\lambda t}$) yields a region-specific effect (η_i) and a time effect (λ_t). The slope coefficients yield elasticity estimates with respect to each input. I modify the basic model in equation (1.4.1.), by augmenting it with all the R&D components (RDCs) and RD intensity, that I will analyse. Real output is proxied by gross value added in constant 2017 prices (y), physical capital stock (C), own R&D capital stock (K), and Labour is in thousands of hours worked (L).

$$Y_{it} = Ae^{\lambda t} + C_{it}^\alpha + L_{it}^\beta + K_{it}^\gamma + BERD_{it}^\gamma + GOVRD_{it}^\gamma + HERD_{it}^\gamma + RD_{Intensity}_{it}^\gamma + \varepsilon^{uit} \quad (1.4.2.)$$

$$\text{Log}Y_{it} = \beta_1 \log BERD_{it} + \beta_2 \log GOVRD_{it} + \beta_3 \log HERD_{it} + \beta_1 \log RD_Intensity_{it} + \varepsilon^{uit} \quad (1.4.2a.)$$

$$e^{uit} = e_c + e_j + d_t + V_t \quad (1.4.2b.)$$

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Here c , j and t are region specific. The composite error term (e^{uit}) comprise of time effects (e_c and e_j), the year specific effects (d_t) and the idiosyncratic error (V_t).

Dynamics

Equation (1.4.2.) can be re-written in level form with dynamic control for the lagged dependent variable as follows:

$$\log Y_{it-1} = \alpha_{it} \log Y_{it-1} + \beta_1 \log BERD_{it} + \beta_2 \log GOVRD_{it} + \beta_3 \log HERD_{it} + \beta_1 \log RD_Intensity_{it} + \varepsilon^{uit} \quad (1.4.3.)$$

The remark to note here is that the first lag control is based on the GMM estimates, the first lag of the output (Value-added) affects its contemporaneous.

Where;

i = subscript for the NUTS-2 subdivisions; t = subscript for time in years from 2009 to 2016.

Y_{it} = real output (gross value added in constant 2017 prices)

C_{it} = physical capital stock ($C_t = I_{t-1} + (1-\delta_c)C_{t-1}$; where I = real GFCF; δ_c = 6%, 8% and 9% respectively)

L_{it} = labour (thousands of hours worked)

K_{it} = own R&D capital stock ($K_{bt} = R_{bt-1} + (1-\delta_k)K_{bt-1}$; where K_t represents R&D capital stock for each, R is real R&D, b type of R&D), depreciation rate for R&D (δ_k) was set at 6%, 8%.

Physical capital stock is constructed using the perpetual inventory method as follows: $C_t = I_{t-1} + (1-\delta_c)C_{t-1}$, where I is real GFCF. δ_c is the rate of depreciation or the rate of obsolescence, which, following the literature, was assumed to be 6% per annum (Vandenbussche et al., 2006; Coe and Helpman, 1995; Bernstein and Nadiri, 1998; Bloom and Caleb, 2017; Driffield, 2006). Initial capital stock (C_0) was constructed as follows: $C_0 = \frac{I_0}{g+d_c}$, where I_0 was GFCF in 2000 (the first year that GFCF was available in our dataset), and g is the growth rate between 2000 and 2009 (the start date of my analysis).

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It is noteworthy that, own R&D capital stock consists of Total R&D capital stock (TERD) and its components: Business R&D capital stock (BERD), Government R&D capital stock (GOVRD), and Higher Education R&D capital stock (HERD). Like physical capital stock, the perpetual inventory method was also used to calculate R&D capital: $K_{bt} = R_{bt-1} + (1 - \delta_k)K_{bt-1}$, where K_t represents R&D capital stock for each b type of R&D (Total R&D, Business R&D, Government R&D and Higher Education R&D),³ R denotes real R&D expenditure. In line with previous studies, I deflated the nominal R&D expenditures using the GDP deflator (Cameron, 1996).

