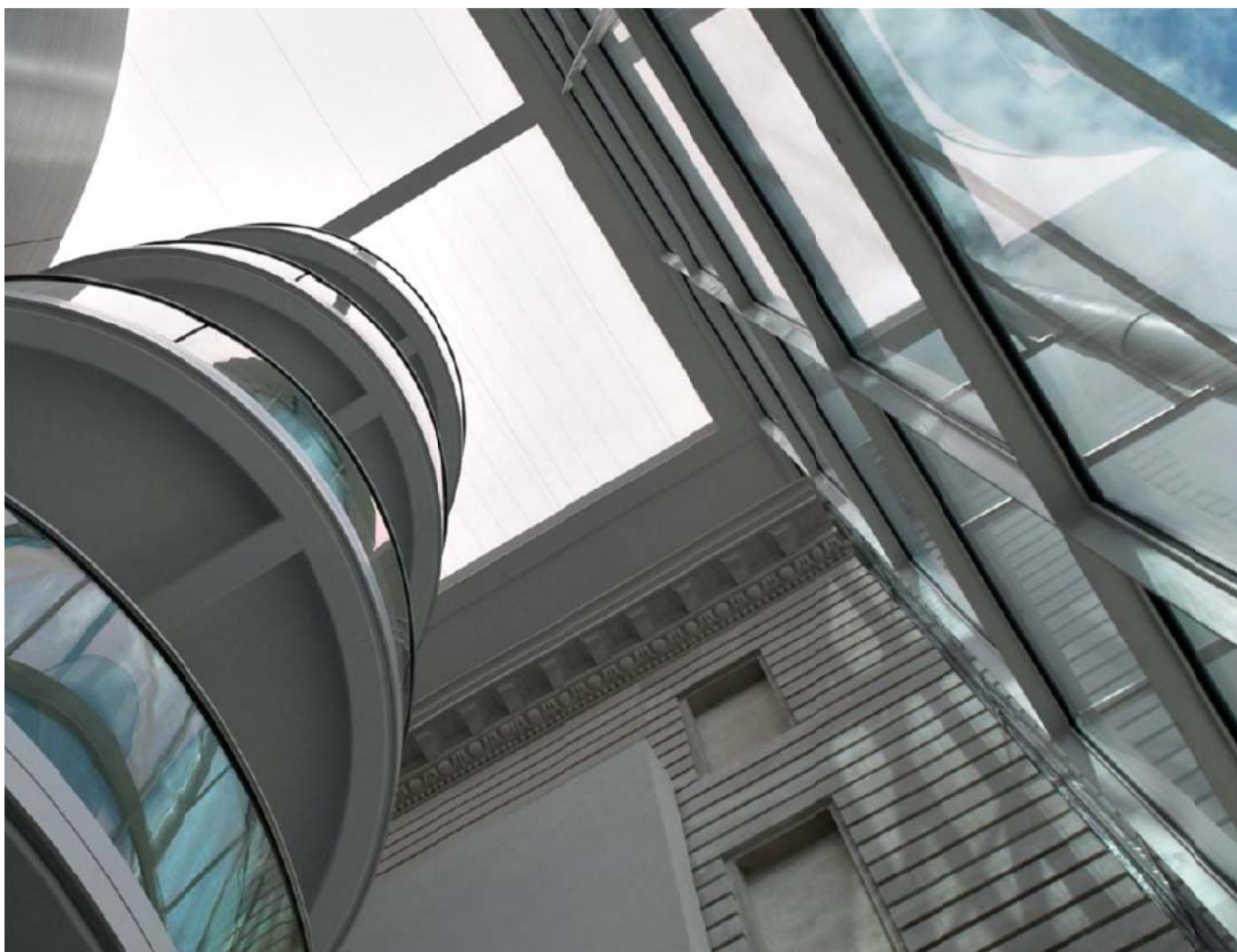


The contribution of public and private R&D to UK productivity growth

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The Contribution of Public and Private R&D to UK Productivity Growth*

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Abstract

We estimate the contribution of public and private R&D to UK productivity growth on industry data, 1992-2007. R&D affects productivity growth via (1) R&D input, valued at competitive factor shares and (2) (Domar-Hulten weighted) industry TFP growth if there are (a) within-industry spillovers (b) between-industry spillovers and (c) spillovers from public-sector R&D to the market sector. Thus effects depend upon factor shares, spillovers and industrial structure. We estimate all these effects and perform counter-factual experiments such as e.g. additional government spending on the science budget, increased manufacturing R&D spending and the effects of such changes with a different industrial structure.

Keywords: productivity, R&D

JEL classification: O47, O38, O32

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1 Introduction

The effect of R&D on UK economic growth remains a key economic and policy question. What for example is the effect of private and public R&D on productivity? How much of that effect, if any, is due to spillovers, and what part, if any, can policy play? Does the UK industrial structure, with its relatively small manufacturing sector (where most R&D is conducted), matter for the impact of R&D? This paper re-examines these questions with some new data and obtains, we think, some new answers.

There are clearly many methods for studying the impact of R&D science on growth, ranging from detailed historical case studies of particular innovations to cross-country studies using aggregate data. This present paper uses just one method, which relies on a sources-of-growth plus spillovers framework, implemented on 7 UK industries, 1992-2007. We emphasise that this choice of aggregation, over a limited time period, using a particular economic framework, is a complement to the other studies in the literature. By its aggregated nature, for example, it cannot do justice to forensic studies of particular innovations in particular industries and is therefore only part of the answer to the questions around R&D. Nonetheless, we think it of some interest since it is capable of answering a number of interesting questions for economists and policy-makers that other datasets might be less suited to: for example, counter-factual questions on the effects of industrial structure.

The canonical description of the sources-of-growth approach to understanding how R&D affects economic growth is set out in, for example, Griliches (1973).¹ Using industry data we may write total (market sector) value added growth as growth in inputs, weighted by their competitive factor shares in market sector value added, plus growth in industry TFP, weighted by their Domar-Hulten weights (Domar (1961), Hulten (1978)). Thus R&D-induced productivity growth is due to (a) changes in the market-sector R&D knowledge stock times its competitive factor rental share of market sector output and (b) spillovers working through TFP growth. Spillovers consist of (i) any spillovers from industry 1's private R&D within industry 1 (ii) any spillovers from industry 1's private R&D to any *other* industry and (iii) any spillovers from public R&D to all industries. The direct effect (a) we recover simply from measurement of private sector R&D and its rental cost. The spillover effects we obtain from estimating three coefficients capturing spillovers of R&D (i) within and (ii) between industries and (iii) spillovers from the public sector. Estimation of these effects, and Domar-Hulten weighting, allows us to answer some questions such as (a) what are the effects of raising public R&D support on growth (b) how do they compare with other policies, such as tax credits that might raise private R&D and (c) how do these effects interact with the structure of the economy (of interest in the UK since the manufacturing base is relatively small)?

Existing datasets cannot, to the best of our knowledge, answer these questions. Incorporating private R&D into industry data requires changing both inputs but also outputs (since both gross output and value added have to be recalculated if R&D is counted as an investment not an intermediate: Griliches (1973); Schankerman (1981) set out some of the biases involved if one does not do this). Current UK National Accounts data is not available at an industry level with R&D so capitalised. The leading industry productivity database, www.euklems.net, O'Mahony and Timmer (2009), does not incorporate R&D either. We therefore construct industry data, based on EU-KLEMS (O'Mahony and Timmer (2009)), but that capitalises private R&D and maintains consistent bottom-up Domar-Hulten aggregation. Thus we believe that one contribution

¹ In this work, the R&D growth impact is ratio of R&D spend to GDP times the rate of return to R&D, with the spend public and private and the rate of return reflecting private and social returns. To get some idea of the UK numbers, in the UK, the R&D/GDP ratio is about 2%. If the rate of return is, say, 30% (Griliches (1992)), then the contribution is 0.6%pa (set against typical growth rates of, say 3%pa). Note that the private rate of return to R&D is typically suggested to be about 20%, so the figure of 30% reflects (a) spillovers from private R&D and (b) an assumed rate of return of 30% to public R&D.

of this paper is bring new data to bear on these questions.

We estimate spillovers from *private* R&D in other industries using the industry-level method of for example, Griliches (1973); Griliches and Lichtenberg (1984). This weights the private knowledge stock in outside industries by weights based on flows of intermediate consumption or labour between industries. We estimate spillovers from *public* R&D by looking for effects on private industry TFP growth, and also experimenting with weights (based on industry private sector R&D and industry private sector co-operation with the public sector).