Estimation Issues

In this section of the thesis, I utilize the generalised method of moment (GMM) estimator, proposed by Arellano and Bond (1991) and Blundell and Bond (1998) to account for the problems of endogeneity and simultaneity. The empirical specification test proposed by Arellano and Bover (1995) are employed to test for the validity of the instrument set used in the GMM estimator. The Arellano and Bond tests for serial correlation and checks if there is a second order serial correlation among the first-differenced residuals. The null hypothesis holds that the residuals are serially uncorrelated. Therefore, if the null hypothesis cannot be rejected, it indicates evidence that second order serial correlation does not hold and the GMM estimator is consistent. Further, the Hansen and the Diff-in Hansen tests are used to test for the validity of the instrument and the validity of the additional moment constraint used in system GMM. When the null hypothesis is not rejected, it is said that the instruments sets are valid.

In this thesis, I adopt further approach to enhance the efficiency of system GMM. As shown in Roodman (2009) the instrument sets are collapsed and the orthogonal option is selected. In addition, region-specific and time-specific effects are incorporated in the regression in order to capture the region and trend effects, the OLS and FE estimators are used to validate the GMM results. The econometrics package used in the estimation is Stata 16.

³ Business R&D (BERD), Government R&D (GOVRD) and Higher Education R&D (HERD) refer to R&D expenditures from the Business, Government and Higher Education sectors. Total R&D is defined as total intramural R&D expenditures and is the sum of BERD, GOVRD and HERD.

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Data

This research concentrates on regions contained in the UK's NUTS-2 levels, which consists of 35 regions after cleaning the dataset, with study period from 2000 to 2016. Table 1.6. presents the summary statistics of the variables employed in my empirical estimation.

Table 1. 3: Descriptive Statistics

No	Variable	Obs	Mean	Std dev.	Min	Max
1	Real Gross Value Added (£m)	627	42600.79	51410.24	7424.295	409864
2	Log Real Gross Value Added	627	10.38099	.6600369	8.912513	12.92358
3	Log Physical Capital stock	628	11.29008	.6148948	9.863955	13.42103
4	Employment (Thousands of hours)	628	13.73487	.6168803	12.41771	15.87982
5	Log Total R&D capital stock -TERD	396	7.830336	1.183782	4.804796	10.1411
6	Log Government R&D capital stock - GOVRD	484	4.76865	1.78713	.5297427	7.783835
7	Log Business R&D capital stock - BERD	495	7.313269	1.223871	4.616252	9.431847
8	Log Higher Education R&D capital stock - HERD	407	5.957243	2.020745	-2.862248	9.415187
9	Log HRSTE	620	4.840211	.6963233	3.148453	7.41397
10	RD_intensity	412	.0173443	.0121784	.0008748	.0661057

Table 1. 4: Correlations Matrix

Variable	1	2	3	4	5	6	7	8	9	10
1.	1									
2. Log Value-added	0.8183	1								
3. Log CapitalStock	0.7630	0.9721	1							
4. Log Employment	0.7713	0.9860	0.9624	1						
5. Log TotalRD	0.5440	0.8629	0.8677	0.8406	1					

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6. Log GOVRD	0.4462	0.6158	0.6262	0.5647	0.7429	1				
7. Log BERD	0.4537	0.7701	0.7801	0.7498	0.9368	0.6530	1			
8. Log HERD	0.4638	0.7201	0.7368	0.7150	0.7323	0.5425	0.5061	1		
9. Log HRSTE	0.7644	0.9679	0.9600	0.9664	0.8478	0.6029	0.7528	0.7138	1	
10. RD_Intensity	0.0860	0.3915	0.4472	0.3600	0.7362	0.6013	0.7555	0.3798	0.3761	1

Source: Author's calculation from the dataset

Table 1.6. shows the summary statistics of my dataset. The real average output for the region was about £42 billion on average, ranging from £7 billion in region to £40 billion in region. Mean employment across the regions was about 13, 734 with very little variation across the regions. The average value for BERD (£7.3 million) is the highest among of the R&D components. The mean value for HERD and GOVRD is about £5.9 million and £4.7 million, respectively. The mean R&D intensity in the sample was 1.7% with a standard deviation of about 1.2%, showing some variation in the amount of R&D intensity across the regions.