Our method depends upon the data and assumptions in constructing TFP and our other measures. We therefore check to see if our results are robust. We argue they are robust to, for example, different measures of industry R&D, depreciation, asset capitalisation and spillover mechanism, different lag structures and allowing for imperfect competition and non-constant returns to scale.

How does our study relate to others for the UK? Regarding time series, Guellec and de la Potterie (2004) use cross-country (including the UK) and Haskel and Wallis (2013) market sector UK data on total factor productivity and publicly and privately funded R&D. At the industry level, Añón Higón (2007) uses a panel of eight UK manufacturing industries, but does not study public R&D.² She surveys three UK industry panel surveys that use TFP, all of which use data for the 1970s and 1980s and do not capitalise TFP. Bonte (2004) studies TFP and public and private R&D for using German manufacturing industries.

Our findings are as follows. First, we find evidence of spillovers of private R&D and public R&D, with an estimated rate of return to public R&D of 20%. Second, our data are consistent with the idea that the public R&D spillover to an industry depends, however, on the absorptive capacity of the industry (its R&D spend or involvement with the public sector). Third, our counter-factual policy experiments suggest a 10% rise in public R&D would raise private TFP growth by 0.03pppa (relative to a baseline of TFP growth at 1.46%pa). This would be 0.04pppa if the UK had Germany’s industrial structure.

The rest of the paper is as follows. The next section sets out the conceptual framework and measurement, section 3 the data, section 4 the results, section 5 some policy implications, and robustness checks and section 5 concludes.

2 Framework and existing literature

We set out our framework and then discuss how we think we add to the existing literature.

2.1 Model

Suppose an industry i has a gross output production function, which might be translog for example, of the form

$$G_{it} = A_{it}F(L_{it}, K_{it}, M_{it}, R_{it}, R_{-it}) \quad (1)$$

where G , L , M , K are gross output, and, respectively, labour, materials and tangible capital services. R are the intangible capital services in industry and R_{-i} is flow of intangible services from *outside* the industry, some of which might yield a flow of productive services to the industry via spillovers. It might include

² Regarding the effects of public sector R&D, Salter and Martin (2001) in their survey quote nine studies, all for the US, all of which are on agriculture (including Griliches, 1958 on hybrid corn). They also survey non-econometric studies, notably Mansfield (1991). More recent UK analyses for the health sector have estimated rates of return to public sector R&D of over 30% of which however around 20% is assumed on the basis of the earlier US studies. For this and a review of public sector R&D impacts more generally see Hughes and Martin (2012).

publicly financed R&D; knowledge produced elsewhere in the world etc. A_{it} is any increase in output not accounted for by the increase in the other inputs. Stocks of capital are assumed generated by a perpetual inventory model so that for R we have

$$R_t = N - \delta^R R_{t-1} \quad (2)$$

where N_t is spending on new ideas, and δ is their depreciation/obsolescence.

Define industry-level gross output TFP growth as:

$$\Delta \ln TFP_{it}^G \equiv \Delta \ln G_{it} - \sum_{X=L_{it}, M_{it}, K_{it}, R_{it}} \bar{s}_{X,it} \Delta \ln X_{it} \quad (3)$$

where the Tornquist share of each factor X is

$$\bar{s}_{X,it} \equiv \frac{1}{2} \left(\frac{p_{X_{it}} X_{it}}{p_{G_{it}} G_{it}} + \frac{p_{X_{it-1}} X_{it-1}}{p_{G_{it-1}} G_{it-1}} \right), \quad X = L_{it}, M_{it}, K_{it}, R_{it} \quad (4)$$

i.e. the bar above $s_{X,it}$ denotes a time average so that this expression holds if, for example, the underlying production function is translog (Caves et al. (1982)). Using a flexible functional form such as this is important since we shall use a panel of industries and it can accommodate different output elasticities in e.g. utilities compared with business services. If equation 1 is separable in all elements beside M then we can write the relation between industry gross output and aggregate value added growth as follows ((Jorgenson et al. (2007))). Define aggregate value added Q as

$$Q_t = A_t F(L_t, K_t, R_t) \quad (5)$$

Then we can write

$$\Delta \ln (Q/H)_t \equiv s_t^{Q,L} \Delta \ln (L/H)_t + s_t^{Q,K} \Delta \ln (K/H)_t + s_t^{Q,R} \Delta \ln (R^{PRIV}/H)_t + \sum DH_{it} (\Delta \ln TFP_{it}^G) \quad (6)$$

where the final term is a Domar-Hulten weighted average of industry gross output $\Delta \ln TFP_{it}^G$ (DH weights captures the effect that a TFP improvement in one sector can boost growth in other sectors depending on the extent to which that output is, in turn, an input into other sectors, see Domar (1961) and Hulten (1978)). Expression 6 holds as an accounting identity in our data³.

We now set out a behavioural assumption for $\Delta \ln TFP_{it}^G$ which is

$$\Delta \ln TFP_{it}^G = \Delta \ln A_{it} + \gamma_1 \Delta \ln R_{it}^{PRIV} + \gamma_{i,-i} \Delta \ln R_{-it}^{PRIV} + \gamma_{i,PUB} \Delta \ln R^{PUB} \quad (7)$$

which says that $\Delta \ln TFP_{it}^G$ depends on own R , outside R that is private, $\ln R_{-it}^{PRIV}$ and outside R that is public, $\ln R^{PUB}$ (since we use market sector industry data, we assume that R&D in industries is private and so denote is R^{PRIV}).

Measuring $\Delta \ln R_{-it}$ is typically done by assuming a matrix that weights the various $\Delta \ln R_{-it}$ in some way e.g. by technological distance, input/output relations etc. If we assume this amounts to a weighted sum over industries with weight $\omega_{i,-i}$,⁴ so that $\gamma_{i,-i} \Delta \ln R_{-it}^{PRIV} = \gamma_2 (\sum \omega_{i,-it} \Delta \ln R_{-it}^{PRIV})$ we are now in a

³ By which we mean, that $\Delta \ln TFP^Y$ is constructed so that 6 holds, which in turn is done such that real industry gross output growth is a superlative index number weighted average of value added and intermediate growth: this is a standard procedure in, for example, EUKLEMS, to ensure adding up between industries and overall value added.

⁴ That is, industry i has a vector of weights on other industries $-i$.

position to see how much R&D impacts on overall growth

$$\begin{aligned} \Delta \ln(Q/H)_t &= s_t^{Q,L} \Delta \ln(L/H)_t + s_t^{Q,K} \Delta \ln(K/H)_t + s_t^{Q,R} \Delta \ln(R^{PRIV}/H)_t \\ &+ \sum DH_{it} \left(\Delta \ln A_{it} + \gamma_1 \Delta \ln R_{it}^{PRIV} + \gamma_2 (\sum \omega_{i,-it} \Delta \ln R_{-it}^{PRIV}) + \gamma_{i,PUB} \Delta \ln R^{PUB} \right) \end{aligned} \quad (8)$$

This is the expression that we shall calculate and hence it is worth explaining. The effect of R&D on overall growth arises from four channels. First, $s_t^{Q,R} \Delta \ln(R^{PRIV}/H)$ is the effect of R&D capital (per hour) multiplied by the rental cost share of R&D. This is the contribution of private R&D evaluated at the private sector's private rate of return i.e. the output elasticity consistent with a private rate of return under competition and constant returns. Note that we shall relax these assumptions in our robustness checks and find our results robust. Second, we have three spillover effects in the second line of (8). The $\gamma_{i,i} \Delta \ln R_{it}^{PRIV}$ term reflects spillovers within the industry; the $\gamma_{i,-i} (\sum \omega_{-it} \Delta \ln R_{-it}^{PRIV})$ term is spillovers from outside the industry and finally the $\gamma_{i,PUB} \Delta \ln R^{PUB}$ are spillovers from public R&D, which might be public sector or another source of ideas e.g. the internet, foreign R&D etc. Note that all the spillover terms, which affect (gross output based) $\Delta \ln TFP^Y$, are weighted by the Domar-Hulten weight. To obtain the γ s we shall estimate 7 econometrically. For the avoidance of doubt, when it comes to measurement we will not be able to distinguish between pecuniary and non-pecuniary spillovers (Griliches (1992)) but use the term "spillovers" for convenience.

2.2 Existing literature

To work out the effect of R&D on $\Delta \ln Q/H$ we shall calculate the terms in (8) which will need us to estimate the γ s in (7) econometrically. How does this relate to the existing literature? As mentioned above the spillovers from private R&D to other industries is estimated using the industry-level method of for example, Griliches and Lichtenberg (1984) where ω is based on flows of intermediate consumption or labour between industries. Spillovers from public R&D also use weights based on industry private R&D and co-operation with the public sector. Based on the survey by Añón Higón (2007)⁵ we note that (a) to the best of our knowledge, no UK studies have looked at the effect of public R&D, (b) very few studies capitalise R&D into TFP (c) none include spending on non-R&D intangibles (such as software, training etc.) to knowledge investment (our results are robust to dropping this). Note finally we base our work on industry gross output, which is less restrictive than other studies and use DH weights to obtain aggregated effects. Thus this approach contrasts with that taken in some papers which is to ignore the industry dimension, use an aggregate value added term, V , without R&D capitalised and so write down

$$\Delta \ln(V/H)_t = s_t^{V,L} \Delta \ln L/H_t + s_t^{V,K} \Delta \ln K/H_t + \varepsilon_t^R \Delta \ln R + a \quad (9)$$

If R does not depreciate this may be simplified to

$$\Delta \ln(V/H)_t = s_t^{V,L} \Delta \ln L/H_t + s_t^{V,K} \Delta \ln K/H_t + \rho_t^R \left(\frac{N}{V} \right) + a \quad (10)$$

⁵ See her Table 1. She surveys six UK studies based on TFP, one cross-sectional, two time series and three panel. Of these studies, one uses the input/output tables to generate outside R&D knowledge flows, Sterlacchini (1989) who uses a cross-section of 15 industries, 1945-83 (and finds spillovers). Higon studies eight manufacturing industries, 1970-97 and also finds spillovers, using the I/O tables to generate outside knowledge flows.

Table 1: R&D performed in the UK in each sector according to source of funding, 2011

	<i>Sector performing the work</i>					Total
	Government	Research Councils	Higher Education	Business Enterprise	Private Non-Profit	
<i>Sector providing the funds</i>						
Government	977	86	406	1,601	68	3,138
Research Councils	47	819	1,979	11	86	2,942
Higher Education Funding Council	-	-	2,257	-	-	2,257
Higher Education	2	11	290	-	14	317
Business Enterprise	203	26	284	11,957	85	12,556
Private Non-Profit	3	47	987	104	165	1,306
Abroad	77	51	923	3,734	79	4,864
TOTAL	1,308	1,040	7,127	17,408	496	27,380

Source: ONS, GERD release, Table 1.

Notes to table: Columns 1+2= GovERD, column 3=HERD, column 4=BERD, column 5=PNP, sum of columns is GERD. - denotes not available

where ρ^R is a social rate of return on R&D spend since R&D is not capitalised. An aggregate approach is adopted in, for example, Guellec and de la Potterie (2004) (cross-countries) and Haskel and Wallis (2013) for the UK⁶. Our use of (8) brings in cross-industry variation and enables us to examine the effect of industry structure on growth by looking at DH weights. Bonte (2004) uses gross output German industry data with R&D capitalised, just as we do, and input/output and technology measures for ω .

3 Data

3.1 Public R&D

If we are to measure $\Delta \ln R^{PUB}$ we need to be clear what we mean by "public" R&D. There are a number of issues here, most of which are anticipated in Griliches (1979) prescient discussion. The bulk of the questions arise around the possible public goods aspect of knowledge. To see this, table 1 sets out 2011 UK R&D data taken from the official national accounts data (GERD) on R&D by the sector *providing* the funds, in the rows and *performing* the work, in the columns.⁷ On the far right bottom corner shows the total spend, £27.380bn in 2011 current prices. The column headed "business enterprise" shows that in total £17.408bn of that spending/performing was performed by business. The other columns show £1.3bn, £1.04bn, £7.127bn and £0.496bn was performed by government departments, research councils, higher education and charities. Turning to the rows, the business enterprise row and column cell show that £11.957bn was both funded and performed in the business sector.

What then is *public* R&D: funded or performed? First, the most self-contained is the Higher Education Funding Council which provides £2.257bn of funding of R&D which is wholly performed and funded in one locus, higher education. Second, research councils fund £2.942bn of which a very small fraction, £11m, is performed in the business sector. The majority is performed in Higher Education, £1.979bn, or in public

⁶ Using cross-country data, Guellec and de la Potterie (2004) find elasticities of total factor productivity to publicly (privately) funded research of 0.17 (0.13): Haskel and Wallis (2013) find a similar public elasticity, but smaller private elasticity using UK time series data.

⁷ The Appendix provides further information on some of the items in this table.

research institutes, (£47m+£819m=)£866m.⁸ Third, "government departments" (so not including research councils) spent £3.138bn of which just over 50%, £1.601bn, is performed in the business sector⁹, and just over 33%, (£977m+£86m=)£1.063bn, is performed by government departments, that is by public research institutes and government owned laboratories.¹⁰

All this shows that government *funding* of R&D is not the same as government *performance* of R&D. What is the most appropriate to use? From a productivity point of view, we wish to relate input to output, so we are interested in the knowledge investment that builds knowledge capital in the industry for which we have corresponding output data. If we use R&D *performed* in industry J, we assume that such R&D builds knowledge capital in industry J. This would be appropriate if the industry builds its knowledge capital stock by performing R&D. One might however argue that if *performed* R&D in industry J is *funded* by industry K, we should allocate investment not to J, but to the funding industry K. Note for example, in the "government" spending line, £1.6bn of government spending is performed in the business sector. This would assume that knowledge capital resides in the funding industry, if for example, funding confers ownership, and no knowledge resides in the industry where it is performed.

One might assume that funding conferred ownership. To shed light on this assumption, ONS has recently extended its R&D questionnaire to ask firms about both the funding and also the ownership of R&D, see Steer and for na Ker (2013). They find for example, that even though 64% of the R&D conducted by the UK Business sector is funded by the business sector, 72% of it is owned by the business sector. As for government, it funds 8.3% of business sector R&D but owns 6.3% of it. This suggests that using funding as a rule for allocating ownership will understate business investment and overstate government ownership.

In our econometric work we shall test robustness to a number of different allocations, but to construct a baseline case we stick essentially to allocation by performer. First, we use the data from GERD since we wish to relate our work as closely as possible to national accounts (where, at time of writing, R&D is not yet available capitalised by industry into national accounts and no UK satellite accounts are published). Second, to construct private R&D, we use £17.406bn, that is, according to the sector that performs the R&D. As the table shows, this implicitly includes some Government funded R&D that is performed by business (£1.601bn=6%), but a large fraction of that will actually be owned by business. For government R&D, we started with performance by government, research councils and higher education (that is, the sums of columns 1, 2 and 3). From that, we subtracted off that funded by business (i.e. row 5) (our results turn out to be robust to this).

In summary, private R&D is that performed in the business sector. Government R&D is that performed by government, research councils and higher education, less that amount performed in these sectors but funded by business.¹¹ We describe how we allocate private R&D to industry below.

We can get some sense of the time series behaviour of these data in Figure 1 below. $\Delta \ln TFP$ was low in the 1990s, but accelerated in the early 2000s, before slowing again. $\Delta \ln K^{R\&D}$ was high in the early 1990s (in

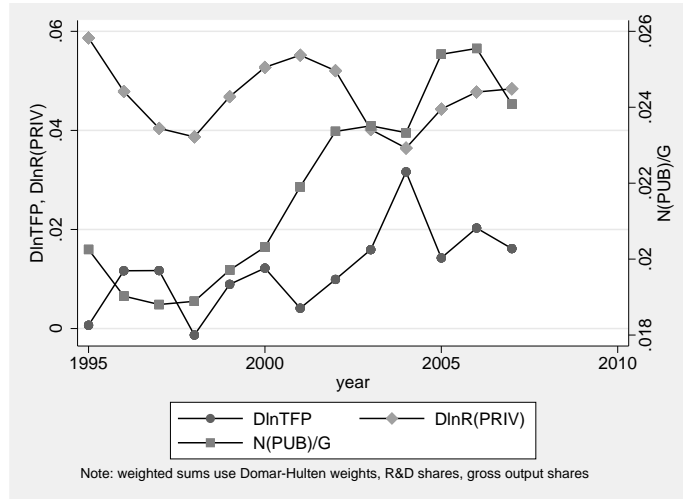
⁸ Here £47m is allocated to performance by government departments and £819m to performance by research councils. Figure 7 in the GERD release (flow of funds) shows that this £866m is performed by public research institutes.