Table 1.7. shows the correlations matrix. There is a moderate correlation among the independent variables with a particularly high correlation between log employment and log capital stock (0.9624).

Discussion of Estimated Results

Results for Static Model

The static model results of the impact of own R&D on regional productivity are shown in Tables 1.8 to Table 1.10. OLS regressions with robust standard errors are reported in all tables.

The effect of Total R&D on regional productivity is presented in Table 1.8. There are 395 region-year observations. Time and regional dummies are excluded from column 1 but included in columns 2 and 3. Hence, columns 2 and 3 are effectively fixed effects regressions. In addition, column 3 includes a dummy variable for regions with R&D intensities higher than the median. The results show that capital and labour elasticities are in line with the literature. Total R&D has a positive and significant effect on productivity. Specifically, a 1% increase in total R&D capital is predicted to increase productivity by about 0.04% on average. The R&D intensity dummy is insignificant, showing that regions with higher R&D intensities are not more productive than regions with lower R&D intensities, after controlling for total R&D.

The Effect of Total R&D capital on Regional Productivity: OLS Regressions: 2005-2016

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Dependent variable: Log of Real Gross Value added			
	(1)	(2)	(3)
Log of Employment	0.735*** (0.0333)	0.594*** (0.0653)	0.599*** (0.0661)
Log of Physical Capital stock	0.282*** (0.0383)	0.248*** (0.0564)	0.250*** (0.0568)
Log of Total R&D capital stock	0.0370*** (0.0104)	0.0431*** (0.0145)	0.0397*** (0.0152)
High R&D intensity dummy			0.00404 (0.00426)
Time and regional dummies	No	Yes	Yes
<i>Region-year observations</i>	395	395	395
R^2	0.981	0.999	0.999
adj. R^2	0.980	0.999	0.999

Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$, Robust standard errors used, The high R&D intensity dummy=1 if R&D intensity in region is higher than the median R&D intensity in the sample.

Table 1. 5: Effect of R&D capital on Regional Productivity by R&D type: 2005-2016

Dependent variable: Log of Real Gross Value added			
	(1)	(2)	(3)
Log of Employment	0.766*** (0.0316)	0.606*** (0.0764)	0.591*** (0.0745)
Log of Physical Capital stock	0.275*** (0.0359)	0.316*** (0.0617)	0.284*** (0.0606)
Log of Government R&D capital stock	0.0208*** (0.00307)	0.00807*** (0.00304)	0.00855*** (0.00328)

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Log of Business R&D capital stock	0.00443 (0.00872)	-0.00497 (0.0115)	-0.00566 (0.0131)
Log of Higher Education R&D capital stock	-0.00293 (0.00291)	0.00373 (0.00386)	0.00361 (0.00391)
High R&D intensity dummy			0.00934** (0.00433)
Time and regional dummies	No	Yes	Yes
<i>Region-year observations</i>	403	403	374
R^2	0.981	0.999	0.999
adj. R^2	0.981	0.999	0.999

Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$, Robust standard errors used, the high R&D intensity dummy=1 if R&D intensity in region is higher than the median R&D intensity in the sample

In Table 1.9., Total R&D capital is broken down into its components: Business R&D capital stock (BERD), R&D capital stock from the higher education sector (HERD) and R&D capital stock from the government sector (GOVRD). This allows us to check whether the three R&D types can be regarded as substitutes or complements. The results show that only GOVRD has a positive and significant effect on productivity (with an elasticity estimate of 0.008), even after controlling for regions with higher R&D intensities.