⁹ Of the £1.601bn funded by government but performed by business, the GERD (2013) release states that such government awarded contracts include those to UK business to develop aircraft, naval ships, submarines and their systems and equipment. Similarly, for the US, Hall (1996) notes, table 6-2, that of the \$33bn spent by government in 1991 performed in industry, \$26bn was defence, \$4.2bn NASA and \$2.6bn Energy.

¹⁰ The largest ministries spending this £977m are Ministry of Defence, BIS (spending on space and agricultural safety at the Purbright Institute), the National Health Service (NIHR) and DEFRA (various agricultural and animal health research).

¹¹ Strictly, we should then allocate the R&D performed by the public, but funded by business back to the business sector funding it, but we do not have these data. We omit private non-profit from this current study since we have no consistent back data.

Figure 1: Time series of UK market sector $\Delta \ln TFP$, $\Delta \ln R^{PRIV}$ and N^{PUB}/G



fact it was higher in the 1980s), dipped and then speeded up and then slowed again in the early 2000s. Public R&D spend, as a proportion of gross output fell in the mid 1990s, but was then expanded very substantially over most of the period with the exception of 2002-4.

3.2 Public R&D

Before proceeding to other measurement issues, we are now in a position to review the different concepts of public and private used in the extant literature. Hall (1996) is particularly clear on this point, stressing that of total US Federal government spending on R&D in 1991, around 50% is performed in private industries (of which 3/4 is in defence), 25% in universities and 25% within government facilities (mostly defence and space). As she points out, there are (at least) two research questions: what is the rate of return to (a) publicly financed R&D performed in industries and (b) publicly financed R&D performed in universities and government facilities? On question (a) she reports the industry studies of Griliches and Lichtenberg (1984) and Bartelsman (1990) who find little impact on TFP growth of R&D performed in an industry that is federally funded (for a similar discussion and more studies, see Hall et al. (2009), section 3.3.2: Levy and Terleckyj (1983) find more positive results for government-funded R&D). This could be due to a range of factors such as benefits being too diffuse to capture in one industry, to measurement problems (especially acute in an industry like defence where government is a purchaser). These issues are discussed below. On question (b), Hall reports few studies and that such spending is likely much too diffuse to measure.

3.3 Other data

3.3.1 Industries

As in (7), we also estimate spillovers from the conduct of private R&D inside and outside the industry. Estimates for growth in the stock of private industry R&D and TFP come from our industry-level dataset in which estimates of intangible investment are capitalised in a way fully consistent with the national accounting framework; for a full discussion of data derivation and detailed sources see Borgo et al. (2013). This work

Table 2: Industries used in our market sector definition

SIC(2003)	Number	Industry Description
ABC	1	Agriculture, Forestry, Fishing and Mining
D	2	Manufacturing
E	3	Electricity, Gas & Water Supply
F	4	Construction
GHI	5	Distribution; Hotels & Restaurants; Transport, Storage & Communications
J	6	Financial Services
K	7	Business Activities (excluding real estate)

Note: Regressions and figures omit industry ABC due to land being unmeasured.

uses the seven broad industries as set out in Table 2. We use the seven broad industries due to limited industry detail in the intangible data. We have data from 1992 to 2007.

We start in 1992 due to the IO tables not being available earlier. We end in 2007 since we rely on EUKLEMS data, and more up to date real industry intermediates and gross output are not available from the ONS. The quality of most of our industry-level intangible investment data improves greatly from 1992, the first year of published IO analysis. Data are extended further back but there is inevitably some imputation for earlier years. We estimate initial capital stock in 1990 using the standard method (e.g as in Oulton and Srinivasan (2003)). So that estimates are not too affected by initial values problems, we conduct our analysis over the period 1995 to 2007. We exclude real estate from SIC K which therefore excludes imputed rents due to owner-occupied housing which is not counted as capital in our data. In our analysis we also exclude Agriculture. In Agriculture land is a major factor of production, but is not treated as a capital asset in the National Accounts framework by (European) national accounting convention. This makes TFP difficult to interpret and in fact we find it to be measured as negative for agriculture over much of our data period.

3.3.2 Data on output and tangible investment

Our output and tangible data come from EUKLEMS (O'Mahony and Timmer (2009)) which is based on UK National Accounts and uses a consistent set of real and nominal output variables which sum to the aggregate. In computing TFP we adjust both the input and also the output data. All the input shares sum to one and the rental prices are calculated consistently using the ex post method so that the sum of capital rental payments, including intangibles, equals total capital payments. Because we are working at the industry level, TFP is calculated on a gross output basis, which does not impose restrictions on the form of the production function that value added would. We make sure that the bottom-up data aggregates to the market-sector.

3.3.3 Data on intangible investment including private R&D

In estimating TFP we also account for the contributions of the full range of intangible assets set out in Corrado, Hulten and Sichel (2005). Since our focus here is on spillovers from R&D, we just focus on that asset below. For a full discussion of all of our other data on intangibles, see Goodridge et al. (2012).

Industry-level business R&D data are derived from the Business Enterprise R&D survey (BERD). The largest 400 R&D performers are sent a "long" form, where they set out their spend on R&D in the form of wages, materials and investment and are asked to allocate such spend to "product groups" e.g. pharmaceuticals, chemicals etc. Other performers are sent a "short form" and are asked for spend on all their R&D

activities regardless of product group.

To allocate such spending to industries we take a number of steps. First, one component reported BERD expenditure data is investment in tangible assets used in R&D production. We convert this into a rental cost of tangible capital. Second, we then assign detailed product groups to industries, assuming, for example, that R&D performed on pharmaceutical products is performed in the pharmaceuticals industry. Third, to avoid double counting of R&D and software investment, R&D spending in "computer and related activities" (SIC 72) is subtracted from R&D spending, since this is already included in the software investment data (around £1.7bn 2011). Fourth, all firms who get a short form, and firms who get a long form, but where the product groups are either missing or they are unable to assign their spending to them, have their spending allocated by ONS to the product group "Research & Development Services", which includes the R&D conducted by the R&D services industry (SIC 72) that is sold to outside industries. In the raw data this is around £600m, but is likely a mismeasure since it is a residual allocation. Thus we allocate this spending to the industries that purchase R&D services from SIC73, using shares constructed from the IO tables. So this re-allocation is done on a funder basis which would seem to be inconsistent with the performer principle used above. However, we would argue that the initial allocation to that industry does not truly reflect the industry of the performer, but rather statistical uncertainty. Thus, by performing this re-allocation we shall not find apparent spillovers due solely to the classification of this section of R&D into R&D services. Both these last two steps increase the skewness of the R&D cross-industry distribution since they allocate R&D towards manufacturing. We test to see if our results are robust to these assumption and find they are (see below).¹²

3.3.4 "Outside" R&D

The above gives us data on growth in R&D capital internal to the industry. For our measures of growth in R&D capital external to the industry, we weight the industry measures using (a) labour transitions between industries and (b) intermediate consumption flows between industries: this follows for example Griliches and Lichtenberg (1984). Labour transitions come from panel labour force survey data indicating the fraction of workers employed in industry K who were previously in industry J. Intermediate inputs use data from the Input-Output tables for 1992-2007. We then apply these weights to our industry estimates of knowledge stocks. For each industry we construct a term for growth in available outside knowledge as the industry weight multiplied by growth in the relevant capital stock from the other six industries. Therefore, say for example, 50% of IC in industry X comes from within the industry, the weights for other industries will sum to 0.5. For more details, see Haskel et al. (2012)

¹² An alternative allocation system is to allocate spending into the "industry" that the enterprise returning the form is recorded in. This raises a number of issues. First, ONS follows the rule in the IO tables and in the R&D by industry tables they publish that any R&D performed in a physically distinct addresses i.e. a separate reporting unit is allocated to the SIC "Scientific R&D" industry (so e.g. here R&D done by a pharmaceutical company in a distinct address that reports a pharmaceutical product code is allocated to pharmaceutical industry, whereas on the IO tables to Scientific R&D). Note too that in the official BERD data spending by product group "R&D services" is much smaller than spending by SIC Scientific R&D, because ONS allocate as much spend as they can to the relevant product group (compare for example Table 2 and Table 27 in the 2012 BERD release, (<http://www.ons.gov.uk/ons/rel/rdit1/bus-ent-res-and-dev/2012/stb-berd-2012.html>)). A second conceptual point, discussed in, for example, Griliches and Lichtenberg (1984) is whether it is more appropriate to allocate by product group or industry. As they point out, some large firms might undertake R&D across a number of different industries e.g. an automotive firm working on bulldozers and headlamps is by "origin" in the auto industry, but the "use" of the R&D is in construction equipment and electrical machinery industries. They prefer the "use" concept, and so use, as we do, the product class to allocate R&D spending across industries.

3.3.5 Co-operation

As we set out below, we try to measure the absorptive capacity of industries. One indicator will be R&D spend. Another is the extent of co-operation between industries and the public sector. We obtain this from four waves of the UK Community Innovation Survey (UKIS) (UKIS3 covering 1998-2000, UKIS4, covering 2002-2004, UKIS 5 covering 2005-2007 and UKIS6, covering 2006-2008). We aggregate company responses to form an industry fraction of the firms reporting they have formal co-operation agreements with universities or government research centres; henceforth termed *COOP*. Firms are also asked separately if they find these institutions useful sources of information, but there is in fact very high correlation across these two measures, so we just use co-operation. For more details, see Haskel et al. (2014).

4 Econometric method and results

4.1 The transition to econometric work

We aim to estimate (7) which with the outside term substituted in is

$$\Delta \ln TFP_{it}^G = \Delta \ln A_{it} + \gamma_1 \Delta \ln R_{it}^{PRIV} + \gamma_2 (\sum \omega_{i,-it} \Delta \ln R_{-it}^{PRIV}) + \gamma_{i,PUB} \Delta \ln R^{PUB} \quad (11)$$

To estimate it we take the following steps. First, to construct $\Delta \ln TFP_{it}^G$ we capitalise all intangible investments and construct using all inputs. This ensures that the coefficients on the right-hand side are excess returns. Second, turning to the right hand side, we enter industry and time effects to control for $\Delta \ln A_{it}$.¹³ Third, to measure $\Delta \ln R_{it}^{PRIV}$ we enter the own-industry R&D capital stock used in measuring $\Delta \ln TFP_{it}$: this is private R&D since the industries are all in the market sector which is overwhelmingly private. Fourth, as above to measure $(\sum \omega_{i,-it} \Delta \ln R_{-it})$ we weight outside industry $\Delta \ln R_{it}^{PRIV}$ with labour transition or intermediate input weights.

Fifth, regarding $\Delta \ln R_t^{PUB}$ we proceed as follows. As is conventional, we assume that public R&D does not depreciate: to the extent it is “basic” then is likely to at least become less obsolete than R^{PRIV} : the ONS report using a depreciation rate of 5% for government R&D (Whittard et al. (2008)). Using the standard transformation, since from the PIM, $\Delta \ln R_t^{PUB} = N^{PUB}/R_{t-1}^{PUB}$ when $\delta^{PUB} = 0$, the final term in (11) can be written $(\partial G/\partial R^{PUB})(R^{PUB}/G)_{it} = (\rho_{it})(R^{PUB}/G)_{it}$ where $\rho_{it} = (\partial G/\partial R^{PUB})_{it}$ which is the rate of return of public R&D. Thus we can write (11) as

$$\Delta \ln TFP_{it}^G = a_i + a_t + \gamma_1 \Delta \ln R_{it}^{PRIV} + \gamma_2 (\sum \omega_{i,-it} \Delta \ln R_{-it}^{PRIV}) + \rho_{it} \left(\frac{N_t^{PUB}}{G_{it}} \right) \quad (12)$$

A number of factors militate against estimating a precise effect of N^{PUB}/G_{it} (see for example the discussion of measuring the impact of NASA on productivity in Griliches (1979) and the papers referenced therein such as Terleckyj (1975). First, as discussed above, since we are using a performer concept, publicly financed R&D that is performed in business is subsumed in $\Delta \ln R^{PRIV}$. Thus the coefficient on that variable

¹³ Fixed and time effects control for industry and common shocks. However, one might argue there are time-varying shocks to individual industries that we cannot pick up with these dummies. Given the internationalisation of R&D, one such shock might be e.g. knowledge flows from R&D in Chinese manufacturing and so our results are biased if $\Delta \ln R$ in industry *i* is correlated with a knowledge flow in that industry from elsewhere in the world. If the endogenous choice of $\Delta \ln R$ is positively correlated with such shocks then our spillover results are upward-biased, but if such shocks mean firms allocate R&D abroad then the results are downward biased.

strictly is an elasticity encompassing some public R&D. At time of writing we do not have the data to extract such R&D from the industry data.¹⁴

Second, consider questions around timing and possible heterogeneity of ρ_{it} , that is, the marginal impact of N^{PUB}/G_{it} across industries. Recall that N^{PUB} is public R&D performed in public labs and research institutes, by research councils and by universities. This creates a number of issues, essentially because any returns are likely to be diffuse and might take time as follows.

First, by its very nature, public knowledge might have an industry-specific marginal impact. For example, most research council sector spend is primarily technical and scientific, some is agricultural and little is directed at the arts (hence ρ might vary across i ; Griliches (1979) section 2.6 discusses this, although agriculture might be an exception where public spending might be readily identifiable with a particular industry). Absorptive capacity might also be another source of heterogeneity, see Cohen and Levinthal (1989) who suggest this propensity might vary by firm R&D but set out a careful description of other factors (such as technology etc.). At the industry level, distinguishing between absorptive capacity and the industry appropriate knowledge is impossible, but all this suggests we should model the heterogeneity ρ_{it} . Thus as a summary measure we write

$$\rho_{i,t} = \rho_0 + \rho_1 \frac{X_{it}}{\sum X_{it}} \quad (13)$$

where X_{it} is entered as a fraction of its sum so that we can read off the rate of return directly. To see this, note that for a particular industry, k , in year t the rate of return is $\rho_K = \rho_0 + \rho_1 X_K / \sum X$: thus the average rate of return over all industries is $\Sigma \rho_K = \Sigma(\rho_0 + \rho_1 X_K / \sum X) = \Sigma \rho_0 + \rho_1$. The $\Sigma \rho_0$ term appears because with the form of (13) a constant rate of return per industry will add up over all industries to an economy-wide return. As it turned out, ρ_0 was never statistically significant in our models and so drop it here. That said, (13) is presentationally convenient, but imposes a particular functional form for ρ_i .

We experiment with two measures of absorptive capacity, X_i , private R&D and second COOP. The co-operation variable has the benefit of being less skewed than R&D spend, which is mostly in manufacturing.

Second, the effects of N_t might take time and so we would want to experiment with lags. Some might be very long: the diffusion of laser technology into retailing for example took 30 years which we would be unable to identify on our data. That said, Adams et al. (2006) find citations of university scientific papers by papers from industrial R&D concerns to have a mean lag of three years, and scientific advance in universities can be implemented into incremental innovation quite quickly. As documented in Hughes and Kitson (2012, 2013), university-industry interactions proceed along multiple pathways of which people-based recruitment, consultancy and collaborative relationships may enter in business practice effects relatively quickly and which may span multiple business functions beyond technological innovation per se. In practice we experiment with lags of up to six years: if they are truly longer, than our estimates are a lower bound on the true effect (Bonte (2004) also uses three year lags).

Third, as Griliches (1979) points out, the extent to which public knowledge gives measured returns depends upon the extent to which it produces quality or quantity improvements, and to which these are measured. So, for example, a publicly-funded quality improvement made freely available to all would cause

¹⁴Such spending is mostly in defence and health where outputs (security, longevity etc. are poorly measured) and purchasers of such services likely do not pay a market price for them. We also note that the defence and health public industries are excluded from our data (although pharmaceuticals and aerospace are of course in manufacturing). In our data, the proportion of business performed R&D that is funded by the government has remained remarkably constant over the data period, 8.9% (1995-2005), varying from 10.4% to 8.0%. As Griliches (1991) notes, industry level returns to state-funded R&D might be different than private returns if such funding is exactly in areas where private returns are low due e.g. to appropriability problems or if the public spending is crowding out or in private spend.

risers in nominal sales by all firms. But if the statistical agency does not quality-adjust prices, then the real sales rise is understated. If the firm concerned is a monopolist over the technology and can change its prices, then even a non-quality adjusting price index will change. So the extent to which a quality increase raises measured productivity depends on an interaction of market structure and statistics agency convention.