Given that only GOVRD is statistically significant, Table 1.10. below, reports OLS regressions where the R&D types are entered separately. Again, only GOVRD is positive and significant, with its elasticity of similar magnitude to Table 1.9. Taken together, the results in Tables 1.9. and 1.10. confirm that the three R&D types can be regarded as substitutes rather than complementary with one another.

Both Tables 1.9. and 1.10. indicate that regions with higher R&D intensities enjoy higher productivity levels than less R&D intensive regions, after controlling for R&D type.

Table 1. 6: Effect of R&D capital on Regional Productivity by R&D type (Separate regressions): 2005-2016

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Dependent variable: Log of Real Gross Value added						
	(1)	(2)	(3)	(4)	(5)	(6)
Log of Employment	0.633*** (0.0626)	0.624*** (0.0678)	0.618*** (0.0614)	0.613*** (0.0690)	0.622*** (0.0763)	0.602*** (0.0743)
Log of Physical Capital Stock	0.321*** (0.0475)	0.264*** (0.0575)	0.329*** (0.0480)	0.269*** (0.0575)	0.316*** (0.0615)	0.284*** (0.0609)
Log of Government R&D Capital Stock	0.00446* (0.00253)	0.00756** (0.00312)				
High R&D intensity dummy		0.0110*** (0.00393)		0.0105** (0.00411)		0.00787* (0.00408)
Log of Business R&D Capital Stock			-0.00607 (0.00942)	0.000323 (0.0119)		
Log of Higher Education R&D Capital Stock					0.00505 (0.00374)	0.00480 (0.00371)
<i>Region-year observations</i>	483	393	494	395	406	375
R^2	0.999	0.999	0.999	0.999	0.999	0.999
adj. R^2	0.999	0.999	0.999	0.999	0.999	0.999

Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors used. Time and Regional dummies used in all regressions. The high R&D intensity dummy=1 if R&D intensity in region is higher than the median R&D intensity in the sample

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Finally, the full sample is used in the estimations in Tables 1.7. to 1.10. However, it is common practice in the literature to allow a gap between the construction of initial capital stock and the actual estimation period to allow measurement error in the construction of capital to be depreciated away over time (e.g., Coe and Helpman, 1991, Ugur et al., 2020). In my dataset, initial physical capital stock was in 2000 but initial stock for R&D capital ranged from 2002 for Government and Business R&D to 2005 for total R&D. Therefore, to allow for the depreciation of possible measurement error in the construction of the different R&D capital stocks especially for total R&D, I also estimated the regressions with a start period of 2009. The results are presented in Tables 1.11. to 1.15. (as indicated in section 1.3). The results are very similar showing that measurement error in the construction of the capital stock variables might not be a serious concern.

Table 1. 7: The effect of Total R&D on Regional Productivity: GMM Estimates

Dependent variable: Log of Real Gross Value added						
	Restricted sample: 2009-2016			Full sample: 2005-2016		
	1	2	3	4	5	6
	Pooled OLS	Fixed Effects FE	System GMM	Pooled OLS	Fixed Effects	System GMM
Log (Real Gross value added) _{t-1}	1.000*** (58.44)	0.456*** (6.92)	1.072*** (10.62)	1.007*** (70.20)	0.616*** (10.44)	1.024*** (8.23)
Log of Employment	0.00683 (0.36)	0.455*** (4.86)	0.0275 (0.79)	-0.00230 (-0.15)	0.290*** (4.83)	0.0475 (0.91)
Log of Physical Capital stock	-0.00470 (-0.47)	0.00632 (0.32)	-0.0948 (-1.22)	-0.00383 (-0.48)	0.0242 (0.71)	-0.0634 (-0.82)
Log of Total R&D capital stock	0.00112 (0.59)	0.0109 (0.50)	-0.0194 (-0.77)	0.00105 (0.61)	0.0131 (0.95)	-0.0168 (-0.55)
Constant	-0.0900 (-1.06)	-0.776 (-0.70)	0.134 (0.27)	0.0233 (0.32)	-0.356 (-0.49)	-0.0398 (-0.10)

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<i>Region-year observations</i>	262	262	262	394	394	394
No of regions			33			33
No. of instruments			21			21
AR(1) test: p-value			0.00036			0.00023
AR(2) test: p-value			0.481			0.605
Hansen test (p-value)			0.479			0.139
Difference Hansen test (p-value)			0.493			0.194

(1) *t* statistics in parentheses. (2) Time dummies are included in all regressions, (3) Robust standard errors are clustered at the NUTS 2 sub-divisional level, (4) * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. (5) One step system GMM computed with second and third lags of all variables used as instruments.

Results for Dynamic Model

The results for the dynamic model are presented in Tables 1.11. to 1.15., with Table 1.11. focusing on the impact of Total R&D and Tables 1.12. to 1.15., examining the effects of R&D by type. The dependent variable is the log of real GVA. The first three columns present pooled OLS, fixed effects, and system GMM estimates respectively for the full sample (2005-2016). For comparison, results from the restricted sample (2009-2016) are reported in columns 4 to 6.

The table also include specification test results (Hansen test for the validity of all the instruments used, tests for serial correlation in the error term and the Differenced-Hansen test for the validity of all the additional instruments used in the system GMM compared with a standard first differenced GMM). Finally, the table lists the number of observations, the number of the NUTS2 regions and the number of the collapsed instruments used in the estimations.

The second and third lags of all variables are used as instruments. This allows for all explanatory variables to be treated as endogenous but the lagged dependent to be treated as predetermined. To avoid overfitting, which could lead to bias and significantly reduce the

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reliability of the specification tests (Roodman, 2009), the instruments were collapsed to restrict their number (see section 1.3.). The rule of thumb in Roodman (2009) is that the number of instruments should be less than the number of cross-sections. Table 1.13. to 1.15., shows that the instrument set is less than the number of regions.

Across the tables, the p-values of the AR(1) and AR(2) tests shows that there is a significant first order correlation in the first differences of the error term but the second order correlation is insignificant. This suggests an absence of serial correlation in the error terms. The Hansen test supports the validity of the instruments as the p-values are not statistically significant. The p-values of the Difference-Hansen tests are not significant⁴ either, which confirms the validity of the additional instrument used in system GMM over that used in a first-differenced GMM estimation⁵. All estimations include time dummies.

The coefficient on the lagged dependent variable is known to be upwardly biased with the pooled OLS estimator and downwardly biased with the fixed effects estimator (Arellano and Bond, 1991) and system GMM (Arellano and Bover, 1995; Blundell and Bond, 1998) Hence, if GMM is consistent, the coefficient on the lagged dependent variable should be between that of the pooled OLS and the fixed effect estimates. Table 1.11. above, shows that the system GMM is slightly higher than that of the pooled OLS suggesting upward bias in the system GMM. However, when the results are broken into R&D type, the system GMM estimates of the lagged value-added lies in between the pooled OLS and fixed effects regression results.

In Table 1.11., where the impact of total R&D on productivity is examined, the lagged value added is positive and significant, but capital stock is insignificant across all columns. The labour coefficient is also mainly insignificant except in the fixed effects regressions. After controlling for lagged gross value added, and capital stock, the labour elasticity estimates is 0.455 with the restricted sample and 0.290 with the unrestricted sample, which is in line with literature (e.g., Archarya and Keller (2009) who estimated a labour elasticity coefficient of 0.590).

⁴ The exception is in Table 1.15 where the p-value of the Difference Hansen test is 0.0143 which shows that the extra instruments are not valid for this particular regression, which is of the impact of R&D from the higher education sector using the restricted sample. However, the finding that R&D from the higher education sector is not significant is consistent across all tables, so the non-validity of extra instruments in this particular regression does not change the overall finding.