Finally, there are some econometric issues. First, variation in N^{PUB} is by time. If we include time dummies in the regression, we can still estimate ρ_{it} since (N_t^{PUB}/G_{it}) varies by industry and time (this raises identification issues which we discuss below in robustness). Second, $\Delta \ln TFP$ is noisy, and so here we use (three-year) differences to reduce noise (we experimented with a number of different difference lengths; one year differences were very noisy, two/three and four year differences produced similar results to those reported here).¹⁵ Third, to the extent that $\Delta \ln TFP$ is pro-cyclical, (N_t^{PUB}/G_{it}) will induce a negative coefficient due to the dividing by G_{it} , another reason to lag this term. Fourth, theory suggests the appropriate regressor is real public R&D spend over real gross output. The latter is constructed from the data, but the former begs the question of what R&D deflator to use; for the moment, we just use the market-sector value-added deflator.

With all this in mind, our estimating equation can be written, where Δ_3 refers to a three-year difference

$$\Delta_3 \ln TFP_{it}^G = \gamma_1 (\Delta_3 \ln R_{it}^{PRIV}) + \gamma_2 \left(\sum \omega_{i,t} \Delta_3 \ln R_{-i,t}^{PRIV} \right) + \left[\rho_1 \frac{X_{it}}{\sum X_{it}} \right]_{t-3} \left(\frac{N_t^{PUB}}{G_{it}} \right)_{t-3} + a_i + a_t + \varepsilon_{it} \quad (14)$$

5 Correlations, estimates and robustness checks

5.1 Averages

Table 3 sets out some averages. Gross output $\Delta_3 \ln TFP$ varies across industries, being particularly fast in business services. $\Delta_3 \ln R^{PRIV}$ is high in services, reflecting growth from a low base, but falls in utilities, reflecting falls in R&D post-privatisation. Column 3 shows “outside” R&D is high in services. Columns 4 and 5 show public and private R&D intensity. Variation across industries in public intensity is driven by industry gross output (the implications of this for identification are set out below); note that private R&D intensity is very high in manufacturing. Finally, column 6 shows COOP. Notice that it is less skewed than private R&D intensity; COOP is for example very high in utilities and quite high in business services.

5.2 Correlations

Figure 2 shows correlations between the variables in (14) (all in deviations from time and industry mean terms). All correlations are positive, but industry 3 (utilities) seems somewhat of an outlier, so we checked the data: the fall in R&D in general utilities has been documented see e.g. Oxera (2005) who argue it is related to RPI-X regulation: Jamasb and Pollitt (2011) and Cave (2011) document the falls in R&D in electricity and water and their effects on innovation. We check our estimates for these and other potential outliers arising from sector specific effects (e.g the privatisation of Qinetiq in 2001) using robust regression estimates, see below.

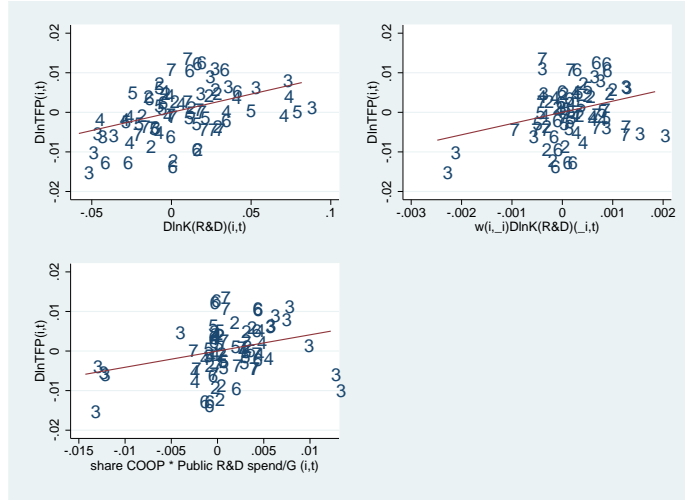
¹⁵ Our main specifications use the three-year lagged effect $(N^{Pub}/G)_{t-3}$ as an explanatory variable for $\ln TFP_t - \ln TFP_{t-3}$. If we sum $(N^{Pub}/G)_{t-3}$ over the three periods (t-3, t-4, t-5) we get very similar results ($(N^{Pub}/G)_{t-3}$ is highly serially correlated). Thus sum however loses us significant degrees of freedom (our data spans 1992-2007, we rely on the input-output tables and therefore 1992 is the furthest we can go back without interpolating across long intervals between pre-1992 IO table releases. We start in 1995 to avoid initial year problems with capital stocks and so if we use a three year sum for a lagged

Table 3: Averages of data (% per annum, 1995-07, all industries except agriculture)

	$\Delta_3 \ln TFP^G$	$\Delta_3 \ln R_{i,t}^{PRIV}$	$\omega_{i,t} \Delta_3 \ln R_{i,t}^{PRIV}$	$N_t^{PUB}/G_{i,t}$	$N_{i,t}^{PRIV}/G_{i,t}$	$Coop_{i,t}$
Manufacturing	0.53%	4.80%	0.31%	1.30%	2.30%	22%
Utilities	0.58%	-1.80%	1.40%	11.00%	0.22%	35%
Construct	0.04%	0.60%	0.65%	4.80%	0.03%	9%
Retail, Hotel	0.77%	6.40%	0.24%	1.40%	0.20%	8%
FinSvcs	0.69%	7.70%	0.43%	4.30%	0.11%	7%
BusSvcs	0.89%	7.30%	0.45%	3.20%	0.09%	20%
Unweighted average	0.58%	4.20%	0.58%	4.30%	0.49%	17%

Notes: Final row are unweighted averages. All Δ_3 are divided by 3 to give annual percentage point changes. Columns are: 1= $\Delta_3 \ln TFP^G$ change in log gross output-based TFP. 2= $\Delta_3 \ln R_{i,t}^{PRIV}$ growth in private sector R&D capital, 3= $\sum \omega_{i,t} \Delta_3 \ln R_{i,t}^{PRIV}$ is outside industry $\Delta_3 \ln R_{i,t}^{PRIV}$ weighted by the fraction of outside industry workers moving to industry i over the period; in other columns, N^{PUB} =Public R&D performed by research councils, higher education and government labs, G_{it} = industry gross output, N^{PRIV} =nominal private R&D performed, COOP is fraction of firms in the industry co-operating with government or universities. The unweighted average $\Delta_3 \ln TFP^G$ for these market sector industries in the final row = 0.58%, the Hulten-Domar weighted = 1.44%pa.

Figure 2: Correlations with three-year growth rates of TFP



Note to figure: all data in deviation from time and industry mean. Each point is an industry at a point for each year 1995-2007. Each vertical axis shows $\Delta_3 \ln TFP_{it}$. The horizontal axes show, clockwise from the top left (a) $\Delta_3 \ln R_{it}^{PRIV}$, (b) $\left(\sum \omega_{i,t} \Delta_3 \ln R_{i,t}^{PRIV}\right)$ using labour force transitions across industries to measure $\omega_{i,t}$, and (c) $(X/\Sigma X) (N^{PUB}/G)_{i,t-3}$ where the measure of X is COOP, i.e. the fraction of firms in the industry reporting co-operation with universities or government labs.

Table 4: Regression results of estimating (14) (dependent variable: $\Delta_3 \ln TFP_{it}$).

	(1)	(2)	(3)	(4)	(5)
VARIABLES	R&D	R&D	COOP	COOP	COOP
$\Delta_3 \ln R_{i,t}^{PRIV}$	0.10 (4.16)	0.11 (2.72)	0.08 (3.48)	0.09 (6.59)	0.10 (2.60)
$\Sigma \omega \Delta_3 \ln R_{i,t}^{PRIV}$	0.82 (2.41)	0.92 (1.78)	-0.68 (-1.73)		
$((R\&D)/\Sigma R\&D) * (N^{PUB}/G)_{i,t-3}$	0.41 (3.00)				
$((R\&D)/\Sigma R\&D) * (N^{PUB}/G)_{i,t-6}$		0.82 (3.30)			
$(COOP/\Sigma COOP) * (N^{PUB}/G)_{i,t-3}$			0.36 (5.62)	0.21 (4.59)	
$(COOP/\Sigma COOP) * (N^{PUB}/G)_{i,t-6}$					0.20 (2.09)
F test for fixed effects equal (F(5,57))	2.17		0.96		
Hausman, FE versus RE ($\chi^2(3)$)	6.51		4.59		
Observations	78	60	78	78	60
Number of ind	6	6	6	6	6

Notes: Robust t statistics in brackets. Sample is 1995-2007, 6 industries excluding agriculture. Estimation by random effects with time dummies. All change variables are three year differences divided by three so that the coefficients on them and the public R&D variables can be interpreted as annual elasticities and rates of return. Memo item: average private R&D intensity=0.0049 for whole regression sample, 0.023 for manufacturing.