⁵ Results are not reported for the first-differenced GMM estimator but are available upon request.

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Table 1. 8: The effect of Business, Higher Education and Government R&D on Regional Productivity: GMM Estimates

Dependent variable: Log of Real Gross Value added						
	Restricted sample: 2009-2016			Full sample: 2005-2016		
	1	2	3	4	5	6
	Pooled OLS	Fixed Effects FE	System GMM	Pooled OLS	Fixed Effects FE	System GMM
Log (Real Gross value- added)t-1	0.996*** (56.40)	0.424*** (6.28)	0.886*** (10.09)	0.997*** (73.72)	0.644*** (8.35)	0.897*** (10.92)
Log of Employment	0.0144 (0.75)	0.451*** (4.70)	0.106*** (2.89)	0.0125 (0.85)	0.306*** (4.55)	0.150* (1.90)
Log of Physical Capital stock	-0.00344 (-0.32)	0.0244 (0.99)	0.0108 (0.12)	-0.00562 (-0.69)	0.0459 (1.01)	-0.0224 (-0.61)
Log of Government R&D capital stock	0.00242** (2.47)	0.00645** (2.12)	0.0115*** (2.92)	0.00253*** (3.09)	0.00406 (1.64)	0.00917* (1.71)
Log of Business R&D capital stock	-0.00244 (-1.40)	0.00360 (0.18)	-0.00392 (-0.41)	-0.00230 (-1.58)	-0.00348 (-0.41)	-0.0150 (-0.81)
Log of Higher Education R&D capital stock	-0.00150 (-1.58)	-0.00220 (-0.64)	-0.00467 (-1.40)	-0.000806 (-0.99)	0.00275 (0.94)	-0.00218 (-0.58)
Constant	-0.140 (-1.52)	-0.557 (-0.50)	-0.382 (-1.28)	-0.0382 (-0.54)	-1.018 (-1.19)	-0.644 (-1.21)
<i>Region-year observations</i>	244	244	244	402	402	402
No of regions			33			33
No. of			31			31

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instruments						
AR(1) test: p-value			0.000486			0.0000257
AR(2) test: p-value			0.386			0.497
Hansen test (p-value)			0.322			0.234
Difference Hansen test (p-value)			0.122			0.173

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. (2) Time dummies are included in all regressions, (3) Robust standard errors are clustered at the NUTS 2 sub-divisional level, (4) (5) One step system GMM computed with second and third lags of all variables used as instruments.

Table 1.12. reports the dynamic results of all the R&D types, with restricted period (2009 to 2016) and with full sample (2005 to 2016). The first three columns report results from Pooled OLS, fixed effects, and system GMM for the restricted sample, while the last three columns present pooled OLS, fixed effects, and system GMM results for the full sample. The system GMM is expected to lie between the Pooled OLS and FE which is the case in the full sample but not in the restricted sample where it is slightly higher than that of the pooled OLS, suggesting a slight upward bias in the system GMM in the restricted sample.

As in Table 1.12, lagged value added is positive and significant across all models but capital stock is insignificant. However, the employment coefficient is positive and statistically significant with the fixed effects and system GMM estimators and of similar magnitude to that of Table 1.12. Comparing the coefficients on BERD, GOVRD & HERD, only R&D capital from the government sector has a significant effect on regional productivity. A 1% increase in Government R&D capital is predicted to increase productivity by 0.0115% (for restricted sample) and 0.00917% (full sample).

To mirror the static results, I re-run the estimations separately for each R&D type in Tables 1.13. to 1.15. Only R&D from the government sector (GOVRD) has a significant effect on productivity, with an elasticity of 0.01 in the restricted sample, although the coefficient becomes insignificant in the full sample. The results mainly hold whether we use the full or

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restricted sample and are robust to the inclusion of persons with tertiary education as a control variable for differences in skills across regions (Table 1.6 in the Appendix).

The static and dynamic results confirm the finding that of the three R&D types, only R&D performed in the government sector has a positive and significant effect on regional productivity, with an elasticity of about 0.01. The results mainly hold whether we use the full or restricted sample and are robust to the inclusion of persons with tertiary education as a control variable for differences in skills across regions. (as shown in Table 1.6 in Appendix). This is similar in magnitude to the static results.

Table 1. 9: The effect of Business R&D on Regional Productivity: GMM Estimates

Dependent variable: Log of Real Gross Value added						
	Restricted sample: 2009-2016			Full sample: 2005-2016		
	1	2	3	4	5	6
	Pooled OLS	Fixed Effects FE	System GMM	Pooled OLS	Fixed Effects FE	System GMM
Log (Real Gross value added)t-1	1.001*** (56.99)	0.461*** (7.05)	1.032*** (12.96)	0.996*** (76.25)	0.682*** (10.62)	0.942*** (8.61)
Log of Employment	0.00615 (0.32)	0.459*** (4.76)	0.0389 (1.53)	0.00774 (0.57)	0.297*** (4.80)	0.130 (1.15)
Log of Physical Capital stock	-0.00361 (-0.36)	0.00249 (0.12)	-0.0796 (-0.98)	-0.00321 (-0.47)	0.0598* (1.96)	-0.0656 (-1.59)
Log of Business R&D capital stock	0.000295 (0.19)	0.00832 (0.47)	-0.00419 (-0.40)	-0.0000993 (-0.08)	-0.00247 (-0.31)	-0.0107 (-0.78)
Intercept	-0.0963	-0.821	0.0951	-0.00382	-1.429	-0.336

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	(-1.19)	(-0.73)	(0.27)	(-0.06)	(-1.65)	(-0.60)
<i>Region-year observations</i>	262	262	262	493	493	493
No of regions			33			33
No of instruments			27			27
AR(1) test: p-value			0.000358			0.0000218
AR(2) test: p-value			0.495			0.810
Hansen test (p-value)			0.322			0.564
Difference Hansen test (p-value)			0.422			0.607

(1) *t* statistics in parentheses, (2) The dependent variable is the log of real gross value added, (3) Time dummies are included in all regressions, (4) Robust standard errors are clustered at the NUTS 2 sub-divisional level, (5) * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 1. 10: The effect of Government R&D on Regional Productivity: GMM Estimates

Dependent variable: Log of Real Gross Value added						
	Restricted sample: 2009-2016			Full sample: 2005-2016		
	1	2	3	4	5	6
	Pooled OLS	Fixed Effects FE	System GMM	Pooled OLS	Fixed Effects FE	System GMM
Log (Real Gross value added)t-1	0.467*** (7.02)	0.467*** (7.02)	0.970*** (10.65)	0.677*** (10.87)	0.677*** (10.87)	1.006*** (6.89)

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Log of Employment	0.458*** (5.03)	0.458*** (5.03)	0.107** (2.56)	0.305*** (4.87)	0.305*** (4.87)	-0.00129 (-0.01)
Log of Physical Capital stock	0.00541 (0.28)	0.00541 (0.28)	-0.107 (-1.09)	0.0571** (2.12)	0.0571** (2.12)	0.00747 (0.14)
Log of Government R&D capital stock	0.00545* (1.82)	0.00545* (1.82)	0.0102** (2.22)	0.00350* (1.78)	0.00350* (1.78)	0.00548 (1.06)
Intercept	-0.865 (-0.79)	-0.865 (-0.79)	0.0449 (0.09)	-1.501* (-1.78)	-1.501* (-1.78)	-0.156 (-0.60)
<i>Region-year observations</i>	262	262	262	482	482	482
No of regions			33			33
No of instruments			21			27
AR(1) test: p-value			0.000264			0.0000793
AR(2) test: p-value			0.531			0.650
Hansen test (p-value)			0.260			0.327
Difference Hansen test (p-value)			0.716			0.233