5.3 Estimates

Table 4 sets out our results of estimating (14). Columns 1 and 2 use the R&D share to measure $X_i/\Sigma X_i$ and 3, 4 and 5 use COOP. Estimation is by random effects: as the test statistics show, we can drop the fixed effects and the Hausman test shows no significant difference between fixed and random effects coefficients. Column 1 shows a positive and statistically significant effect from $\Delta_3 \ln R_{it}^{PRIV}$ and $(\Sigma \omega_{i,t} \Delta_3 \ln R_{-i,t}^{PRIV})$, consistent with R&D spillovers within and between industries. The coefficient on $(R\&D_i/\Sigma R\&D_i) (N^{PUB}/G)_{t-3}$ is likewise positive and significant suggesting $\rho^{PUB}=41\%$. Column 2 shows robust pattern of significance using the longer lagged $(R\&D_i/\Sigma R\&D_i) (N^{PUB}/G)_{t-6}$. Column 3, using $(COOP_i/\Sigma COOP) (N^{PUB}/G)_{t-3}$ is shows a similar pattern with $\rho^{PUB} = 36\%$; column 4 drops the statistically insignificant $(\Sigma \omega_{i,t} \Delta_3 \ln R_{-i,t}^{PRIV})$ term, with $\rho^{PUB} = 21\%$: a similar figure obtains in column 5 with a six year lag.

5.4 Robustness of ρ^{PUB}

Before exploration of the economic significance of the results, Table 5 sets out some robustness checks, taking as a basis table 4, column 4, which gave $\rho^{PUB} = 20\%$. Column 1 checks for outliers by using robust regression techniques ρ^{PUB} is the same.

Column 2 uses a different measure of government R&D (provided by the Department of Business, Innovation and Skills), which is the sum of research council and HEFCE funding. So this is both a funding

variable we lose degrees of freedom).

Table 5: Robustness tests of estimates of (14)(dependent variable: $\Delta_3 \ln TFP_{it}$).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
VARIABLES	robust reg	BIS SET measure	half dep rate	double dep rate	no intang capitalised	soft&R&D capitalised	R&D in BSvcs	Intermed weights	imperf comp nonCRS
$\Delta \ln K_{i,t}^{R\&D}$	0.09 (4.74)	0.10 (5.72)	0.09 (6.57)	0.09 (6.58)	0.10 (6.06)	0.10 (6.44)		0.09 (6.10)	0.10 (3.25)
$(COOP/\Sigma COOP) * (N^{PUB}/G)_{i,t-3}$	0.19 (3.01)		0.21 (4.54)	0.21 (4.61)	0.23 (5.02)	0.22 (5.16)	0.19 (3.76)	0.21 (4.92)	0.16 (1.87)
$((COOP)/\Sigma COOP) * (N^{PUB,SET}/G)_{i,t-3}$		0.31 (4.38)							
$\Delta \ln K_{i,t}^{R\&D,BSvcs}$							0.08 (4.50)		
$\omega \Delta \ln K_{i,t}^{R\&D}$								0.04 (1.13)	
$\Sigma s_x \Delta \ln X_{i,t}$									0.01 (0.22)
$\Sigma s_x^{(K,R)} \Delta \ln X_{i,t}^{(K,R)}$									-0.05 (-1.07)
Observations	78	78	78	78	78	78	78	78	78
Number of ind	6	6	6	6	6	6	6	6	6

concept, rather than performing, but also a slightly different data source, namely BIS: the implied $\rho = 0.31$, somewhat higher than 20%. Columns 3 and 4 return to the original regression, Table 4, column 4, but halve and double all intangible depreciation rates respectively: ρ is hardly affected. Columns 5 and 6 construct $\Delta \ln TFP$ with no intangibles capitalised and only software and R&D capitalised: ρ stays the same. Column 7 leaves R&D reported as located in the business services sector in that sector as opposed to allocating to other sectors, and Column 8 intermediate input weights for $X/\Sigma X$: again ρ is not much affected.

Finally, column 9 uses controls for imperfect competition and non-constant returns to scale (see Haskel et al. (2012) and Appendix 1). The point estimate of ρ^{PUB} falls somewhat, but the additional terms are statistically insignificant.

5.5 Discussion

First, to get some sense of the economic magnitude of these results, we may use them to find out the contributions of $\Delta \ln R^{PUB}$ and N^{PUB} to $\Delta \ln TFP$ which using (14) are

$$\begin{aligned}
 &= \Sigma DH_{it} \left(\hat{\gamma}_1 (\Delta_3 \ln R_{it}^{PRIV}) + \hat{\gamma}_2 \left(\Sigma \omega_{i,t} \Delta_3 \ln R_{-i,t}^{PRIV} \right) \right) \\
 &\quad + \Sigma DH_{it} \left(\hat{\rho}_1 \left[\frac{X_{it}}{\Sigma X_{it}} \right]_{t-3} \left(\frac{N^{PUB}}{Y_i} \right)_{t-3} \right)
 \end{aligned} \tag{15}$$

where in the top line, the impact of $\Delta \ln R^{PRIV}$ is the impact of within-industry spillovers and the between industry spillovers, all then weighted and summed by DH). The impact of N^{PUB} is via ρ_1 , again DH weighted. Using the coefficients in column 1 and column 3 of Table 4 we obtain contributions of $\Delta \ln R^{PRIV}$ and N^{PUB} to $\Delta \ln TFP$ of 1.83%pa and 0.29%pa using R&D interacted N^{PUB} with as in column 1 and 1.13%pa and 0.19%pa using COOP interacted N^{PUB} with as in column 3. The COOP terms are less because there is no ‘‘outside’’ R&D growth term and ρ_1 is smaller. The numbers using the R&D interactions seem quite high, suggesting we might favour the COOP results. That said, note that the UK science base is generally viewed as being very good and most of the period is one of very low spending so one might expect high marginal returns.

Table 6: Policy experiments (pppa changes in $\Delta \ln TFP$ due to row policy change)

	R&D spec	COOP spec	R&D, German weights
Memo: Baseline $\Delta \ln TFP$	1.46%	1.46%	1.51%
<i>Pppa deviation from baseline:</i>			
Raise N^{PUB} by 10%	0.03	0.02	0.04
Raise $\Delta \ln R_{Mfring}^{PRIV}$ by 1pppa (4.4%pa to 5.4%pa)	0.09	0.06	0.12
Raise all $\Delta \ln R_{i,t}^{PRIV}$ by 1pppa (econ average from 3%pa to 4%pa)	0.35	0.20	0.34
Raise all $\Delta \ln R_{i,t}^{PRIV}$ by 1pppa (econ average from 3%pa to 5%pa)	0.70	0.37	0.68
Raise all $\Delta \ln TFP^{retail}$ by 0.1pppa (0.89%pa to 0.99%pa)	0.07	0.07	0.06

Second, our industries are quite aggregated. Many papers on spillovers use, for example, just data on manufacturing, whereas we have manufacturing as a whole. Thus our γ_1 coefficient, which we describe as an “inside” industry effect is an “outside” effect relative to some other studies.

Third, on the public sector returns estimate, most of the variation in $(X_K/\Sigma X) * (N_t^{PUB}/G_{it})$ is between-industry variation. Thus the margin that identifies ρ is mostly driven by changes in the spread of G between industries, or the share of R&D or co-operation. This might be misleading if such variation has a different return to time series variation in N^{PUB} . To look at this, we ran a simple time series regression using the average data from Figure 1, which just uses therefore time series variation: the coefficient was much higher, 1.2 (t=2.05) so these estimates might be an understatement.

6 Policy counterfactuals

Finally, Table 6 sets out some policy experiments. The first two columns use UK data and coefficients based on Table 4, column 1 and column 4. The final column uses coefficients from Table 4, column 1, but German DH weights. As a memo item, Domar-Hulten weighted $\Delta \ln TFP$ is 1.46%pa but 1.51%pa with German DH weights.