(1) *t* statistics in parentheses, (2) The dependent variable is the log of real gross value added, (3) Time dummies are included in all regressions, (4) Robust standard errors are clustered at the NUTS 2 sub-divisional level, (5) * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 1. 11: The effect of Higher Education R&D on Regional Productivity: GMM Estimates

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Dependent variable: Log of Real Gross Value added						
	Restricted sample: 2009-2016			Full sample: 2005-2016		
	1	2	3	4	5	6
	Pooled OLS	Fixed Effects FE	System GMM	Pooled OLS	Fixed Effects FE	System GMM
Log (Real Gross value added)t-1	1.003*** (56.74)	0.432*** (6.48)	0.954*** (8.13)	1.004*** (74.29)	0.651*** (8.61)	1.001*** (12.04)
Log of Employment	0.00379 (0.20)	0.457*** (4.62)	0.0217 (1.38)	0.00238 (0.16)	0.312*** (4.69)	0.0448 (0.80)
Log of Physical Capital stock	-0.00177 (-0.17)	0.0280 (1.28)	0.0333 (0.23)	-0.00438 (-0.56)	0.0415 (0.94)	-0.0569 (-0.67)
Log of Higher Education R&D capital stock	-0.000868 (-0.87)	-0.000986 (-0.33)	-0.00177 (-0.89)	-0.000174 (-0.20)	0.00348 (1.20)	0.000618 (0.15)
Intercept	-0.104 (-1.06)	-0.701 (-0.59)	-0.179 (-0.39)	-0.000858 (-0.01)	-1.142 (-1.34)	0.0309 (0.11)
<i>Region-year observations</i>	244	244	244	405	405	405
No of regions			33			33
No of instruments			21			25
AR(1) test: p-value			0.00105			0.0000245
AR(2) test: p-value			0.354			0.517
Hansen test (p- value)			0.0549			0.320
Difference			0.0143			0.561

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Hansen test (p-value)						
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(1) *t* statistics in parentheses, (2) The dependent variable is the log of real gross value added, (3) Time dummies are included in all regressions, (4) Robust standard errors are clustered at the NUTS 2 sub-divisional level, (5) * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Conclusion

The study has examined the impact of R&D on regional productivity. I investigate the direct effects of business, government, and higher education R&D on regional productivity using a panel dataset of 35 UK NUTS-2 regions from 2005 to 2016. The objectives of this research are to: (i) compare productivity effects of own R&D and regional knowledge from business, government, and higher education research at the NUTS-2 region levels; (ii) Establish whether business R&D, government R&D and higher education research funding are complements or substitutes.

To conduct the analysis, static and dynamic models of the augmented Cobb-Douglas production function are run. I utilise three different estimators-the pooled OLS estimator, the fixed effects estimator and the System GMM estimator that was proposed by Arellano and Bond (1991) and Blundell and Bover (1998). I am able to control for time and regional unobserved heterogeneity and (with the system GMM), endogeneity.

The study reports several results. First, the static results indicate that total R&D has a positive and significant impact on regional productivity. However, with the R&D components (BERD, HERD, and GOVRD), only government R&D was positive and significant. Second, the dynamic results confirm the findings of the static results that only government R&D has a positive and significant effect on regional productivity. I also find that: (i) regions with higher R&D intensity enjoy higher productivity levels; (ii) the R&D types can be considered as substitutes as opposed to complements. These results translate that government expenditure on R&D increases regional productivity directly, through stimulating R&D investments in the region. Comparably, these findings are in line with Guellec and van Pottlesberghe de la Potterie (2001) but, contrasts with Lichtenberg (1984). The results also implies that R&D investment by the government could promote R&D expenditures in the NUTS-2 regions of the UK.

From a policy perspective, the findings support government spending on R&D as a means of stimulating regional productivity.

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University of Greenwich, London, UK

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Lecturer – International Business

University of Greenwich, London, UK

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University of Greenwich, London, UK

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