The first row, first and second column, shows the effect of raising public R&D (here, that is spending on research councils and HEFCE) by 10%. As the table shows, this raises $\Delta \ln TFP$ by 0.03pppa and 0.02pppa reflecting different returns to public R&D. The final column shows a higher rise with German DH weights. The second row raises growth in manufacturing R&D ($\Delta \ln R^{PRIV, Mfring}$) by 1pppa, from 4.4%pa to 5.4%pa. This raises $\Delta \ln TFP$ by 0.09pppa and 0.06pppa, but 0.12pppa in Germany. Rows three and four raise all industry $\Delta \ln R^{PRIV}$ by 1pppa and 2pppa respectively, raising economy-wide $\Delta \ln TFP$ by 0.22pppa and 0.45pppa for the co-op case, and 0.34pppa and 0.68pppa with German weights. Finally, to get some sense of the comparative numbers row six raises $\Delta \ln TFP$ in retailing by 0.1pppa which is an estimate of the loss in $\Delta \ln TFP$ in retailing due to planning restrictions (Haskel and Sadun, 2012): this raises overall $\Delta \ln TFP$ by 0.07pppa (but by less with German HD weights, reflecting UK industrial structure being tilted to retailing).

What do we learn from this exercise? First, the returns to each reform depend upon the structure of the economy. So, for example, if the UK economy was more high value manufacturing orientated, as is the German economy, the marginal impact of public R&D would be higher. Second, the most substantial productivity gains are to be seen with $\Delta \ln R^{PRIV}$ in all industries is raised to 5%pa. An industry R&D/GDP ratio of 5%pa has not been seen in the UK since the 1950s and so this would be a remarkable turnaround. Third, one might of course argue that these policies are interdependent: if for example $\Delta \ln R^{PUB}$ crowded

in $\Delta \ln R^{PRIV}$, the public sector effects would be enhanced.

Finally, recall that the effect of N^{PUB} was mediated by industry R&D spend. Thus the marginal impact of N^{PUB} rises with more industry R&D spend, although the effect is not quite so straightforward since in our specification it depends upon R&D spend relative to the average: this stays the same if all industries raised their spend by, say 7%. We examined the change in the impact of a 10% rise in N^{PUB} , as set out in Table (6), row 1, if there was a rise in manufacturing R&D spend by 7%; the impact of N^{PUB} is larger, but to the fourth decimal place (the manufacturing R&D share rises only a very small amount from 0.886 to 0.879).

7 Conclusion

We have tried to estimate the contribution of public and private R&D to UK productivity growth on a new set of industry data, 1992-2007. Private R&D affects productivity growth are (1) R&D input, valued at competitive factor shares and (2) (Domar-Hulten weighted) industry TFP growth if there are spillover either within or between industries. Public sector R&D affects productivity growth via spillovers to the private sector. Thus overall effects depends upon factor shares, spillovers and industrial structure. We check our results therefore for robustness to a host of measurement and modelling assumptions e.g. allocation of R&D, choice of interindustry spillover weights and imperfect competition.

Our findings are as follows. First, we find evidence of spillovers of private R&D and public R&D, with an estimated rate of return to public R&D of 20%. Second, our data are consistent with the idea that the public R&D spillover to an industry depends on the absorptive capacity of the industry (its R&D spend or involvement with the public sector). Third, our counter-factual policy experiments suggest a 10% rise in public R&D would raise private TFP growth by 0.03pppa (relative to a baseline of TFP growth at 1.46%pa). This would be 0.04pppa if the UK had Germany's industrial structure.

As mentioned, we regard these findings as complementary to others, for example, those documenting the precise routes by which public R&D knowledge spreads. Better data over a longer period would help relate these findings to others and test for robustness. Finally, our policy simulations are illustrative of various changes. To study the relative impacts of, say R&D tax incentives and public support for universities, we would have to estimate a demand for private R&D equation, simulate the dynamic effects of changes in R&D spend on the R&D stock and thence on TFP growth and compare with the public spend impact. We hope to pursue this in future work.

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A Appendix: Imperfect competition

A.1 Assumptions and definitions

Following Haskel et al. (2012), based in turn on Basu and Fernald (2001) we may control for imperfect competition and non-constant returns as follows. Write (1) as

$$\Delta \ln G_{it} = \Delta \ln A_{it} + \varepsilon_{Mit} \Delta \ln M_{it} + \varepsilon_{Lit} \Delta \ln L_{it} + \varepsilon_{Kit} \Delta \ln K_{it} + \varepsilon_{Rit} \Delta \ln R_{it} \quad (\text{A.1})$$

where ε is an output elasticity

$$\varepsilon_{Xit} \equiv \frac{\partial F_{it}}{\partial X_{it}} \frac{X_{it}}{F_{it}}, \quad X_{it} = M_{it}, L_{it}, K_{it}, R_{it} \quad (\text{A.2})$$

Profit maximising implies

$$\begin{aligned} \varepsilon_{Xit} &\equiv \mu s_{X,it} \\ s_{X,it} &\equiv \left(\frac{P_{X_{it}} X_{it}}{P_{G_{it}} G} \right), \quad X = L_{it}, M_{it}, K_{it}, R_{it} \end{aligned} \quad (\text{A.3})$$

where μ is a product mark-up over costs. Note that μ is not input specific, since it refers to a product market mark-up (implicitly assuming firms have no input market monoposony power). Returns to scale, ϕ are related to the output elasticities (Basu and Fernald (2001)) by

$$\phi \equiv \sum_{X=M_{it}, K_{it}, L_{it}, R_{it}} \varepsilon_{X,it} \quad (\text{A.4})$$

Finally, as above, define

$$\Delta \ln TFP_{it} \equiv \Delta \ln G_{it} - \sum_{X=L_{it}, M_{it}, K_{it}, R_{it}} s_{X,it} \Delta \ln X_{it} \quad (\text{A.5})$$

leaving aside issues around Tornquist shares etc.

A.2 Implications

This completes the model. The implications are as follows. First, note the relation between ϕ , returns to scale, and μ from combining (A.3) and (A.4) is

$$\phi \equiv \mu \left(\sum_{X=M_{it}, K_{it}, L_{it}, R_{it}} s_{X,it} \right) \quad (\text{A.6})$$

As Basu and Fernald (2001) point out, mark-ups ($\mu > 1$) require increasing returns ($\phi > 1$) as e.g. in Chamberlinian/Robinson monopolistic competition. Second, suppose we have independent measures of all factor prices, $P_{X_{it}}$ (and of quantities X_{it}). Then we can write (A.1) as

$$\Delta \ln G_{it} = \Delta \ln A_{it} + \mu \sum_{X=M, L, K, R} s_{X,it} \Delta \ln X_{it} \quad (\text{A.7})$$

and thus a regression of (changes in log) outputs on summed inputs will, with assumptions on A, return an estimate of μ . This is essentially the method in Basu and Fernald (2001)), which, using (A.6) also estimates ϕ . Third, suppose we do not have independent measures of $P_{K_{it}}$ and $P_{R_{it}}$ but we are willing to assume constant returns, $\phi = 1$. Then we can use (A.6) to write (A.1), using also (A.5) as

$$\Delta \ln TFP_{it} = \Delta \ln A_{it} + (\mu - 1) \left(\sum_{X=M,K,R} s_{X,it} \Delta \ln(X/L)_{it} \right) \quad (\text{A.8})$$

which is more or less the method of Hall (1988) to estimate μ (he omits M and R). Finally, if we neither assume $\mu = 1$ nor $\phi = 1$ we have

$$\begin{aligned} \Delta \ln TFP_{it} &= \Delta \ln A_{it} + (\mu - 1) \left(\sum_{X=M,L,K,R} s_{X,it} \Delta \ln(X)_{it} \right) \\ &+ (\phi - \mu) \left(\sum_{X=K,R} (s_{K,R}^X \Delta \ln X_{it}) \right) \end{aligned} \quad (\text{A.9})$$

where in the last equation $s_{K,R}^X = P_X X / (P_K K + P_R R)$ i.e. the shares of the two capital categories whose factor shares are derived residually: the final terms in (A.9) disappear if $\mu = \phi = 1$. These final terms are added to the spillover terms in Table (5), column 9: the rest of the paper omits them which corresponds to the traditional assumptions of $\mu = \phi = 1$.

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